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# Contribution to Flexible Optical Network Design: Spectrum Assignment and Protection

Hai Dao Thanh

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En accréditation conjointe avec l'Ecole Doctorale Sicma  
Mention : Sciences et Technologies de l'Information et de la Communication

présentée par

**Hai Dao Thanh**

préparée dans le département Optique

# Contribution to Flexible Optical Network Design : Spectrum Assignment and Protection

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Sous le sceau de l'Université européenne de Bretagne

## Télécom Bretagne

Ecole Doctorale - SICMA

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# Contribution to Flexible Optical Network Design: Spectrum Assignment and Protection

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## Thèse de Doctorat

Mention : STIC

Présentée par **Dao Thanh Hai**

Département : Optics

Laboratoire : Lab-STICC - Pôle

Directeur de thèse : Jean-Louis de Bougrenet de La Tocnaye

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*“The first principle is that you must not fool yourself - and you are the easiest person to fool. ”*

Richard Feynman

# *Abstract*

The explosive growth of Internet traffic driven by proliferation of broadband services necessitates for a paradigm change in transport network. Introducing flexibility into optical layer has been considered as a guiding direction for improving network cost and energy efficiency. The traditional fixed network paradigm is therefore migrating to flexible one where a number of transmission parameters could be tuned and adapted to various network conditions. This changing paradigm clearly leverages new opportunities for addressing the very important problem, resiliency, in network design. On the other front, as the network becomes more flexible with an increasing number of degree of freedom, and consequently more complex, the role of algorithm in designing, operating and managing network has turn into of paramount importance when efficient algorithms are sought to achieve not just best use of resources but also to meet stricter requirement on running time and scalability issues. In this context, the works carried out in the thesis presents new protection schemes enabled by adaptive operation of flexible transponders, and new algorithms for solving the routing and spectrum assignment considering both single and multi-objective cases. Novel scientific contributions are presented into three following chapters:

In Chapter 2, the rate-adaptive operation with multi-line rate transponder for efficient protection is presented and benchmarked with traditional approach. The survivable network design with both dedicated and shared protection is formulated and investigated over extensive simulations to study the impact of introducing such new protection schemes in term of transponder count, cost and power consumption.

Chapter 3 is dedicated to algorithms for solving the routing and spectrum assignment. In single-objective case, the novel algorithm based on genetic algorithm is proposed and benchmarked with other heuristics as well optimal solutions obtained from exact formulation. The contribution also includes the proposing of feeding good solutions from heuristic algorithms to warm-start the solvers. Afterwards, the multi-objective cases are examined extensively considering two scenarios whether or not the objective preferences is taken into account.

Chapter 4 focuses on path protection in OFDM-based network considering novel scheme based on modulation-adaptive operation. The scheme is enabled by the reconfiguration capability of OFDM transponder to work at different modulation formats and consequently different spectrum assignments for the working and protection path in network-side protection. The dimensioning of network with both dedicated and shared path protection considering this new scheme is performed and examined in compared with conventional approach to demonstrate the spectrum and power consumption efficiency.

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In Brest, May 2015

Dao Thanh Hai



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*Dedicated to my interest in photonic communication*

# Résumé

L'ère du "data storm" arrive avec l'utilisation croissante d'applications nécessitant une bande passante élevée, telles que la vidéo en ligne, les services de cloud computing, grâce à la pénétration massive de nouvelles générations de terminaux. Des chercheurs de Bell Labs estiment que de 2013 à 2017, les opérateurs feront face à un accroissement de plus d'un facteur cinq de la demande en bande passante pour les services de cloud computing (par exemple, le stockage, les plates-formes, les infrastructures), et de plus de sept pour la vidéo IP à travers des réseaux fixes et mobiles. Dans l'ensemble, cela se traduira par une multiplication par trois fois du trafic dans le réseau cœur. De toute évidence, cette croissance du trafic impose des innovations dans le réseau de transport afin de répondre aux exigences de trafic tout en veillant aux coûts et à la consommation d'énergie.

En outre, comme d'énormes quantités de trafic (plusieurs Térabit/s) sont transportées sur le réseau optique et que la société est toujours plus dépendante de l'information, toute défaillance aurait un impact massif. La résilience du réseau a donc une importance cruciale et doit être prise en compte dans le processus de planification de celui-ci. Comme les réseaux de transport optiques évoluent dans un paradigme de flexibilité croissante, les questions de résilience sont un sujet de recherche intéressant pour l'étude des nouvelles possibilités offertes par cette flexibilité. Par ailleurs, comme les réseaux deviennent plus complexes, l'utilisation efficace des ressources du réseau devient un enjeu très important, qui dépend beaucoup des algorithmes mis en œuvre. L'identification d'algorithmes d'optimisation des ressources efficaces est une direction prometteuse pour améliorer l'efficacité du réseau. Dans ce contexte, la thèse se fixe pour objectifs d'étudier de nouveaux systèmes de protection s'appuyant sur l'adaptation de transpondeurs flexibles, ainsi que certains aspects des algorithmes permettant de résoudre le problème de routage et d'allocation des fréquences dans un réseau flex-grid. La thèse est organisée en cinq chapitres qui sont brièvement décrits comme suit.



## **Chapitre 1: Introduction**

Le premier chapitre présente le contexte de la recherche et la motivation de la thèse, ainsi que des connaissances de base nécessaires pour comprendre les chapitres suivants. Il commence par le cadre de la thèse et de son orientation. Il continue par une introduction aux technologies des réseaux optiques, leurs architectures et leur évolution. Une revue des problèmes de planification de réseau et des outils d'optimisation associés est enfin présentée.

## **Chapitre 2: Application de transpondeurs à débit variable pour une protection efficace**

Le chapitre 2 est intitulé "Application de transpondeurs à débit variable pour une protection efficace". Ce chapitre examine l'application du transpondeur MLR (Multi-Line Rate) 100/200 Gb/s pour la protection d'un réseau WDM opaque. Le réseau est dimensionné de sorte qu'il est résilient à toute coupure de fibre qui est la défaillance la plus courante dans la pratique. En particulier, un nouveau fonctionnement adaptatif est proposé pour le transpondeur MLR de telle sorte que le débit le plus bas soit utilisé pour le en fonctionnement normal et en cas d'événement de défaillance, le transpondeur MLR peut être réglé temporairement à débit plus élevé, par exemple, double pour assurer la protection du trafic. Ce choix est motivé par l'observation que la période au cours de laquelle le réseau est en mode de protection peut être considérée comme négligeable par rapport au mode normal, et donc utilisant le transpondeur MLR à un débit supérieur uniquement pour la période de protection pourrait être potentiellement efficace énergétiquement plutôt que la solution traditionnelle basée sur transpondeurs à débit unique (SLR: single line rate). Par ailleurs, la commutation de 100 à 200 Gb/s devrait avoir un effet transitoire négligeable sur les amplificateurs optiques, en comparaison de la commutation entre modes veille et de travail. En terme de vitesse de protection, cette technique basée sur le fonctionnement adaptatif de MLR reste presque comparable à la solution SLR. En effet, le processus de changement de format de modulation a été expérimentalement démontré être très rapide et une durée négligeable par rapport à celle du processus de détection de panne. La conception d'un réseau résilient classique avec une protection dédiée et partagée est réexaminée avec ce nouveau schéma de protection et la comparaison avec un schéma traditionnel est étudiée.

### **Modèles de transpondeur SLR, MLR et hypothèse**

Le modèle conceptuel des transpondeurs SLR 100G et MLR 100/200G est présenté dans la figure 1. En plus, les hypothèses sur les coûts et la consommation de puissance sont indiquées dans un tableau 1 . Le paramètre  $\alpha$  rend compte du sur-coût d'un transpondeur MLR. Le paramètre

$\beta$  exprime le fait que la gestion de MLR est plus complexe que celle d'un SLR de même débit binaire

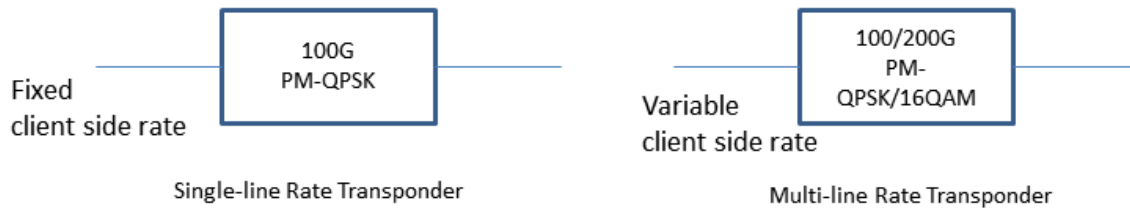


FIGURE 1: Modèles de transpondeur SLR, MLR

TABLE 1: Paramètres de transpondeurs hypothèse

Parameters	SLR (Tx+Rx)	MLR (Tx+Rx)
Cost	1	$1 + \alpha$
Power Consumption	1	100G mode: $1 + \beta$ 200G mode: $1 + \beta + 0.38$

## Framework Design Survivable Réseau

La conception d'un réseau opaque résilient classique est revisitée. Elle se compose de deux étapes. La première étape implique l'allocation de routage et de débit. L'étude est pour le scénario où les ressources sont apparemment assez grandes pour accepter toutes les demandes. Donc, compte tenu de la topologie et de la matrice trafic physique, nous cherchons à trouver le travail et la capacité de réserve sur chaque lien pour que le réseau soit résistant à toute défaillance d'un seul lien et avec l'objectif de minimiser la capacité globale de lien alloué. Le problème est formulé comme programmation linéaire entière mixte. A partir des résultats du sous-problème d'allocation de routage et de débit, nous connaissons les flux de travail et de protection nécessaires pour chaque lien. La deuxième étape porte sur l'allocation des transpondeurs de façon à transporter ces flux. Pour le nouveau schéma de protection basé sur la variation de débit des MLR, nous proposons deux modes opératoires qui diffèrent dans la manière de gérer le trafic de protection lorsque sur un lien il est supérieur au trafic de travail. Ces modes sont formulés ci-dessous.

**Proposition 1:** Les transpondeurs MLR sont utilisés pour traiter toute la capacité pouvant servir à la fois au travail et à la protection. La capacité restante (soit purement protection ou de travail) est traitée en utilisant la capacité restante de MLR et des transpondeurs supplémentaires SLR. En faisant cela, lors du passage du mode normal en mode de protection, la protection

partielle ou complète est effectuée en augmentant temporairement la charge des transpondeurs MLR.

**Proposition 2:** Le schéma 2 est différent du schéma 1 dans la façon de gérer la capacité de protection quand elle est supérieure à la capacité de travail. Dans ce cas la capacité restante est traitée en ajoutant préférentiellement des transpondeurs MLR (à débit maximal) et au plus un seul transpondeur SLR

## Résultats numériques

La simulation est effectuée sur trois topologies différentes afin de démontrer la faisabilité du nouveau système de protection. Trois ensembles de résultats portent respectivement sur le nombre de transpondeur, le coût du transpondeur et la consommation d'énergie. Ils sont présentés dans les tableaux suivants

TABLE 2: Résultats de nombre des transpondeurs

Scenario	Topologies	Conventional	Proposal 1			Proposal 2		
		(SLR)	SLR	MLR	Gain	SLR	MLR	Gain
Dedicated	1	80	28	26	31%	14	33	40%
	2	140	48	47	32%	18	62	42%
	3	220	87	69	30%	42	92	40%
Shared	1	63	13	25	39%	7	29	43%
	2	92	21	37	37%	20	38	37%
	3	147	42	55	34%	39	57	35%

TABLE 3: Résultats d'excès de coûts

Scenario	Protection Scheme	"Break-even" value	Topo1	Topo2	Topo3
Dedicated	Proposal 1	Max	100%	100%	100%
		Min	80%	80%	80%
		Average	89%	90%	89%
	Proposal 2	Max	100%	100%	100%
		Min	80%	80%	80%
		Average	91%	91%	91%
Shared	Proposal 1	Max	100%	100%	100%
		Min	80%	70%	70%
		Average	88%	86%	86%
	Proposal 2	Max	100%	100%	100%
		Min	80%	70%	70%
		Average	90%	90%	89%

TABLE 4: Les résultats de gain de consommation d'énergie

Scenario	Gain	Topo1		Topo2		Topo3		
		$\beta = 0\%$	$\beta = 50\%$	$\beta = 0\%$	$\beta = 50\%$	$\beta = 0\%$	$\beta = 50\%$	
Dedicated	Proposal 1	Min	24%	10%	29%	13%	24%	11%
		Max	38%	18%	38%	18%	35%	17%
		Average	31%	15%	32%	15%	30%	14%
	Proposal 2	Min	32%	14%	29%	18%	36%	15%
		Max	45%	23%	45%	22%	42%	21%
		Average	40%	19%	42%	20%	40%	19%
Shared	Proposal 1	Min	24%	12%	30%	12%	29%	13%
		Max	48%	24%	43%	20%	38%	19%
		Average	39%	18%	37%	17%	34%	15%
	Proposal 2	Min	32%	15%	33%	12%	30%	12%
		Max	48%	24%	42%	20%	39%	19%
		Average	43%	20%	37%	17%	35%	15%

### Chapitre 3: Routage et d'allocation du spectre

Le chapitre 3 est consacré à l'étude du problème de routage et d'allocation du spectre dans les différents scénarios. Les progrès importants des technologies optiques au plans matériel et logiciel ont ouvert la voie à un réseau optique plus efficace, flexible basé sur le paradigme flex-grid.

Etant considéré comme l'architecture prometteuse pour le réseau optique de prochaine génération pour répondre à un trafic Internet toujours croissant, de façon économique et avec une bonne efficacité énergétique, le réseau optique flex-grid a reçu une attention croissante de part de la communauté de recherche et des organismes de standardisation. Parmi d'autres axes de recherche importants, des algorithmes efficaces ont été constamment recherchés afin d'exploiter pleinement les avantages de cette nouvelle architecture de réseau. A l'instar du problème de routage et d'allocation des longueurs d'onde (RWA) dans les réseaux conventionnels à grille de multiplexage fixe, le problème de, routage et d'allocation de spectre (RSA) est une tâche cruciale pour la planification et fonctionnement du réseau avec un espacement élastique des canaux multiplexés en longueurs d'onde. Une des motivations principales pour abandonner la grille de longueurs d'onde actuelle est d'utiliser plus efficacement le spectre ; dans une large mesure, ce résultat dépend de la capacité à résoudre le problème RSA. Ce chapitre traite de la version statique du problème RSA pour les deux scénarios mono- et multi-objectifs. Pour le cas mono-objectif, la contribution est double. Tout d'abord, nous avons proposé une méta-heuristique efficace basée sur un algorithme génétique (GA) pour fournir des solutions quasi-optimales au problème. L'efficacité de l'heuristique basée-GA est comparée avec d'autres heuristiques pour un ensemble de scénarios de réseau. Il est démontré dans la littérature qu'en plus d'une performance meilleure que celle d'une heuristique typique, l'heuristique GA proposée est susceptible de fournir des solutions optimales dans la plupart des cas, avec un temps d'exécution encore raisonnable. Deuxièmement, nous proposons d'utiliser de très bonnes solutions de base fournies par la (méta) heuristiques pour définir la limite supérieure pour la formulation de la programmation linéaire entière (démarrage à chaud). Cette combinaison s'avère très efficace pour réduire le temps d'exécution et augmente significativement la probabilité d'obtenir une solution optimale dans un intervalle de temps donné par rapport à une exécution séparée du modèle de programmation linéaire entière.

Pour le scénario multi-objectif, nous avons abordé deux contextes. Le premier est quand un objectif est préféré aux autres et nous exploitons les caractéristiques des objectifs afin de définir correctement un poids reflétant cette préférence et convertir le problème multi-objectifs en un problème mono-objectif avec une fonction de coût intégrée. De plus, nous démontrons en résolvant des modèles de programmation linéaires entières que l'optimisation sur la base d'un permet d'atteindre de meilleures solutions qu'en ne retenant que l'objectif principal sans tenir compte des autres objectifs. A la différence du premier contexte, le second ne présuppose aucune information préalable sur les préférences relatives des objectifs. Dans ce cas, nous utilisons un algorithme génétique multi-objectif pour obtenir un front non-dominant (front de Pareto). Un nouveau modèle de codage génétique tenant compte à la fois du routage et de l'allocation des fréquences a été employé.

## Cas mono-objectif avec algorithme génétique

Nous considérons le problème RSA avec pour objectif la minimisation de la largeur du spectre. Il est décrit comme suit: compte tenu de la topologie physique et d'un ensemble d'exigences à respecter, trouver l'itinéraire et assigner des fréquences à chaque demande selon un certain nombre de contraintes (continuité du spectre, contiguïté du spectre et non-recouvrement du spectre, de sorte que tous les demandes soient servies et en minimisant la largeur totale du spectre, mesurée en terme de nombre de tranches de spectre.

L'algorithme GA est utilisé pour aider à trouver un bon (éventuellement optimal) ordre des demandes à servir séquentiellement de façon à minimiser la largeur spectrale nécessaire. La qualité des solutions GA est comparé d'une part avec une heuristique typique, dénommée MSF (les plus grosses tranches d'abord) et d'autre part avec la solution optimale de la formulation ILP. Le tableau 5 indique les paramètres utilisés pour l'algorithme GA à être utilisés et le tableau 6 présente les résultats de la comparaison avec les deux autres algorithmes.

TABLE 5: GA paramètres

Parameters or Operator	Value
Population size $P_{size}$	chromosome length $\times 2$
Crossover rate $X_{rate}$	0.5
Mutation rate $\mu$	0.05
Maximum number of generations $G$	{50, 200}
Mating selection	random pairing
Crossover scheme	single-point

TABLE 6: Comparaison des performances

Network	k	MSF		GA-50		GA-200		ILP	
		$\phi$	T (s)	$\phi$	T (s)	$\phi$	T (s)	$\phi$	T (s)
Topo1	2	13.15	0.04	10.75	8.50	10.65	33.58	10.55	196.63
	3	12.75	0.06	10.75	12.25	10.65	48.29	10.55	489.12
Topo2	2	15.65	0.09	13.25	29.63	13.15	116.76	12.6	2746
	3	14.4	0.16	12.65	41.79	12.55	164.71	12.15	-

Nous avons également étudié sur l'utilisation des solutions heuristiques afin de fournir des conditions initiales permettant d'accélérer le temps d'exécution du solveur. Pour l'analyse comparative, nous considérons trois options pour le fonctionnement de l'ILP. D'abord l'option traditionnelle lorsque la taille du spectre  $S$  est choisie en aveugle ou sur la base d'un cas très défavorable de façon à ce qu'il puisse satisfaire aux hypothèse de demande les plus exigeantes. Dans la deuxième et la troisième option,  $S$  est défini par la valeur de la fonction d'objectif trouvée en exécutant une heuristique MSF ou GA. Par ailleurs, les solutions de MSF et GA (l'acheminement et le spectre alloué pour chaque demande) sont également utilisées comme point de démarrage

à chaud pour l'exécution de l'ILP. Les deuxième et troisième options diffèrent par le fait que les solutions de l'algorithme GA sont meilleures que celles de MSF et ainsi, définissent plus strictement des conditions initiales pour l'ILP. Le tableau 7 montre la comparaison des temps de fonctionnement, calculés en moyennant les résultats obtenus avec 20 matrices de trafic différentes, lorsque les trois modèles fournissent des solutions optimales en un temps inférieur à 2 heures (par exemple, avec un réseau de taille réduite: Topo1). Le tableau 8 montre aussi les résultats lorsque la formulation ILP basé sur l'estimation de S à partir du pire cas n'est pas résolue en moins de 2 heures pour tous les 20 cas, par exemple, le réseau est plus grande échelle: Topo2)

TABLE 7: Comparaison des temps d'exécution

Network	$k$	$T_{ILP}(s)$ with $ S  = 50$	$T_{ILP-MSF}(s)$	$T_{ILP-GA}(s)$
Topo1	2	196.63	0.26	0.08
	3	489.12	0.28	0.08
	4	1211.20	0.28	0.12

TABLE 8: Comparaison de l'optimalité

Network	$k$	ILP with $ S  = 50$	ILP-MSF		ILP-GA	
		$\alpha$	$\alpha$	$T(s)$	$\alpha$	$T(s)$
Topo2	4	$\frac{11}{20}$	$\frac{20}{20}$	12.5	$\frac{20}{20}$	2.9
	6	$\frac{7}{20}$	$\frac{20}{20}$	20.5	$\frac{20}{20}$	5.1
	10	$\frac{1}{20}$	$\frac{20}{20}$	52.2	$\frac{20}{20}$	25.2

## Cas multi-objectif

De nombreux problèmes du monde réel nécessitent l'optimisation simultanée de plusieurs d'objectifs. On parle alors d'optimisation multi-objectifs. Souvent, dans ces problèmes, certains des objectifs requis peuvent être en conflit avec un autre. Par exemple, dans la conception de réseau en minimisant à la fois l'utilisation globale du spectre et le niveau de congestion des liens. Comme la minimisation du niveau de congestion est réalisée en répartissant le trafic sur des chemins diverses (différent du plus court chemin) il en résulte intrinsèquement une augmentation du spectre total utilisé.

Une réduction de l'utilisation du spectre utilisé d'autre part, signifie que la demande prend simplement les itinéraires les plus courts ce qui conduit potentiellement à un goulot d'étranglement du fait de la congestion.

Nous considérons le problème RSA multi-objectifs en essayant de minimiser à la fois l'utilisation du spectre sur les liens et le niveau de congestion. De toute évidence, l'extension à plus de

deux objectifs est tout à fait simple. Nous étudions le problème sous deux perspectives. Dans la première, nous supposons qu'il y a des informations sur la priorité d'un des deux objectifs et nous proposons alors une méthode pour régler correctement le poids qui reflète cette préférence. Dans la seconde perspective, tous les objectifs sont également importants (i.e., sans aucune préférence préalable). Nous employons dans ce cas un algorithme génétique multi-objectifs qui est basé sur le tri rapide non-dominé (NSGA-II), de façon à trouver le meilleur front non-dominant

## **Chapitre 4: Protection des chemins du côté réseau dans un réseau OFDM**

L'OFDM optique (Optical orthogonal frequency-division multiplexing) suscite beaucoup d'intérêt grâce à sa capacité à offrir une très haute efficacité spectrale et beaucoup de flexibilité. Cela a ainsi permis de proposer un réseau optique élastique basé sur la technologie OFDM. L'élément clé dans un tel réseau est le transpondeur OFDM transpondeur, disposant de fonctionnalités avancées de traitement du signal numérique et permettant ainsi d'adapter le format de modulation et l'encombrement spectral.

Le dimensionnement d'un réseau optique employant une technologie OFDM adaptative pose de nouveaux défis tels que la sélection des paramètres de transmission, qu'il est maintenant possible d'adapter à chaque demande individuelle plutôt que choisir en fonction du pire cas comme dans un réseau WDM traditionnel à grille fixe. Dans ce chapitre, nous proposons d'exploiter la modulation OFDM-adaptative du transpondeur dans le cadre de la protection côté réseau. L'idée est inspirée par l'observation que dans un réseau de portée diversifiée, la différence de longueur entre chemin de travail et de protection d'une connexion peut être assez grande, et donc, il est possible d'utiliser un format de modulation différent selon le chemin, plutôt qu'un format unique compatible avec le chemin le plus long. Nous décrivons le design d'un réseau protégé en considérant un chemin de protection dédié ou un chemin partagé. Nous effectuons une étude de cas sur une topologie réaliste (COST 239) afin de comparer trois cas différents en termes de degrés de liberté, à savoir i) SCSF: formats de modulation et allocations du spectre identiques pour les chemins de travail et de protection ii) DCSF: formats de modulation identiques pour les deux chemins tout en permettant une allocation différente du spectre entre les chemins iii) DCDF: des formats de modulation différents et des allocations de spectre différentes sont autorisées entre chemins de travail et de protection. L'étude est considérée dans deux scénarios. Le premier est appelé capacité non limitée où toutes les demandes sont acceptées et la métrique de comparaison est basée sur la largeur spectrale nécessaire et la consommation d'énergie des transpondeurs. Dans le deuxième scénario, les ressources sont limitées, par conséquent toutes les demandes ne peuvent pas être servies et donc la métrique considérée est un taux de blocage du trafic.



La figure ci-dessous met en évidence la différence entre protection côté réseau et côté client. La seconde permet de protéger les transpondeurs mais nous ne la considérerons pas car nous mettons l'accent sur les coupures de lien.

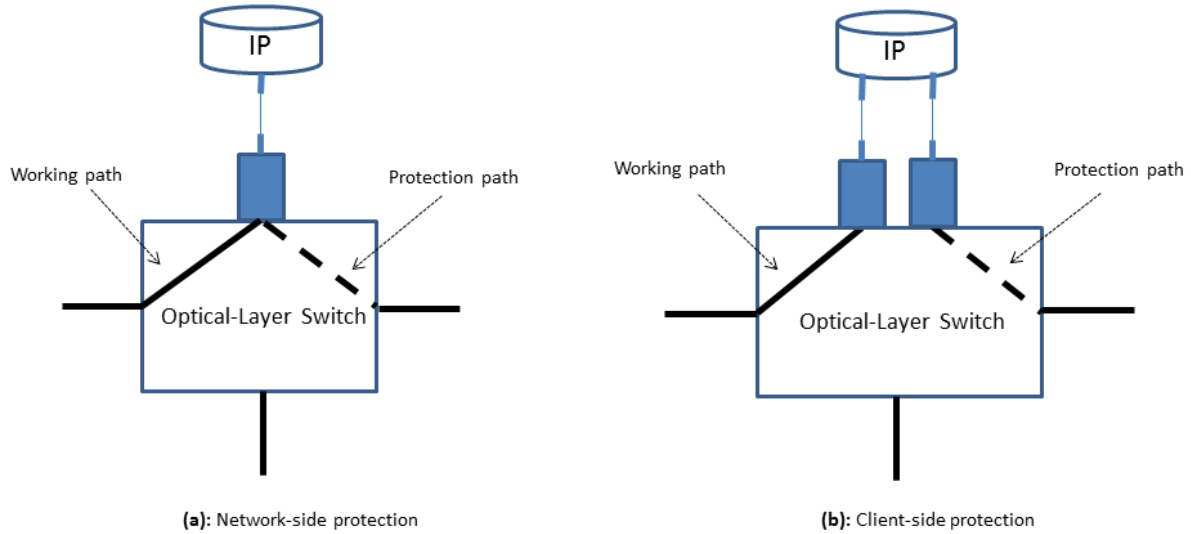


FIGURE 2: La différence entre protection côté réseau et côté client

Les tableaux 9 et 10 montrent le résultat pour la protection dédiée et partagée dans le scénario "capacité non limitée", pour ce qui concerne la largeur du spectre.

TABLE 9: La largeur du spectre pour la protection dédiée

Number of Connections	20	30	40	50	60
SCSF	14.8	19.4	22.1	23.8	24.5
DCSF	14.3	19.1	21.1	23.2	23.9
DCDF	12.1	16.9	17	18.4	19.6
Max difference DCSF vs. SCSF: 5%					
Max difference DCDF vs. SCSF: 21%					

TABLE 10: La largeur du spectre pour la protection partagée

Number of Connections	20	30	40	50	60
SCSF	14.6	18.4	20.4	21.6	22.5
DCSF	14.3	18	19.9	21.1	22.2
DCDF	12	15.6	16.1	18.3	19
Max difference DCSF vs. SCSF: 2%					
Max difference DCDF vs. SCSF: 19%					

Les figures 3 et 4 montrent la consommation d'énergie relative du transpondeur DCSF et DCSF à DCSF pour la protection de chemin dédiée et partagée.

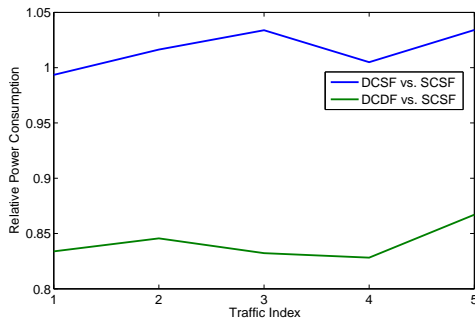


FIGURE 3: Protection dédiée

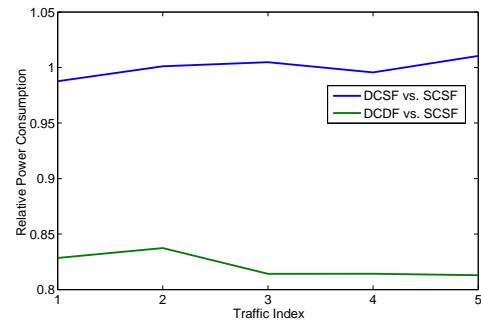


FIGURE 4: Protection partagée

Les tableaux suivants montrent les résultats pour la protection dédiée (le tableau 11) et partagée (le tableau 12) dans le scénario à capacité limitée. La métrique ici est le taux de blocage du trafic.

TABLE 11: Le taux de blocage du trafic pour la protection dédiée  $k = 4$ 

Operation Mode	Number of Connections				
	20	30	40	50	60
SCSF	16.69%	22.06%	24.97%	26.25%	34.31%
DCSF	16.12%	21.85%	23.98%	25.06%	32.67%
DCDF	9.97%	16.10%	18.04%	19.77%	29.76%
Max difference DCSF vs. SCSF: 1.64%					
Max difference DCDF vs. SCSF: 6.93%					

TABLE 12: Le taux de blocage du trafic pour la protection partagée  $k = 4$ 

Operation Mode	Number of Connections				
	20	30	40	50	60
SCSF	14.53%	18.61%	20.43%	22.70%	29.56%
DCSF	14.53%	18.36%	20.14%	22.41%	29.09%
DCDF	8.12%	12.54%	14.86%	16.28%	23.00%
Max difference DCSF vs. SCSF: 0.46%					
Max difference DCDF vs. SCSF: 6.41%					

## Chapitre 5: Conclusion

Le chapitre 5 résume les principales activités de la thèse et met en évidence ses nouvelles contributions. Par ailleurs, il fournit des suggestions intéressantes sur des travaux qui pourraient menés dans le prolongement direct de la thèse

# Chapter 1

## Introduction

### 1.1 Research Context and Motivation

The "data storm" era is coming with the increasing usage of high bandwidth application such as online video, cloud services, fueled up by massive penetration of end-user devices. Researchers from Bell Labs estimated that from 2013 to 2017, operators will see a more than five-fold increase in bandwidth demand for cloud services (e.g., storage, platform, infrastructure), and more than seven times bandwidth demand increase for IP video across fixed and mobile networks. Overall, this will result in a more than three times traffic in the core network [5]. Clearly, the traffic growth picture is pushing for innovations in transport network to not only meet traffic requirement but also in a cost and energy-efficient manner. Besides, as the huge amount of traffic (e.g., multi Terabit) are carried over optical network and the society is more reliant on information, any failure would cause massive impact. Network resilience is thus of crucial importance and must be taken into account in network planning process. As the optical transport networks are evolving into a more flexible paradigm, resilience issues are interesting venue for research as new opportunities are arriving for improving efficiency. On the other front, as the network becomes more complex, the efficient utilization of network resources becomes of great concern and it is in turn dependent on well-designed algorithms. Seeking efficient algorithms for optimizing the resource capacity is promising direction on the way of improving network efficiency.

The thesis work has been carried in the framework of ANR project (100G Flex, 2010-2013), and in the ongoing EU Celtic+ SASER SIEGFRIED project. The thesis started in November 2011 and lasted for more than three years. During that time-span, the thesis endeavors to address network resilience and algorithm aspect of next-generation flexible optical network.

## 1.2 Background Information

For a better understanding in the following chapters, this section provides briefly some background information regarding optical network technologies and network optimization techniques.

### 1.2.1 Evolution of Optical Networks

The story behind the evolution of optical telecommunication is an exciting history with several transformative innovations and undoubtedly, fiber-optic communication plays an enabling role in nowadays information society era.

The birth of fiber-optic communication could be counted practically from the day, more than 40 years ago, that Charles Kao proposed silica as a practical material for long haul distance optical fiber communication [6]. This innovation sparked up for revolution of optical telecommunication starting in 1970s time-frame and are still on the way today. From the beginning of simple point-to-point at low rate and short distance, today's optical connection is entering the era of multi-terabit transmission and ultralong-haul distance in dense-wavelength division multiplexed systems. Behind this evolution are remarkable progress in technologies, capacity, reliability and cost.

It is important to note that fiber optic not only provide huge venue for transmission but also give rise to optical networks and the field of optical networking. The development of optical network is linked to capability in manipulating lightstream. The first milestone was the ability to carry multiple channel on a single fiber, leading to wavelength division multiplexing system (WDM). From the earliest WDM systems supported few wavelength on a single fiber, 100 Gb/s per channel WDM system technology up to thousand km and up to 80 channels on C-band (i.e., 1530 – 1565 nm) has been commercialized nowadays, providing a tremendous growth in network capacity. Besides, the advent of erbium-doped fiber amplifier and later, Raman amplifiers leverage the transmission reach of WDM system to order of thousand km before regeneration. From architectural point of view, the optical layer evolves from a collection of static transmission pipes to one where it was viewed as networking layer supporting network functions such as routing, protection at the wavelength level [1].

Increasing wavelength bit-rate coupled with a greater number of wavelength per fiber is one direction for evolution of optical network to improve the network capacity, cost and energy per bit. For example, upgrading to 400 Gb/s and beyond are under research and likely to be deployed in near future [7]. Another driving force to optical network is from architecture perspective. In

this direction, the optical network has been migrated from opaque architecture to optical bypass one so that a sizable amount of electronic equipment has been eliminated, bringing to not only significant cost reduction but also energy saving. Besides, the fact that the signal in optical bypass network remains for all, or much, of its path in optical domain provides a scalable route for network upgrading to support traffic growth. The commercialization of optical bypass has been beginning in the late of 1990s and are still on-going with a higher degree of bypassing (up to fully transparent).

The optical networks are often segmented in a hierarchical tiers, being differed in the number of customers, the required capacity and the geographic coverage. It should be noted that the technology are often different across the network tiers as the characteristic and requirements are very dissimilar. Figure 1.1 illustrates common classification, including four tiers. The access network is at the edge of the network, closest to the end users. The access part carries different kinds of data to and from both residential customers and private/business ones, serving around tens to hundreds customers and span typically few km. The metro-access part carries highly aggregated traffic from access tier, supporting around thousands of customers and spanning tens to a hundred km. Multiple metro-access networks are inter-connected via metro-core one, with a geographic extent of several hundred to a thousands km. The highest tier is to inter-connect regional traffic, called backbone network. The backbone part is therefore shared among a huge number of customers, up to order of millions and typically span thousands of km.

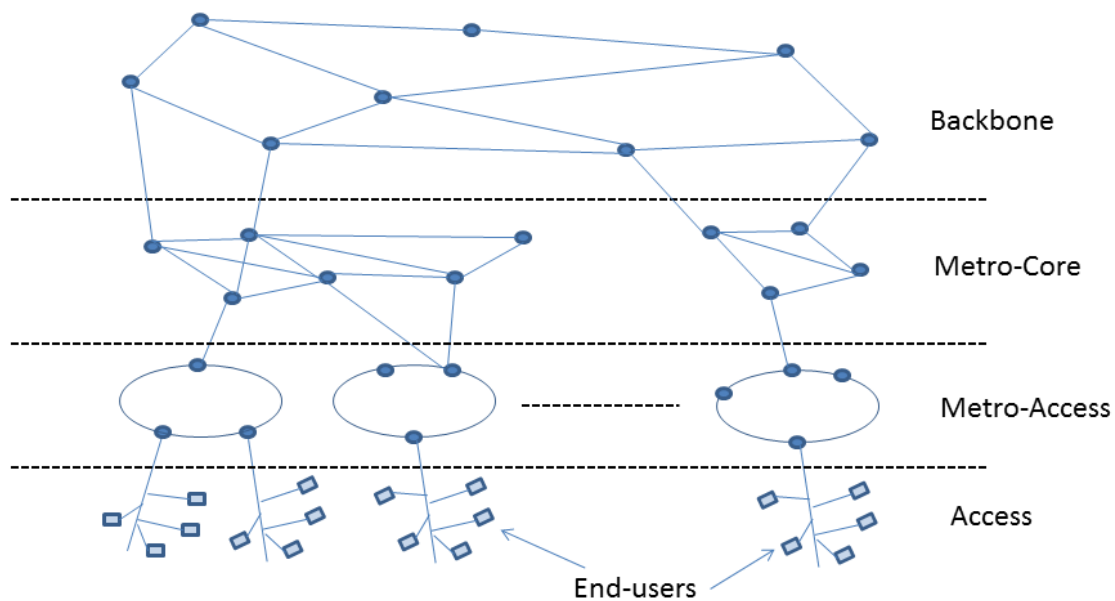


FIGURE 1.1: Network hierarchy classification, adapted from [1]

## 1.2.2 Optical Transport Mode

An optical transport network can operate in different modes depending on the utilization of optical-electrical-optical (O-E-O) conversion. It is generally categorized in three modes, namely, opaque, transparent and translucent. In fact, the term optical bypass mentioned above refers to both transparent and translucent architecture. However, for a clearer classification, we differentiate those two mode of operation. In the following we briefly describe the primary characteristic and highlight the differences between them.

### 1.2.2.1 Opaque Network

A network configured in this mode performs O-E-O conversion of the signals at the endpoints of each transmission system. In this kind of networks, the signal are terminated and regenerated at every node since they have to be converted to the electronic domain. An advantage of this mode is that it eliminates cascading of physical impairments, allows multi-vendor interoperability and full flexibility in signal routing. Besides, it provides good performance monitoring capability because the details of the frames are accessible at nodes, and it can improve capacity utilization of wavelength channels by providing sub-wavelength traffic grooming. The downside of this operation mode is the capital expenditure (CapEx) and operational expenditure (OpEx) burden when a pair of transponders is required for each single WDM channel. In addition, since the transponders are not transparent to the data rate of optical channels, the network upgrade is costly. New electronic switch nodes and higher-bit-rate optical transponders need to be deployed when the network has to support higher bit-rates.

Figure 1.2 depicts the node architecture of opaque network. As seen, a bank of transponder needed at every nodes for add/drop and regeneration purposes. The switch could be either electrical or optical one. In Chapter 2, we will consider opaque architecture.

### 1.2.2.2 Transparent Network

A network operating in a fully transparent mode keeps the signal in the optical domain at every intermediate nodes. Regeneration capability is not available as well. As the signal remains on the same wavelength all the way to the destination node, this architecture implies end-to-end bit-rate and protocol transparency. Besides, it is easier to upgrade to higher bit-rate since only transponders at end-nodes need to be replaced. However, because the absence of O-E-O conversion, the optical signal quality degrade as they traverse and hence, this type of network is limited by geographic extent.

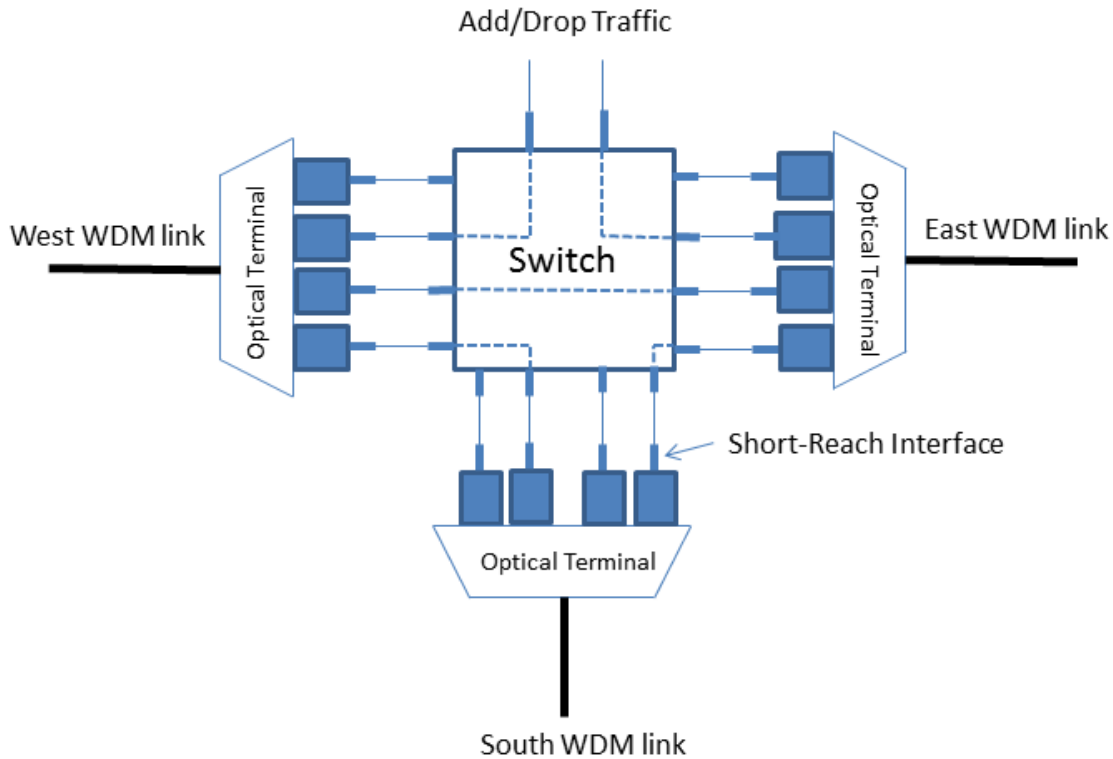


FIGURE 1.2: Opaque Architecture at a degree-three Node, adapted from [1]

Figure 1.3 illustrates a possible transparent configuration of a degree-three node with multi-degree reconfigurable optical add/drop multiplexer (ROADM-MD). As shown, transponders are only needed for add/drop traffic while the remaining traffic could be passed through optically. The transparent architecture will be addressed in chapter 4.

### 1.2.2.3 Translucent Mode

The translucent architecture takes advantage of both opaque and transparent network. In this mode of operation, the optical signal travels in optical domain as far as possible before it needs to be regenerated. Alternatively, the regeneration could also be employed to relax the wavelength continuity constraints. Noticed that the signal can be regenerated several times in the network before it reaches destination and could be used different wavelengths at each segment. We mention this architecture here for completeness and this thesis will not address this architecture

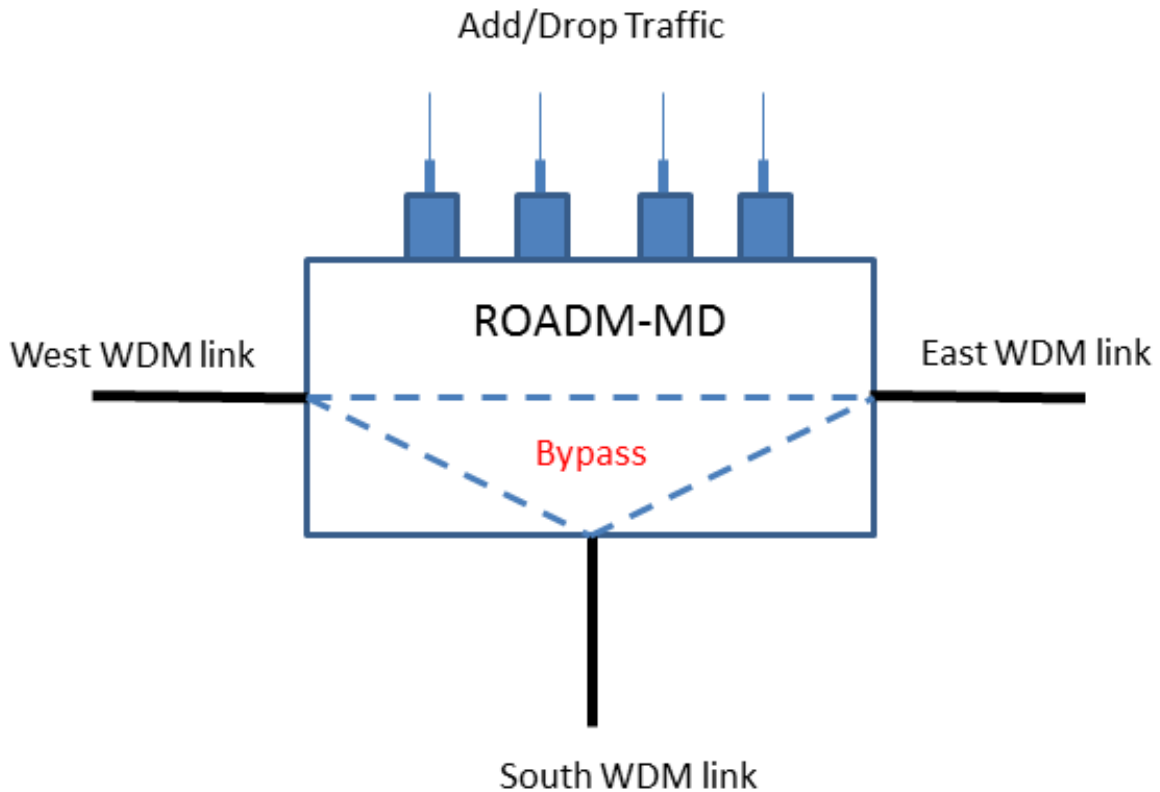


FIGURE 1.3: Transparent Architecture at a degree-three Node with multi-degree reconfigurable optical add/drop multiplexer, adapted from [1]

### 1.2.3 Advanced Modulation Format

The introduction of WDM technology, together with optical amplifiers and advances in filter and laser technology pushes the capacity growth evolution in communication systems. In turn, the proliferation of high-speed services with demanding bandwidth requirement necessitates advances in WDM for more throughput. This push-pull game is shaping the progress of WDM transmission technologies.

Modern WDM networks, incorporating as many as 80 optical channels with 50 GHz grid spacing, have reached the spectral limit of optical fiber amplifiers used in these systems. As a result, further expansion of information throughput through stacking more optical channels is not feasible and thus, seeking solutions for higher spectral efficiency is most likely direction to keep up with traffic growth. In this context, advanced modulation formats based on multi-level schemes coupled with coherent detection has emerged as the excellent solution for upgrading fiber-optic network. Such solution is sometimes referred as vertical stacking meaning that more information



is encoded within given bandwidth through high-level modulation format.

In the previous optical communication systems (i.e., low speed at, say, 10 Gbps), a symbol pulse is represented using an on-off keying scheme where only the real part of the field (i.e., amplitude) is utilized. In this type of modulation, symbol rate and the bit-rate are equal as there are only two symbols constituting the constellations. In other words, the modulation efficiency is 1 bit/symbol. In this approach, the information throughput of a single optical channel has been progressively enhanced to 40 Gbit/s by increasing the corresponding symbol rate and the analog bandwidths of optoelectronic and electronic subsystems. However, this approach is not scalable in the sense that given the current WDM grid spacing of 50 GHz, it is difficult to further increase the symbol rate to, say, 40 Gbaud, while avoiding crosstalk between optical channels [2]. Therefore, it has become necessary to achieve higher spectral efficiency by encoding more field properties, namely, optical phase and optical polarization into the symbol. Exploiting optical phase allows multiplexing two binary data streams, in-phase (I) and in quadrature (Q) to the same optical carrier, as demonstrated by the signal constellation for quadrature phase-shift keying (QPSK), being illustrated in figure 1.4. Besides, polarization division multiplexing allows two different signals to be transmitted at the same wavelength but in two orthogonal polarizations, thus doubling the total data rate. In fact, the telecommunications industry has agreed to utilize dual-polarization QPSK (DP-QPSK) for upgrading optical channels to 100 Gbit/s information rate with a symbol rate of 28 Gbaud (i.e., to carry overhead bits) [2]. By doing so, a symbol carries a higher number of bits that depends on the total number of constellation symbol  $M$ . In a system with  $M$  constellation symbol, each symbol would carries  $\log_2 M$  bits. Clearly, the higher the value of  $M$  is, known as modulation level, the higher the bit-rate is delivered given the same symbol rate. Conversely, given the same bit-rate, the higher value of  $M$  is, the lower the symbol rate is required.

Thanks to improved spectral efficiency, such advanced modulation format based on multi-level modulation has been considered to be adopted in next-generation core network either in a single or multiple-carrier scheme. However, the high value of  $M$  would pose challenges in transmission engineering as symbols are packed closer and thus, a higher signal to noise ratio and more sophisticated detection algorithms are required. The consequence of increasing  $M$  would therefore cause decreased maximum optical reach, often known as trade-off between modulation level and distance. For example, a signal modulated with 16-QAM carries as two times as the QPSK, and thus, requires half the bandwidth to deliver the same bit-rate. Nevertheless, the SNR penalty of 16-QAM compared to QPSK, might impact optical reach requirement [8].

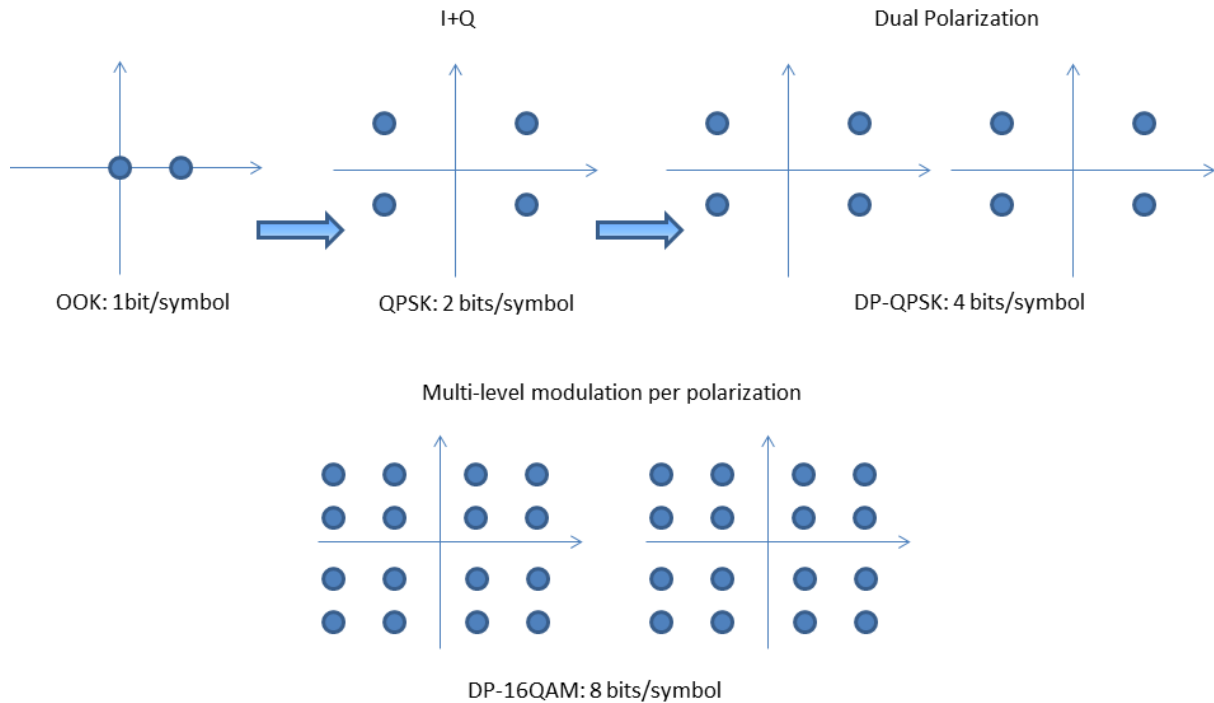


FIGURE 1.4: Evolution of modulation format, adapted from [2]

It is important to notice that flexible transponders with multiple modulation format options are coming into availability. In this type of transponder, thanks to digital signal processing capability, the selection of modulation format and other transmission parameters could be adjusted on demand.

## 1.2.4 Network Planning and Optimization

From an algorithmic perspective, planning and operating optical networks falls in the broad category of network optimization problems. We give a short introduction on optimization techniques usually used in optical network planning emphasizing on linear optimization and heuristics.

### 1.2.4.1 Network Planning Classification

Network planning focuses on the details of how to accommodate the traffic that will be carried by the network. For example, network planning includes selecting how a particular demand should be routed, protected, and groomed, and what wavelength(spectrum) should be assigned to carry it. The planning process can be classified by time-scales, namely, long-term, medium-term and real-time planning. *Long-term* activities are to design or expand the network to meet requirement for period of time, usually from months to years. In this phase, there is sufficient time between the planning and provisioning process such that any additional equipment and capacity required

by the plan can be deployed. It typically takes place before a network is deployed, there is generally a large set of demands to be processed at once. In this context, the planning emphasis is on determining the optimal strategy for accommodating the set of demands. The problem in this phase is also called un-capacitated design, referring to the fact that there is no resource constraints. After the network capacity is installed and operational, *medium-term* planning is performed for the incrementally added traffic. The problem is to optimally allocate demands, normally at once, under the installed capacity constraint to maximize the network capacity utilization and/or the throughput. It is also called capacitated design, indicating the bounded capacity. *Real-time* planning refers to the case where there is little time between planning and provisioning, and the demand arrives in random fashion (i.e., unknown in arrival time, departure time and requested capacity). The goal is to support the demand using whatever equipment is already deployed in the network and minimize the blocking probability. In this thesis, we will deal with long-term and medium-term planning only.

#### 1.2.4.2 Network Optimization

Network optimization techniques serve as excellent means to design, dimension and operate the network in a cost-effective manner. With the increasing complexity of network, the role of optimization becomes more important. We briefly present basic optimization techniques used in optical network.

**Linear Programming** A linear programming (LP) aims at achieving the best solution given a set of linear constraints. It belongs to general class of mathematical optimization. In a special case, where all the variables are integer, the problem becomes integer linear programming (ILP). Alternatively, if some of variables are integers, it is called mixed integer linear programming (MILP). The application of linear programming has been very successful in a wide range of fields, including telecommunication. In particular, several problems in optical network could be modeled as linear programming formulation such as routing, grooming, protection, etc.

The general form of an LP is given belows

$$\text{minimize } \mathbf{c}^T \mathbf{x} \tag{1.1}$$

$$\text{subject to } \mathbf{A} \mathbf{x} \geq \mathbf{b} \tag{1.2}$$

where  $\mathbf{x}$  are decision variables vector,  $\mathbf{c}$  are the objective coefficient vectors while  $\mathbf{A}$  and  $\mathbf{b}$  are constraint coefficient vectors. Note that the objective as well as constraint functions are linear function of decision variables. A solution that satisfies all the constraint is called feasible solution

and a feasible solution that minimizes the objective function value is called an optimal solution.

Pure LP problems can be solved by the well-know simplex algorithm. It has been proved that the optimum value will always be achieved on at least one of the vertices of the feasible set. Based on this insight, the simplex algorithm goes along edges of the feasible region to find higher objective value. When a local optimum is found, it is also global optimum and the algorithm terminates.

Solving ILP and MILP problem poses more challenges than pure LP due to the integer constraints of variables. Branch and Bound, based on divide and conquer approach, is commonly used to obtain the exact optimal solution. Roughly speaking, if a problem is difficult to solve, it is divided into several smaller subproblems. Each subproblems is then considered and may be divided further into smaller ones if it is still unmanageable. The detail description of the technique could be found on [9]

In this thesis, the LP, ILP and MILP problem are solved by IBM CPLEX solver 12.4 with academic version.

**Meta-heuristic** ILP (MILP) formulation for optimization problem (e.g., in optical networks) are known as NP-hard, and thus, the finding of optimal solutions for large-scale problems might be not feasible given a limited running time. Given this drawback, heuristic algorithm are used as complementary to find good solution (ranging from feasible solutions to optimal one) in an efficient time manner. There is compromise between optimality and speed. Typically, a heuristic is designed specifically for each problem taking into account its special traits to find efficient solutions. Greedy heuristics is a class that is widely used in network optimization problem. At each step, it makes a locally optimal choice with the hope of finding a global optimum.

Meta-heuristics are generic methods aiming at solving hard optimization problem in an tractable fashion. Different from problem-specific and the greedy nature of heuristic, meta-heuristic could be adapted to several problems and explore the search space in such a more efficient way due to the combination of greedy feature and random factor. The advantageous feature of meta-heuristic over heuristic is the capability of escaping from local optimum by accepting, to certain extent, lower-quality solutions. The challenging in adapting meta-heuristic to specific optimization problem lies in the representation or encoding the solution in a proper way, defining the objective cost and iterative procedure to obtain new solutions. Popular meta-heuristic that are often used in optical network optimization include genetic algorithms, simulated annealing, tabu-search, etc. In the chapter 2 of this thesis, we will demonstrate the efficiency of genetic

algorithm in solving the routing and spectrum assignment problem.

### 1.3 Research Problems and Outline

The coming into availability of flexible transponder introduces new opportunities to improve the network efficiency. The utilization of such transponder enables the adjustment of transmission parameters according to network condition, thereby providing a number of degree of freedom for the network. The thesis aims at efficient protection schemes and spectrum allocation for flexible optical network enabled by the usage of flexible transponder. To this end, we have been working on following directions

The first research work is on proposing rate-adaptive operation of multi-line rate transponder for efficient protection. The context of this study is on the partial upgrading of 100 Gbit/s transponder to 100/200 Gbit/s one in regional opaque network. The availability of such multi-line rate transponder with modulation format adaptation in a rapid manner motivates the study. This study will be presented in chapter 2.

The second study is on the algorithm aspect of solving routing and spectrum assignment problem (RSA). The context of this study is on the flex-grid network where elasticity/flexibility in handling spectrum resources are possible. We conduct the study on static RSA problem in both single and multi-objective scenario. Chapter 3 is dedicated to describe those works

The third research activity is on proposing modulation-adaptive of CO-OFDM transponder in network-side protection. The context of this study is on path protection scheme for OFDM-based flex-grid optical network. The reconfiguration capability of CO-OFDM transponder has been utilized to efficiently adapt modulation format to the transmission condition of working and protection path. We formulate the network design problem for both dedicated and shared path protection and draw a comparison between our proposal to traditional approach in literature. Chapter 4 will describe in detail this contribution.

Finally, there are some words of conclusion and perspective in chapter 5.

## Chapter 2

# Rate-adaptive Operation of Multi-line rate Transponder for Efficient Protection

Optical network is susceptible to a number of failures (e.g, fiber cut, equipment failures) during its operation. With the increasing bit-rate per channel, survivability to fault must be guaranteed to avoid interruption of a large amount of services. Fault tolerance by providing alternative paths and/or backup resources is therefore an integral part of network design process. However, adding spares resources for protection purpose gives rise to cost and energy burdens for the network. Therefore, finding efficient protection schemes in terms of both capital expenditure (CapEx) and operational expenditure (OpEx) has been an important subject of study for both academic and industry. With the recent advances in optical transmission and coherent detection, a new type of transponder with adaptation capability is coming into availability in which a number of transmission parameter could be adjusted flexibly according to network condition. This opens up new opportunities to efficiently address the survivable network design problem by exploiting the flexible operation of such transponder. This chapter will introduce the conceptual operation of simple multi-line rate (MLR) transponder having two bit-rate options and thereby propose a novel protection scheme based on rate-adaptive operation. The MLR transponder is proposed to operate at lower rate to handle working capacity and in case of failure event, it could be temporarily tuned to higher rate to support protection capacity. Such scheme is motivated by the observation that during the network operation, the period at which the network is in protection mode could be considered negligible compared to working mode, and hence utilizing MLR transponder at higher rate only for protection period could be potentially energy-efficient.

## 2.1 Introduction

The introduction of optical wavelength division multiplexing (WDM) technology serves as ideal venue for transporting huge amount of data and thereby accelerate the growth of traffic via new services. This could be made possible thanks to the increasing capacity of a wavelength, e.g., from 40 to 100 Gb/s and beyond, together with a large number of wavelengths (e.g., 80 wavelengths in C band) that a fiber could support. Given a large amount of traffic of several  $Tb/s$  being carried over a fiber, the risk of traffic loss due to fiber cuts or other failures could severely affect the customers businesses as well as revenue. The issue of network resilience thus becomes a critical requirement for high capacity networks and should be taken into account when performing network design. The network dimensioning with protection requirement is often referred as survivable design. Including the protection against failures in network design process implies adding spare resources, e.g., spare equipments and spare link capacity. These amount of redundancy depends on protection scheme which in turn is decided by a number of requirements such as speed recovery, operational complexity and cost issues. For example, in dedicated protection, the resources are generally doubled aiming at providing rapid recovery and enabling ease of operation while in shared protection, the amount of spare capacity could be shared among various demands that do not fail simultaneously, hence leading to resources saving. However, shared protection comes at a lower failure recovery speed and more complex operation since the coordination among several demands are needed [1, 10].

Survivable network design aiming at reducing capital expenditure (CapEx) and operational expenditure (OpEx) has been constantly receiving particular attention from research community as its role becomes crucially important [1]. Apart from cost perspective which is traditionally considered, energy issue becomes more and more concerning due to environmental impact and also growing cost of energy. The fact that guaranteeing survivability for a network requires the provisioning of redundant resources not only incurs increased capital cost but also put a burden on power consumption issues. Over the past few years, there has been several research activities toward energy-efficiency issue, which are collectively known as power-efficient or energy-aware design [11, 12]. The basic idea for such designs is to reduce active resources as much as possible by algorithms in routing the traffic. Moreover, it also relies on the sleep mode operation of devices which are configured to be at very low-power or inactive state and be ready for sudden wake-up upon an events, e.g., the failure event. The pioneering activities on that context were presented in [11, 12] where the authors addressed the trade-off between survivability and energy-efficiency and proposed the survivable network design based on the assumption on sleep mode operation of backup resources. A considerable power consumption saving could be achieved for both dedicated and shared protection scenarios.

However, the supporting of sleep mode for most of network devices are still rare [13] and thus, it should be emphasized that all devices within layer 1 circuit oriented networks are practically always "on", so power consumption only depends on these amount of resources. Another likely problem associated with sleep mode operation of backup resources is the switching from sleep state to normal working that might give rise to transient optical amplifier effects which are undesirable due to the fact that it is main factor causing error burst [1]. Having recognized the drawbacks of sleep mode approach, a recent research activities [14] exploited the partial bandwidth protection concept and analyzed the impact of reducing power consumption correspondingly. Partial protection is a relatively new business concept exploring the case that the link failures are typically fixed quickly and the customer may be willing to tolerate a decreased rate if it is accompanied by reduced cost [15]. This means that instead of providing full protection, just some part of the traffic could be delivered to receiver upon failure events. By reducing amount of protection requirement, less spare resources might be needed and this brings to the reduction of power consumption and cost as well. Although this approach offers potential cost and energy saving, it comes at an expense of trading protection requirement and thus, the application should be limited to certain scenarios.

With the advances in optical transmission and coherent detection technologies, a new type of transponder with adaptation capability is coming into availability [3, 16, 17]. For such transponders, a perspective is that a number of transmission parameters such as modulation format, baud and/or bit-rate, forward error codes could be tuned according to varied conditions. While the full options of flexibility is still quite far way from current technologies and furthermore it is still unclear whether it is really necessary to have full flexibility, introducing a degree of freedom in bit-rate operation has come into realization [18–20] and has been shown to demonstrate potential benefits [21]. Multi-line rate (MLR) transponder is the one which has the capability to work at different bit-rates, i.e., by changing modulation format.

This chapter will consider the application of MLR transponder 100/200 Gb/s for protection purpose in WDM network with opaque architecture. The network is resilience to any single fiber cut which is most common failure in practice [1]. In particular, a novel adaptive operation is proposed for MLR transponder in such a way that a lower rate is employed for MLR transponder at working mode and in case of failure events, the MLR transponder could be tuned temporarily to higher rate, e.g., doubling rate, to handle protection traffic. Such scheme is motivated by the observation that during the network operation, the period at which the network is in protection mode could be considered negligible compared to working mode, and hence utilizing MLR transponder at higher rate only for protection period could be potentially energy-efficient rather than traditional solution based on "always on" single-line rate (SLR) transponders. Besides, the switching from 100 Gb/s to 200 Gb/s is expected to have negligible transient optical amplifier



effect compared with switching from sleep mode to working mode. In term of speed recovery, protection based on adaptive operation of MLR remains almost comparable to SLR solution since the modulation format change process has been experimentally demonstrated to be very fast and be negligible compared to failure detect process [22, 23]. The idea in this chapter and part of the content was reported at [24].

The chapter is organized as followed. In the next section, a model of MLR transponder with two-rate options, which will be used in this study, is described based on the information presented in [3, 19]. It should be highlighted that this type of transponder has already come into practice, and the 100 Gb/s technology are presently considered to be matured. It is worth to consider the upgrade to multi-line rate one based on existing infrastructure. The study therefore has practical flavor by focusing on actual values of data rates. Also, in that section, an example demonstrating the rate-adaptive operation together with an analysis on potential benefits of such scheme comparing to traditional solution based on solely SLR is given. Section 2.3 addresses survivable network design including dedicated and shared protection. The design process includes two steps: the first one involves the routing and flow allocation and the second step deals with allocating transponders. We propose two protection schemes based on the rate-adaptive operation of MLRs. Section 2.4 is dedicated to present numerical results from extensive simulation, together with an analysis on impact of transponder count, cost and power consumption. Final section will be left for conclusion and perspectives.

## 2.2 Rate-adaptation for Protection with Multi-rate Transponder

This section describes the principle of the rate-adaptive optics technologies, and focuses on specific type of transponder, called multi-line rate transponder. A conceptual model together with assumptions on cost and power consumption are given. Rate-adaptive operation of multi-line rate transponder for protection is presented and benchmarked with conventional approach through an illustrative example.

### 2.2.1 Multi-line Rate Transponder Model and Assumption

#### 2.2.1.1 Multi-line Rate Transponder Model

Thanks to significant progress in optical transmission technologies, rate-adaptive optics has been emerging as promising solution to meet ever growing bandwidth demands and simultaneously reduce network cost. Different from traditional technologies based on fixed transmission scheme,

optical transponder with a number of degree of freedom has been proposed and in on-going realization. Basically, there are two types of flexible transponder being considered depending on whether the transported bit rate is adjusted, i.e., customizable client data rate, or the symbol rate is altered with fixed client rate. The latter one based on symbol rate adaptation is well-suited for the flex-grid network context and has been extensively studied in literature, for example [25, 26]. Moving from fixed-grid to flex-grid is proposed as excellent candidate to efficiently exploit fiber spectrum to meet traffic growth. Despite of clearly demonstrated benefits, that upgrade requires considerable capital investment for new equipments such as flexible transponder and flex-grid reconfigurable optical add-drop multiplexer. This section just focuses on first option where the symbol rate is kept constant and the client rate is varied since this solution is compatible with currently deployed network.

Having the digital signal processing (DSP) in both the transmitter and receiver, several transmission properties could be changed according to channel or network condition. A possible implementation is to rely on modulation format variation which is realized by the generation of various QAM signals on a fixed hardware platform [18, 22]. The figure 2.1 illustrates conceptually the operation of multi-line rate transponder with two modulation format options. The client rate is adaptable in corresponding to selected modulation format. Given the symbol rate, the doubling of client rate could be supported by switching from QPSK to 16QAM modulation.

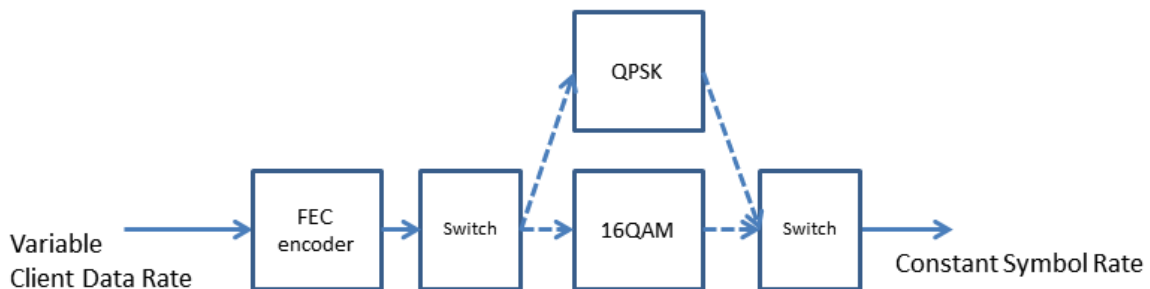


FIGURE 2.1: Rate-adaptable principle, adapted from [3]

Based on the above principle, let's describe a specific type of multi-line rate transponder which will be used for studying in this chapter (Figure 2.2). The MLR transponder has variable client rate supporting two bit-rate options 100 Gb/s and 200 Gb/s corresponding to modulation format QPSK and 16QAM while SLR transponder has a fixed client rate of 100 Gb/s and single modulation format QPSK. It is noted that 100G PM-QPSK is generally accepted as winning solution for 100 Gb/s realm and thus, the consideration of upgrading to multi-line rate 100/200G one could be worth to study together with its associated benefits.

Regarding to the optical reach reduction of MLR transponder when switching from QPSK to 16QAM, we assume that it could be tolerated in regional network or national network and opaque architecture which is focused of this study. The study investigate the impact of cost and power consumption when using MLR transponder compared to SLR one. For the cost, MLR transponder is assumed to have an excess cost compared to SLR due to a more complex structure. The excess cost is a parameter in the study. Concerning the power consumption, it should be distinct between two operation modes of MLR transponder. When MLR is operated at lower rate, being equivalent to SLR rate, we assume that MLR transponder consumes more than SLR by an additional factor  $\beta$  which accounts for the fact that the management of MLR is more demanding than SLR even in the same bit-rate option. Parameter  $\beta$  is also varied for the study. For the higher rate of MLR, since the symbol rate is kept constant, we follow the model from [18] considering that *the doubling of client-rate is owing to doubling of client-side complexities (i.e., client card, FEC,(de)framer) accounting for roughly 38%*. The comparison is summarized in Table 2.1

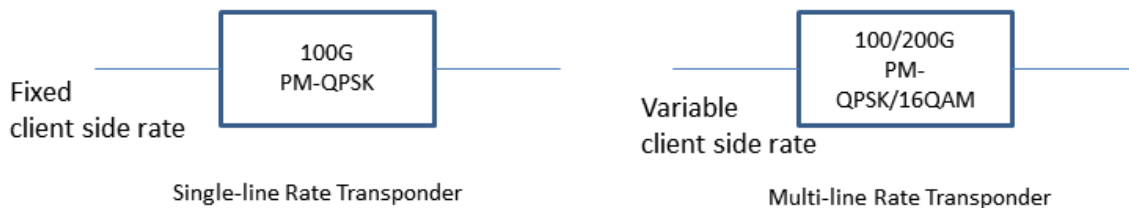


FIGURE 2.2: SLR and MLR model

TABLE 2.1: Transponder Parameters Assumption

Parameters	SLR (Tx+Rx)	MLR (Tx+Rx)
Cost	1	$1 + \alpha$
Power Consumption	1	100G mode: $1 + \beta$ 200G mode: $1 + \beta + 0.38$

### 2.2.2 Rate-adaptation Operation for Protection

This part illustrates our proposal of MLR transponder operation for protection via an example. The associated benefits compared to conventional solution based on SLR transponder is also analyzed.

Let's consider an exemplary network topology in figure 2.3. There are three bi-directional 100Gbps connection between each pair of nodes. The node architecture is opaque and illustrated

in figure 2.4 for node A. As shown, for operation in working mode, two transponders operating at 100G are needed at node A corresponding to connection A-B and A-C. Considering the event that link A-B is failed (i.e., fiber cut), connection A-B would be protected by re-routing the traffic over alternative path A-C-B (Figure 2.5). For the conventional protection approach based on SLR, the protection of connection A-B would require a spare pair of transponder between node A-C and a spare pair of transponder between C-B (2 transponder pairs) as depicted by figure 2.6. It should be noted that all the additional transponder for protecting connection A-B (backup transponders) are "on" and thus, consume as much power as working SLR since we preclude the sleep mode operation here. Now, let's examine the situation if working connection A-C and C-B could be increased to carry an additional amount of 100G for protecting connection A-B (Figure 2.7). Under this condition, clearly, there is no need to have additional transponders for protection connection A-B since it is possible to utilize working transponders temporarily at higher rate for protection purpose. Indeed, such scenario is realized by using MLR transponder 100/200G for connection A-C and C-B. The following observation could be stated for this approach:

1. The reduction of total transponder count by MLR transponder approach compared with SLR transponder one. This is due to the fact that MLR transponder is operated in such a way that at working mode, it is utilized at lower rate to carry working traffic and in case of failure event, it is allowed to work at higher rate for transferring additional protection traffic. Depending on the relative cost of MLR, this could be translated to a gain in network cost.
2. An important observation for using MLR transponder in such rate-adaptive mode is the fact that MLR transponder would be in higher rate for only protection period, i.e., the period at which the failure happens and has not yet been repaired. Thus, given the much smaller of protection duration to working period, MLR transponder is utilized at lower rate and correspondingly at lower power consumption mode for most of the operation time. This could potentially bring energy saving compared to conventional approach which is based on always "on" SLR transponders.

## 2.3 Survivable Network Design Framework

This section firstly recalls the problem of routing and flow allocation for both dedicated and shared protection in an uncapacitated scenario where the resources are presumingly unlimited and thus all demands could be supported. So, given the physical topology and traffic matrix, we aim to find the working and spare capacity on each link so that the network is resilient

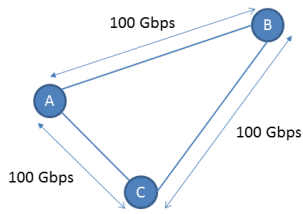
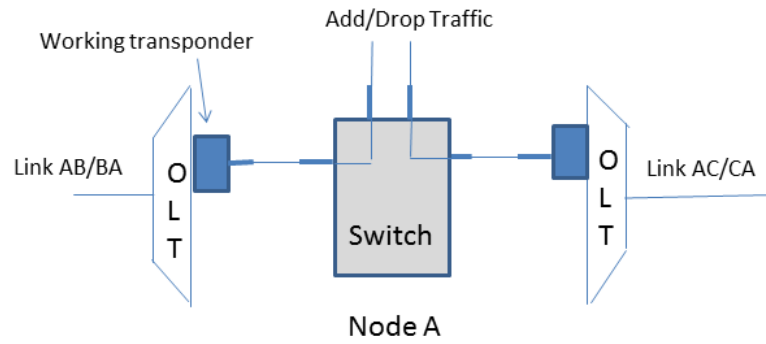


FIGURE 2.3: Exemplary Network



OLT: Optical Line Terminal

FIGURE 2.4: Node Architecture

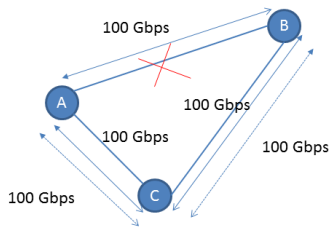


FIGURE 2.5: Single-link Failure with Conventional Protection

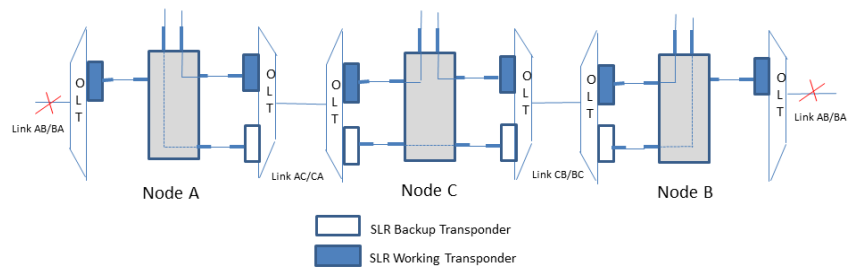


FIGURE 2.6: Node Architecture

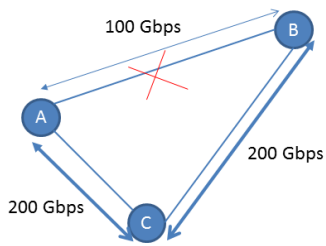


FIGURE 2.7: Single-link Failure with Novel Protection

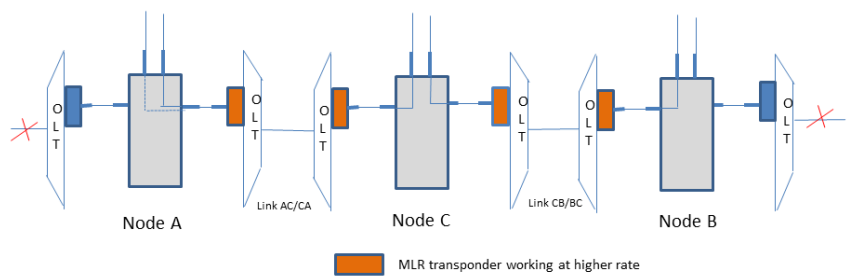


FIGURE 2.8: Node Architecture

to any single-link failure and with the objective to minimize the overall allocated link capacity. The problem is formulated as mixed integer linear programming. Secondly, this section presents transponder allocation algorithms to handle the requested capacity in each link based on conventional approach with SLR and novel approaches with MLR.

### 2.3.1 Dedicated Protection Formulation

Given Information:

- $G(V, E)$ : Physical network topology with  $|V|$  nodes and  $|E|$  links
- $D$ : Set of traffic demands, indexed by  $d$ . Each demand  $d \in D$  request  $t_d$  traffic in Gb/s
- $A_i^+$ : Set of nodes in  $V$  such that it exists a link toward node  $i$  constituted by an item in that set and node  $i$
- $A_i^-$ : Set of nodes in  $V$  such that it exists a link leaving from node  $i$  constituted by node  $i$  and an item in that set.

Variables:

- $x_{ij}^d$ : Binary variable indicates if demand  $d$  is routed over link  $ij$  for working path and then it equals 1. Otherwise, it equals 0.
- $y_{ij}^d$ : Binary variable indicates if demand  $d$  is routed over link  $ij$  for backup path and then it equals 1. Otherwise, it equals 0.
- $w_{ij}$ : Variable with positive real value represents the total working capacity on link  $ij$
- $b_{ij}$ : Variable with positive real value represents the total spare capacity on link  $ij$

The objective function is to:

- Minimize the capacity allocation including working and spare capacity for all the links

$$\min \sum_{\{i,j\} \in E} (w_{ij} + b_{ij}) \quad (2.1)$$

subject to following constraints:

- Flow conservation for working traffic of demand  $d$ . It is noted that by definition of variable  $x_{ij}^d$ , there is no bifurcation routing and thus, demand  $d$  is only routed over a single path.

$$\sum_{i \in A_j^-} x_{ij}^d - \sum_{l \in A_j^+} x_{jl}^d = \begin{cases} -1 & \text{if the node } j \text{ is the source of demand } d \\ 1 & \text{if the node } j \text{ is the destination of demand } d \\ 0 & \text{otherwise} \end{cases} \quad \forall j \in V, \forall d \in D \quad (2.2)$$

- Flow conservation for spare capacity of demand  $d$

$$\sum_{i \in A_j^-} y_{ij}^d - \sum_{l \in A_j^+} y_{jl}^d = \begin{cases} -1 & \text{if the node } j \text{ is the source of demand } d \\ 1 & \text{if the node } j \text{ is the destination of demand } d \\ 0 & \text{otherwise} \end{cases} \quad \forall j \in V, \forall d \in D \quad (2.3)$$

- Link-disjoint condition for working and backup route of demand  $d$ : The working path and backup path of demand  $d$  should be disjoint in order to be protected against any single link failure.

$$x_{ij}^d + y_{ij}^d \leq 1 \quad \forall d \in D, \forall \{ij\} \in E \quad (2.4)$$

- Working capacity on each link definition

$$\sum_{d \in D} x_{ij}^d \times t_d \leq w_{ij} \quad \forall \{ij\} \in E \quad (2.5)$$

- Spare capacity on each link definition

$$\sum_{d \in D} y_{ij}^d \times t_d \leq b_{ij} \quad \forall \{ij\} \in E \quad (2.6)$$

### 2.3.2 Shared Mesh Protection Formulation

Given Information:

- $G(V, E)$ : Physical network topology with  $|V|$  nodes and  $|E|$  links
- $D$ : Set of traffic demand, indexed by  $d$
- $A_i^+$ : Set of nodes in  $V$  such that it exists a link toward node  $i$  constituted by an item in that set and node  $i$
- $A_i^-$ : Set of nodes in  $V$  such that it exists a link leaving from node  $i$  constituted by node  $i$  and an item in that set.
- $S$ : Set of failure events corresponds to single-link failure, indexed by  $s$

Variables:

- $x_{ij}^d$ : Binary variable indicates if demand  $d$  is routed over link  $ij$  for working path (i.e., without failure) and then it equals to 1. Otherwise, it equals to 0.

- $f_{ij,s}^d$ : Binary variable indicates if demand  $d$  is routed over link  $ij$  on occurrence of failure event  $s$  and then it equals to 1. Otherwise, it equals to 0.
- $y_{ij,s}^d$ : Variable with positive real value represents the spare capacity reserved for demand  $d$  on link  $ij$  on occurrence of failure event  $s$
- $w_{ij}$ : Variable with positive real value represents the total working capacity on link  $ij$
- $b_{ij}$ : Variable with positive real value represents the total spare capacity on link  $ij$

The objective function is to:

- Minimize the allocated capacity including working and spare capacity over all links

$$\min \sum_{\{i,j\} \in E} (w_{ij} + b_{ij}) \quad (2.7)$$

- Flow conservation for working traffic. It is noted that by definition of variable  $x_{ij}^d$ , there is no bifurcation routing and thus, demand  $d$  is only routed over a single path.

$$\sum_{i \in A_j^-} x_{ij}^d - \sum_{l \in A_j^+} x_{jl}^d = \begin{cases} -1 & \text{if the node } j \text{ is the source of demand } d \\ 1 & \text{if the node } j \text{ is the destination of demand } d \\ 0 & \text{otherwise} \end{cases} \quad \forall j \in V, d \in D \quad (2.8)$$

- Flow conservation after failure events

$$\sum_{i \in A_j^- : ij \in E} f_{ij,s}^d - \sum_{l \in A_j^+} f_{jl,s}^d = \begin{cases} -1 & \text{if the node } j \text{ is the source of demand } d \\ 1 & \text{if the node } j \text{ is the destination of demand } d \\ 0 & \text{otherwise} \end{cases} \quad \forall j \in V, d \in D, s \in S \quad (2.9)$$

- Working capacity on each link definition

$$\sum_{d \in D} x_{ij}^d \times t_d \leq w_{ij} \quad \forall \{ij\} \in E \quad (2.10)$$

- Working and Spare Capacity on each link meets protection requirements after failure event

$$f_{ij,s}^d \times t_d \leq x_{ij}^d \times t_d + y_{ij,s}^d \quad \forall \{ij\} \in E, \forall s \in S, \forall d \in D \quad (2.11)$$



- Spare capacity on each link must satisfies all protection flows after any failure event. The sharing of spare capacity is represented by this constraint meaning that spare capacity reserved in link  $ij$  will be the maximum needed for all possible failure event and will be shared among demands.

$$\sum_{d \in D} y_{ij,s}^d \leq b_{ij} \quad \forall \{ij\} \in E, \forall s \in S \quad (2.12)$$

### 2.3.3 Transponder Allocation Algorithms

Given the output of solving above routing and flow allocation, we have the working and protection capacity required for each link. This part will present algorithms regarding how to handle the traffic with transponders.

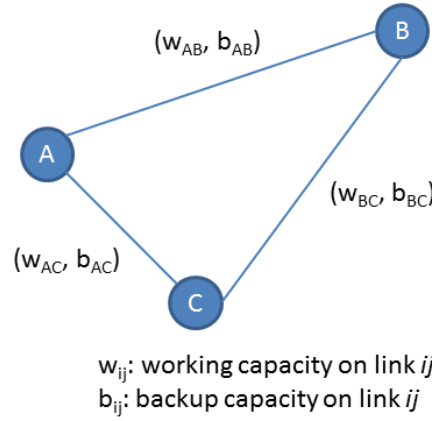


FIGURE 2.9: Link Capacity Dimensioning

#### 2.3.3.1 Conventional Approach based solely on SLR transponder

Without loss of generality, we could assume the capacity of single-line rate transponder as unit (i.e.,  $C_{SLR} = 1$ ). The number of transponder pair on link  $ij$  is defined by the following equation.

$$N_{SLR}^{ij} = \lceil w_{ij} + b_{ij} \rceil \quad (2.13)$$

where  $\lceil w_{ij} + b_{ij} \rceil$  is defined as upper rounding function.

### 2.3.3.2 Novel Approaches with MLR usage at rate-adaptive mode

Our proposal makes use of both SLR and MLR transponder to handle the traffic on each link. The MLR transponder is assumed to be able to work at two rates (i.e., low rate and high rate). The principle is to efficiently use MLR such that at working mode, it is used at low rate and for protection mode, it could be used efficiently at high rate to handle backup traffic. Without loss of generality, we could assume that the capacity of MLR transponder at lower rate as unit (i.e.,  $C_{MLR-l} = C_{SLR} = 1$ ) and its higher rate is as twice as lower rate (i.e., by changing the modulation format). Here we propose two schemes differing in a way to handle the protection traffic

1. **Proposal 1:** The MLR transponders are used to handle the maximum same amount of protection and working capacity. The remaining capacity (either purely protection or working) is handled using the remaining capacity of MLRs and additional SLR transponders. By doing so, when switching from working mode to protection mode, partial or full protection is performed by temporarily increasing working MLR transponders. Mathematically, the scheme is expressed as in algorithm 1

---

#### Algorithm 1 Transponder Allocation 1

---

**INPUT:** Working capacity  $w_{ij}$  and protection capacity  $b_{ij}$  on each link  $ij$

**OUTPUT:** Number of single-line rate transponder  $N_{SLR}^{ij}$  and number of multi-line rate transponder  $N_{MLR}^{ij}$

**if**  $w_{ij} + b_{ij} \leq 1$  **then**

$$N_{SLR}^{ij} = 1$$

$$N_{MLR}^{ij} = 0$$

**else**

**if**  $w_{ij} \geq b_{ij}$  **then**

$$N_{SLR}^{ij} = \lceil w_{ij} - \lceil b_{ij} \rceil \rceil$$

$$N_{MLR}^{ij} = \lceil b_{ij} \rceil$$

**else**

$$N_{MLR}^{ij} = \lceil w_{ij} \rceil$$

$$N_{SLR}^{ij} = \lceil b_{ij} - (\lceil w_{ij} \rceil + \lceil w_{ij} \rceil - w_{ij}) \rceil$$

**end if**

**end if**

---

2. **Proposal 2:** The scheme 2 is differed from the scheme 1 in a way to handle the protection capacity when it is greater than working capacity. In addition to increasing the working multi-line rate transponder, the remaining protection capacity is handled by using additional multi-line rate transponder working at higher rate and at most one single-line rate transponder. It is mathematically expressed as in algorithm 2

**Algorithm 2** Transponder Allocation 2**INPUT:** Working capacity  $w_{ij}$  and protection capacity  $b_{ij}$  on each link  $ij$ **OUTPUT:** Number of single-line rate transponder  $N_{SLR}^{ij}$  and number of multi-line rate transponder  $N_{MLR}^{ij}$ **if**  $w_{ij} + b_{ij} \leq 1$  **then**

$$N_{SLR}^{ij} = 1$$

$$N_{MLR}^{ij} = 0$$

**else****if**  $w_{ij} \geq b_{ij}$  **then**

$$N_{SLR}^{ij} = \lceil w_{ij} - \lceil b_{ij} \rceil \rceil$$

$$N_{MLR}^{ij} = \lceil b_{ij} \rceil$$

**else****if**  $\lceil \frac{b_{ij} - (\lceil w_{ij} \rceil + \lceil w_{ij} \rceil - w_{ij})}{2} \rceil \geq \frac{b_{ij} - (\lceil w_{ij} \rceil + \lceil w_{ij} \rceil - w_{ij})}{2}$  **then**     #  $\lceil x \rceil$ : rounding operator

$$N_{SLR}^{ij} = 0$$

$$N_{MLR}^{ij} = \lceil \frac{b_{ij} - (\lceil w_{ij} \rceil + \lceil w_{ij} \rceil - w_{ij})}{2} \rceil + \lceil w_{ij} \rceil$$

**else**

$$N_{SLR}^{ij} = 1$$

$$N_{MLR}^{ij} = \lceil \frac{b_{ij} - (\lceil w_{ij} \rceil + \lceil w_{ij} \rceil - w_{ij})}{2} \rceil + \lceil w_{ij} \rceil$$

**end if****end if****end if****2.3.3.3 Illustrative Example**

TABLE 2.2: Transponder Allocation Example

Link Flow [Gbps]		Conventional (SLR)	Proposal 1		Proposal 2	
Working	Backup		MLR	SLR	MLR	SLR
200	100	3	1	1	1	1
100	300	4	1	2	2	0

Examples of transponder allocation for different algorithms is presented in table 2.2. In the first example where the working traffic is greater than backup traffic, 200G vs. 100G, the conventional algorithm requires three SLR transponders while both schemes for the new approach requires one MLR and one SLR transponder. For the new approaches, at working mode, MLR is operated at 100G rate to carry working traffic together with another SLR. For protection mode, the rate doubling of MLR is enough to carry protection traffic. The difference lies in two-folds: first, it is evident that the total number of transponders is reduced due to the higher capacity of MLR; second, from energy point of view, the fact that the MLR is operated at lower rate for working mode, and thus consume lower power for majority of the time could be energy-efficient solution.

The second example where working traffic is less than backup traffic illustrate the difference between proposal 1 and proposal 2 in handling the traffic. The proposal 1 needs one MLR and two SLRs transponder. Transponders are operated as follows. The MLR transponder works at lower rate to carry the working traffic. At protection mode, the MLR transponder is utilized at high rate to support protection traffic together with two SLRs. For the proposal 2, there are two MLRs being operated as follows. At working mode, two MLRs works at lower rate and just one MLR carries the working traffic while the other could send unprotected traffic. On occurrence of failure and thus protection traffic needs to be carried, two MLRs are utilized at high rate to carry both working and protection traffic.

## 2.4 Numerical Results

This section presents the simulation framework and extensive numerical results. The survivable network design based on mixed integer linear programming formulation is solved by CPLEX [27] with academic version and default setting.

### 2.4.1 Simulation Parameters

1. Network Topologies: The simulation is performed over diverse topologies as in figure 2.10. In particular, three topologies being different in number of nodes, links and nodal degree are tested. The characteristics of topologies are summarized in table 3.1.

TABLE 2.3: Topology Characteristic

Parameters	Topo 1	Topo 2	Topo 3
Number of Nodes	6	8	10
Number of Links	14	24	36
Average nodal degree	2.33	3	3.6
Min nodal degree	2	2	2
Max nodal degree	3	4	5

2. Traffic Pattern: The traffic matrix is any to any and symmetric. The amount of traffic between each node pair is random and within a range [25 200] [Gbps] with a granularity of 25 [Gbps]. The study is conducted over 100 traffic matrices.
3. Cost Assumption: In our model, we assume that the SLR cost is unit while the MLR cost is  $\alpha\%$  greater. The parameter  $\alpha$  is varied to capture the broad range of possible MLR cost.
4. Transponder Power Consumption Assumption: For the conventional approach, the overall power consumption is simply dependent on the number of SLR transponders. For the new

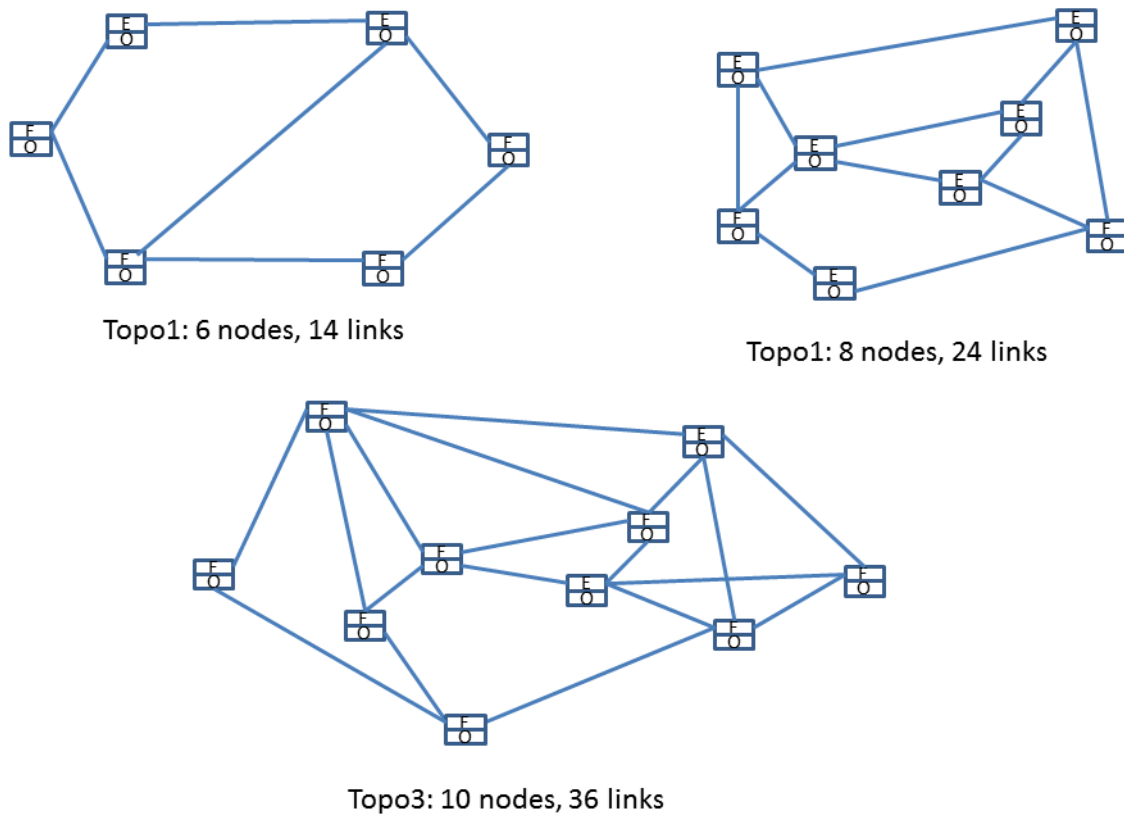


FIGURE 2.10: Network topologies under studies, each line connecting two nodes corresponds to two links (fibers)

approaches by utilizing MLR at rate-adaptive mode, the dimensioning includes both SLR and MLR transponder such that MLR transponders work at lower rate for working mode and at higher rate for protection mode. Since MLRs has two mode of operation and also corresponding two levels of power consumption, it is necessary to have an approximate figure on the relative duration between working and protection mode.

In this study, we focus on national network with opaque architecture such that the optical reach of MLR transponder working at 200G with PM-16QAM modulation (e.g, around 500 *km* according to [19]) long enough for robust transmission between any link). The link length is assumed therefore to be less than 500 *km*. The resilience scheme is against any single link failure which is mostly due to fiber cut. From [28], it is estimated that there are two cuts per 1000 miles (roughly 1600 *km*) per year. Besides, the time to repair a fiber cut is varied and expected to be less than 10 hours. Based on those data for fiber cut rate and repair time, we could estimate the time in hours per year that the network is in protection mode. Here we derive the figure for topology 3 (10 nodes and 36 links) with assumption

that all link length is  $500km$ .

$$T_p = \frac{2 \times 500 \times 36 \times 10}{1600} = 225(\text{hours}) \quad (2.14)$$

The above figure indicates that around ten days (in total) per year the network is in protection mode and thus, some of the MLR transponders need to work at higher rate mode. Since that figure is negligible compared to the duration of working time, it is justifiable to evaluate the transponder power consumption of MLR transponder by the lower rate mode.

### 2.4.2 Transponder Count Impact

The first set of results is about the comparison of total number of transponders among protection schemes and constituent transponders among new protection proposals for both dedicated and shared scenario.

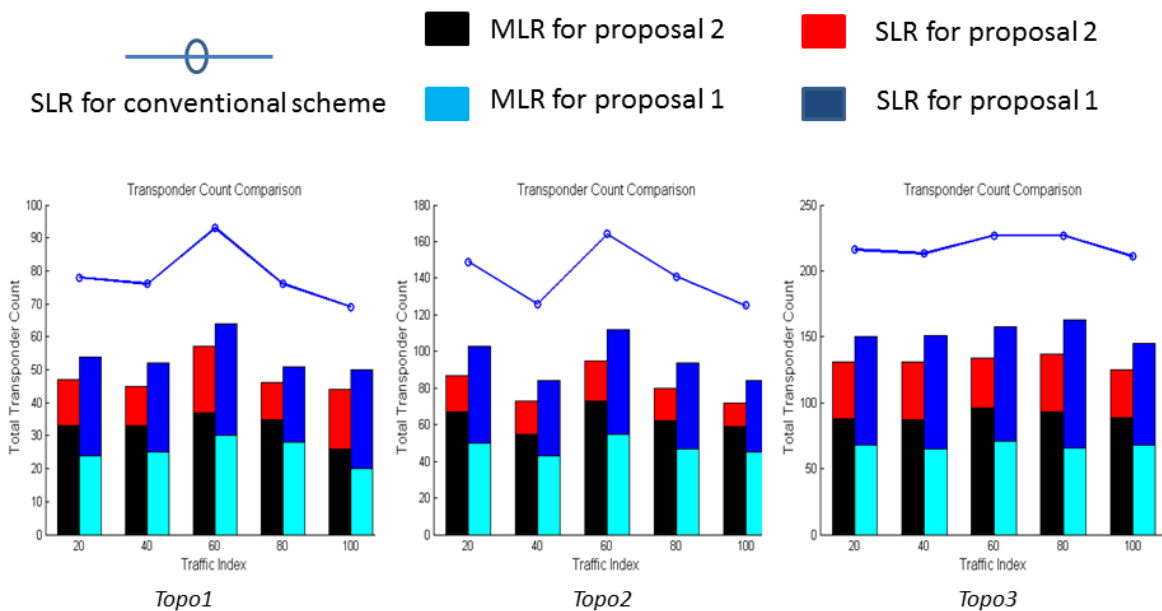


FIGURE 2.11: Transponder Count Comparison for Dedicated Scenario

The figure 2.11 shows the total transponder count of conventional scheme in comparison with new proposals for dedicated scenario. For two new protection schemes based on the rate-adaptive operation of MLR, it also shows the constituent amount of SLRs and MLRs transponder. For ease of representation, we just show the result at some sampling traffic index. It could be clearly seen

for all three examined topologies that new protection proposals significantly reduce the total number of transponders. While the actual gain certainly depends on the traffic and network topology, the average gain has been found relatively similar for three topologies. Specifically, by employing protection proposal 2, the average transponder count gain is 40% for topology 1, 42% for topology 2, and 40% for topology 3. Protection proposal 1 have a lower gain compared with proposal 2, being 31%, 32% and 30% for network 1, 2, 3 respectively. Such gain is possible thank to the utilization of MLRs whose maximum rate is as twice as SLRs, leading to capability of handling more traffic. For comparison between proposal 1 and 2, the first observation is that proposal 2 utilizes less total transponder than proposal 1. This is due to the policy of proposal 2 to favor the use of MLRs in the sense that the MLR transponder is in charge of (together with at most one SLR transponder) handling protection traffic while for proposal 1, the protection traffic would be handled by both MLRs and a necessary amount of SLRs. A consequence of their policy is that proposal 2 employs more MLRs and less SLRs than proposal 1. It could be seen qualitatively in figure 2.11.

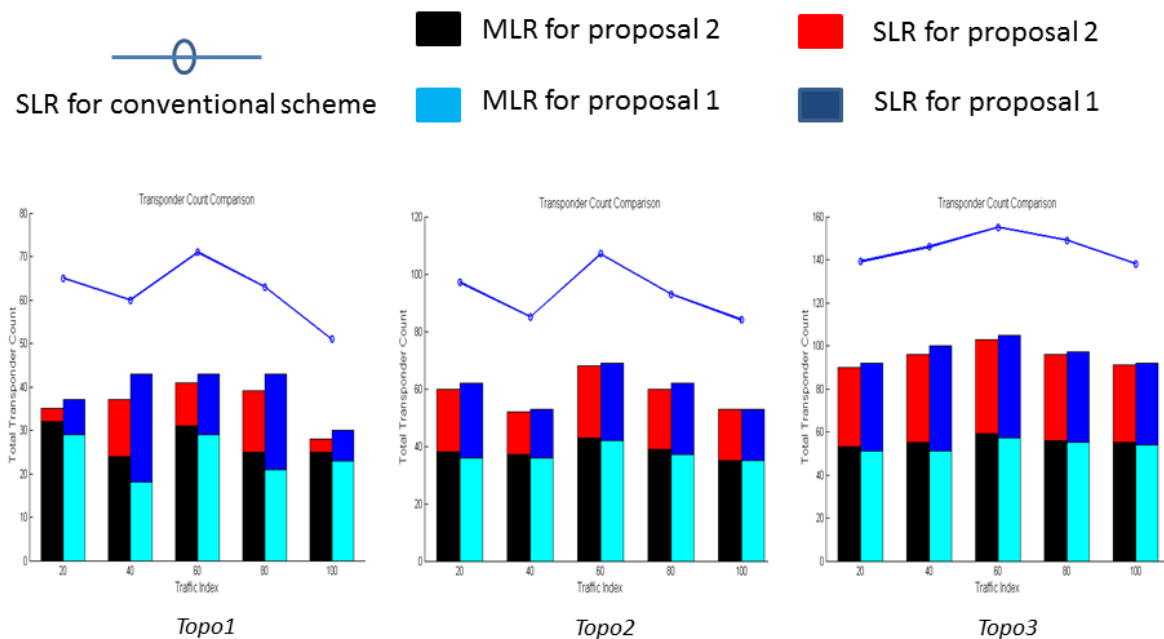


FIGURE 2.12: Transponder Count Comparison for Shared Scenario

For shared protection scenario, the result is shown in figure 2.12. As expected, for all protection scheme, the total number of transponders needed is less than for the dedicated scenario. For example, in percentage, the reduction gain between shared and dedicated is 19%, 33%, 33% for conventional approach with respect to topology 1, 2, 3 respectively. A similar trend to dedicated protection could be observed, that is, there is significant reduction of transponders by employing new protection proposals compared to conventional one. Specifically, the proposal 2 exhibits 43%, 37% and 35% gain for topology 1, 2, 3 respectively. A lower gain is offered by

proposal 1, being 39%, 36% and 34% for network 1, 2, 3. It should be noticed that for the gap in term of transponder count between proposal 1 and 2, the shared scenario is much lower than dedicated one.

The table 2.4 presents the average total of transponder for three schemes over three topologies and the corresponding gains in term of percentage. It is noted that the average value is rounded to reflect the integer nature of number of transponders.

TABLE 2.4: Transponder Count Results

Scenario	Topologies	Conventional	Proposal 1			Proposal 2		
		(SLR)	SLR	MLR	Gain	SLR	MLR	Gain
Dedicated	1	80	28	26	31%	14	33	40%
	2	140	48	47	32%	18	62	42%
	3	220	87	69	30%	42	92	40%
Shared	1	63	13	25	39%	7	29	43%
	2	92	21	37	37%	20	38	37%
	3	147	42	55	34%	39	57	35%

### 2.4.3 Transponder Cost Impact

The previous part illustrated the gain in term of transponder count for the new approach based on MLR transponder. However, MLR transponder is expected to be costlier than SLRs. This part investigates the cost impact of new approaches when the relative cost of MLR to SLR is varied.

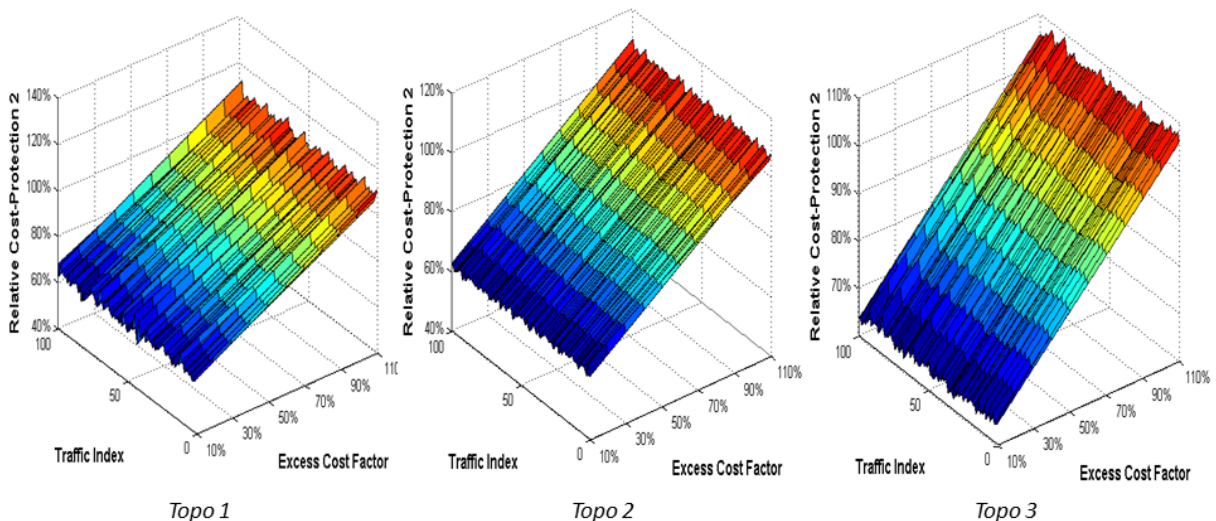


FIGURE 2.13: Relative Transponder Cost of Proposal 2-Dedicated Scenario



For the dedicated protection scenario, figure 2.13 presents the relative transponder cost of survivable network design with proposal 2 to conventional approach when excess cost factor of MLR,  $\alpha$ , is varied from 10% to 110% and at different traffic matrices. It is clear that the lower value of MLR cost brings about more cost-efficient design. Specifically, when  $\alpha$  is as low as 10%, the transponder cost with protection proposal 2 is just, in average, 65%, 62% and 64% compared to conventional approach for topology 1, 2 and 3 respectively. When  $\alpha$  is increased, for example at a value of 50%, proposal 2 cost is proportionally increased, though it is still more cost-efficient than conventional scheme, being around 81% for three topologies.

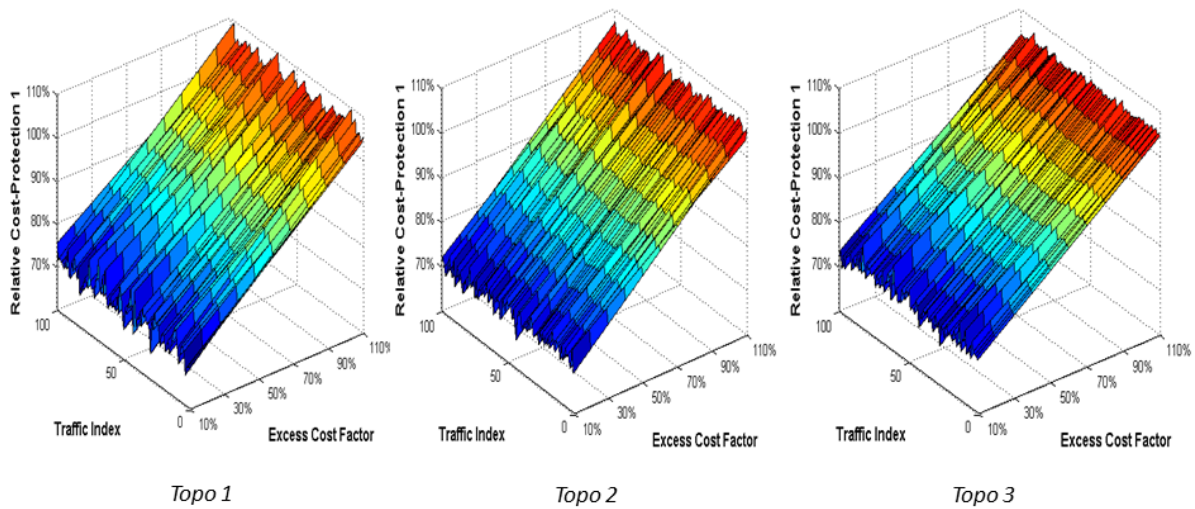


FIGURE 2.14: Relative Transponder Cost of Proposal 1-Dedicated Scenario

Figure 2.14 reports the relative transponder cost of proposal 1 to conventional one as the traffic and excess cost factor is changed. A similar trend could be observed like in the result for proposal 2, that is, the lower value of MLRs cost would lead to lower relative cost of the proposal 1. However, proposal 1 cost is in general higher than proposal 2 for a wide range of  $\alpha$ . For example, when  $\alpha$  is 10%, the mean cost of proposal 1 is roughly 72% of conventional one for all three topologies, at least 7% higher than proposal 2. As the MLR cost increase, the gap between proposal 2 and proposal 1 is also reduced due to the fact that the advantage in proposal 2 of using more MLRs is offset by the higher cost of MLRs. In this study, when MLR cost is more than twice of SLR, proposal 2 design is less cost-efficient than proposal 1.

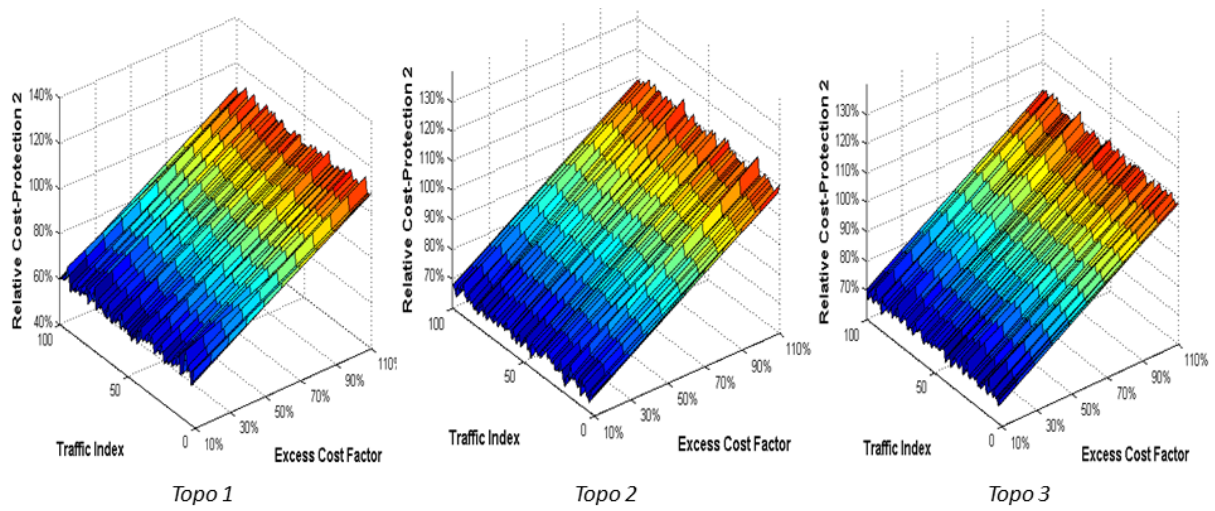


FIGURE 2.15: Relative Transponder Cost of Proposal 2-Shared Scenario

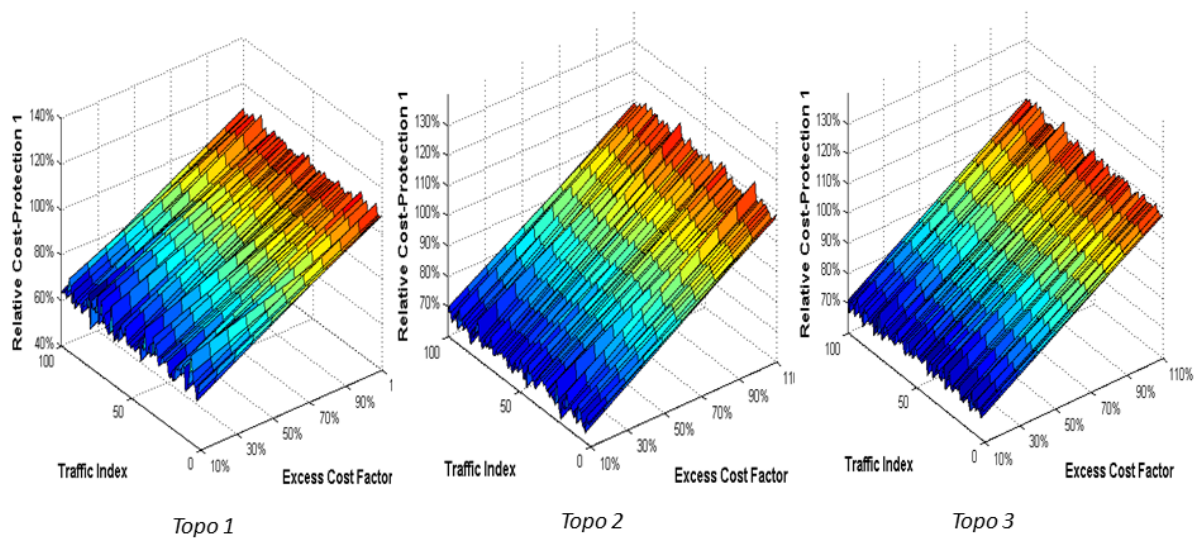


FIGURE 2.16: Relative Transponder Cost of Proposal 1-Shared Scenario

TABLE 2.5: Excess Cost Results

Scenario	Protection Scheme	"Break-even" value	Topo1	Topo2	Topo3
Dedicated	Proposal 1	Max	100%	100%	100%
		Min	80%	80%	80%
		Average	89%	90%	89%
	Proposal 2	Max	100%	100%	100%
		Min	80%	80%	80%
		Average	91%	91%	91%
Shared	Proposal 1	Max	100%	100%	100%
		Min	80%	70%	70%
		Average	88%	86%	86%
	Proposal 2	Max	100%	100%	100%
		Min	80%	70%	70%
		Average	90%	90%	89%

For the shared protection scenario, the figures 2.15 and 2.16 plot the relative cost of proposal 2 and 1 respectively compared to conventional one as the traffic and excess cost factor is varied. It is noticed that slightly different from dedicated scenario, proposal 1 and 2 have quite comparable cost. For example, when  $\alpha = 10\%$ , the design cost with proposal 2 is 62%, 67%, 67% of conventional design for topology 1, 2 and 3 while for proposal 1, those values are 65%, 67%, and 67%. As the MLR cost increases, the relative design cost of proposal 1 and 2 are quite comparable compared to dedicated scenario, being around 83%.

A point of interest would be the question at which cost of MLR, the new approaches is cost-efficient than conventional one. Those result are summarized in table 2.5. It is noticed that the "break-even" value of  $\alpha$  is quite comparable among three topologies. When MLRs cost is more than twice of SLR, the new protection schemes is not cost-efficient. Besides, it is observed that as far as the MLR excess cost is lower than 70%, a cost gain could be realized for new protection schemes and the actual gain depends on the traffic and network topology.

#### 2.4.4 Transponder Power Consumption Impact

The result in this part examines the power consumption aspect of new protection approaches compared to the traditional one. The evaluation is based on the assumption of two-mode power consumption of MLR transponders and the fact that most of the time, it is utilized at lower mode as explained in section 2.4.1. The overhead parameter  $\beta$  accounting for the more complex

operation of MLR transponder is varied from 0% to 50%.

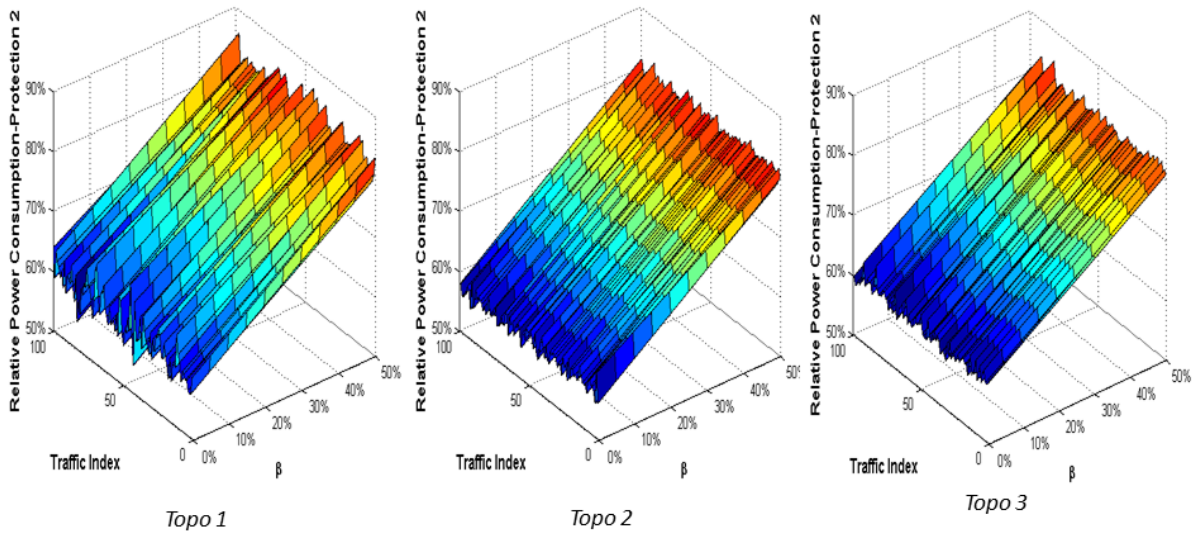


FIGURE 2.17: Relative Transponder Power Consumption of Proposal 2-Dedicated Scenario

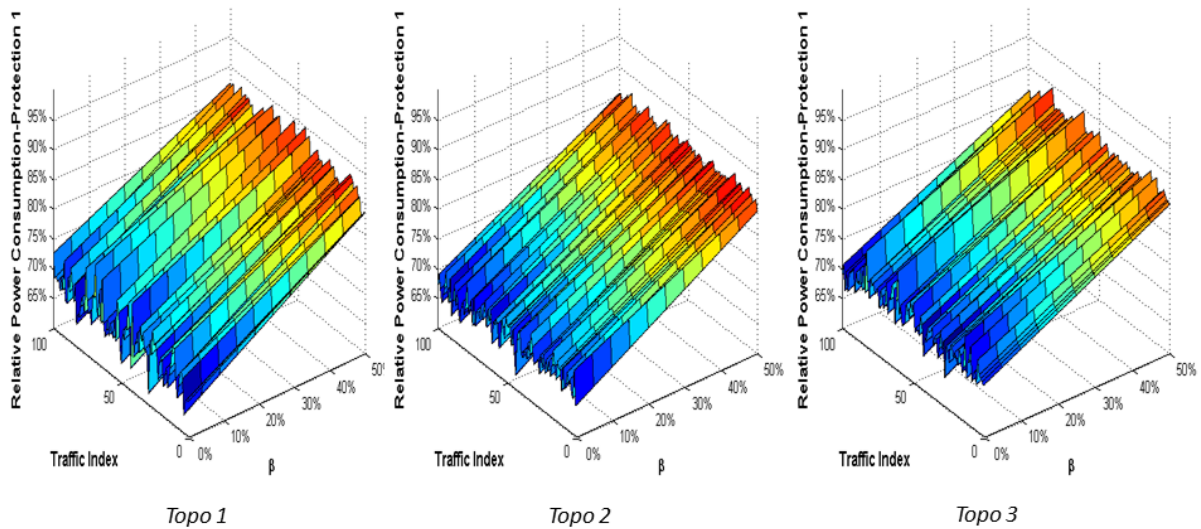


FIGURE 2.18: Relative Transponder Power Consumption of Proposal 1-Dedicated Scenario

For dedicated scenario, the figure 2.17 and 2.18 present the relative transponder power consumption of survivable network design with protection proposal 2 and 1 compared to conventional one when traffic and overhead parameter  $\beta$  is varied. A similar set of of result for shared scenario is shown in figure 2.19 and 2.20. The table 2.6 summarize statistical information at extreme points (i.e.,  $\beta = 0$  and  $\beta = 50\%$ ). It could be seen that at ideal case,  $\beta = 0$ , in dedicated scenario, proposal 2 could achieve around 40% transponder power consumption gain compared

to conventional one while the figure for proposal 1 is around 30%. For shared scenario, the gap between proposal 2 and proposal 1 is reduced, being equal in topology 2 while they are 1% and 3% difference for topology 1 and 3, respectively. When  $\beta$  is increased, the gain is clearly reduced and at  $\beta = 50\%$ , it is reduced to less than 20% for all three topologies. Proposal 2, in general, is considered more power-efficient than proposal 1, particularly at low value of  $\beta$  while at high value of  $\beta$ , they becomes more comparable.

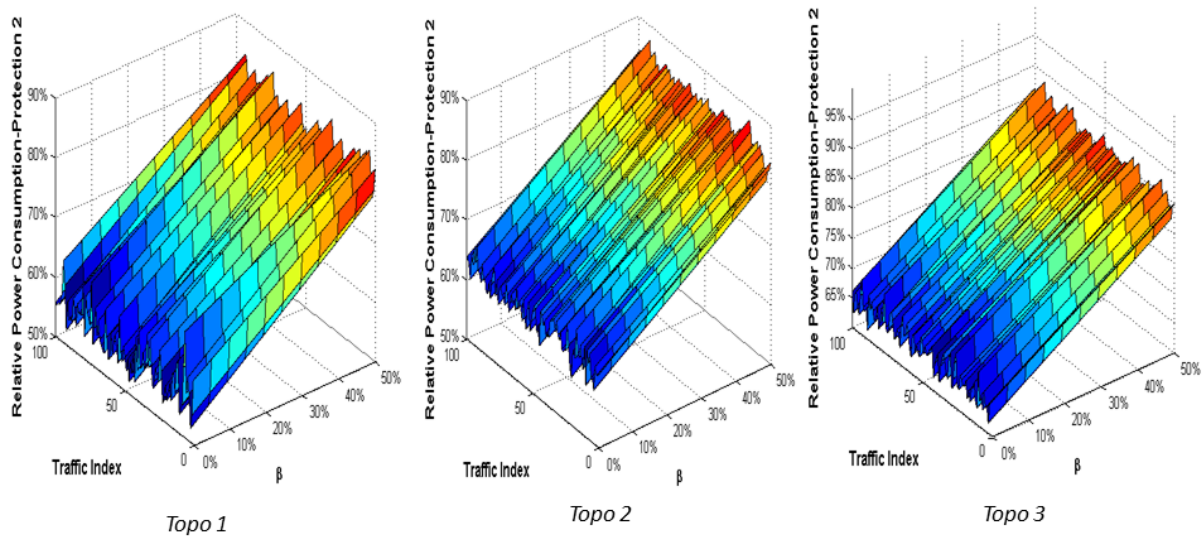


FIGURE 2.19: Relative Transponder Power Consumption of Proposal 2-Shared Scenario

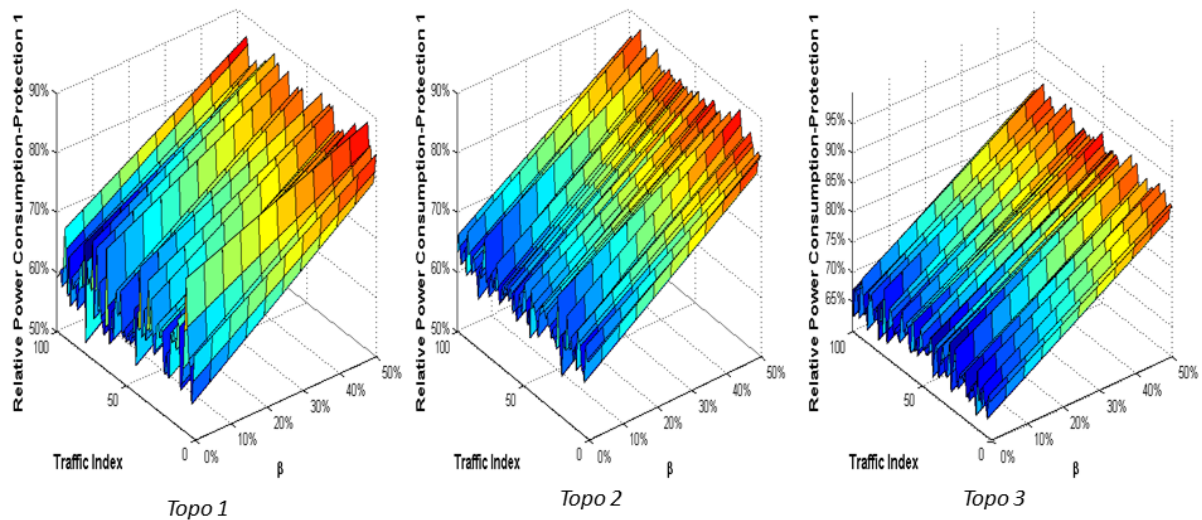


FIGURE 2.20: Relative Transponder Power Consumption of Proposal 1-Shared Scenario

TABLE 2.6: Power Consumption Gain Results

Scenario	Gain	Topo1		Topo2		Topo3		
		$\beta = 0\%$	$\beta = 50\%$	$\beta = 0\%$	$\beta = 50\%$	$\beta = 0\%$	$\beta = 50\%$	
Dedicated	Proposal 1	Min	24%	10%	29%	13%	24%	11%
		Max	38%	18%	38%	18%	35%	17%
		Average	31%	15%	32%	15%	30%	14%
	Proposal 2	Min	32%	14%	29%	18%	36%	15%
		Max	45%	23%	45%	22%	42%	21%
		Average	40%	19%	42%	20%	40%	19%
Shared	Proposal 1	Min	24%	12%	30%	12%	29%	13%
		Max	48%	24%	43%	20%	38%	19%
		Average	39%	18%	37%	17%	34%	15%
	Proposal 2	Min	32%	15%	33%	12%	30%	12%
		Max	48%	24%	42%	20%	39%	19%
		Average	43%	20%	37%	17%	35%	15%

## 2.5 Chapter Conclusion

In this chapter, we have discussed the application of MLR transponders for efficient protection. Based on the recognition that the sleep mode devices is not popularly supported so far, the equipments for backup purpose must be always on and hence, exhibit power consumption concern in addition to cost overhead. 100G PM-QPSK is generally accepted as winning solution for 100G technology and it would therefore be worth to study the upgrade scheme based on existing infrastructure. In this context, we considered MLR transponder working at 100/200G by modulation format change and benchmarked with SLR transponder working at 100G.

We have proposed a novel scheme considering the rate-adaptive mode of MLR transponder. In our proposal, MLR transponder operates at lower rate for working traffic while it could be tuned to higher rate to temporarily carry protection traffic. Under that policy, two algorithms regarding to transponder allocation have been presented and studied. We have justified that most of the operation time, the MLR transponder is operated in lower-rate mode, and thus, the power consumption evaluation could be approximately based on value for lower-mode.

We have performed a survivable network design with opaque architecture for both dedicated and shared protection. The design is formulated as integer linear programming with the objective to minimize the overall flow allocation. The simulation is extensively carried out over 100 traffic

matrices and different network topologies. Impact in term of transponder count, cost and power consumption has been addressed. It was shown that the new protection schemes with MLR transponder could be more cost and power-efficient compared to the traditional. In our studied case, as long as the MLR excess cost is less than 70%, new design with MLR transponder is always cost-efficient than tradition one. Besides, the power consumption gain could be up to more than 40% with overhead value  $\beta = 0$ .

## Chapter 3

# Algorithms for Routing and Spectrum Assignment

The significant progress of optical technologies from both hardware and software aspects has opened the door for a more efficient, flexible optical network based on *flex-grid* paradigm. Being considered as the promising architecture for next-generation optical network to meet an ever increasing Internet traffic in such a cost and energy-efficient fashion, flex-grid optical network has been receiving increasing attention from research community and standard body. Together with other on-going important tasks, efficient algorithms have been constantly sought out in order to fully realize the promising benefits of this new network architecture. In an analogy to the importance of routing and wavelength assignment (RWA) in traditional fixed-grid wavelength-route optical network, routing and spectrum assignment (RSA) is a crucial task for planning and operating network with elastic spectrum spacing. One of the featuring motivations of removing current wavelength grid is to have more efficient spectrum utilization and it is, to a great extent, relied on efficient schemes for solving the RSA problem. This chapter addresses the static version of RSA problem for both single and multi-objective scenarios. For single-objective case, the contribution is two-fold. Firstly, we have proposed efficient meta-heuristic based on genetic algorithm (GA) to provide near-optimal solutions to the problem. The effectiveness of the GA-based heuristic is benchmarked with other heuristics for a set of network scenarios. It is shown that in addition to the better performance than typical heuristic in literature, the proposed GA heuristic indeed could achieve optimal solutions in most cases while the running time is still manageable. Secondly, we propose to make use of very good solutions from (meta-) heuristic approaches to set the upper-bound and warm-start point for integer linear programming formulation. This combination has been shown very effective in reducing running time and significantly increases the probability of achieving optimal solution in a given time period compared to solving integer linear programming model separately. For the multi-objective scenario, the study is carried out in two contexts. The first one is when there is preference of any objective over the others and



we exploit the characteristic of the constituent objectives to properly set the weight that reflect such preference and to convert multi-objective problem into single one with integrated objective function. Moreover, we demonstrate by solving integer linear programming models that the integrated objective optimization could achieve better solutions than the case of optimizing single constituent objective and not taking into account other objectives. Different from the first context, the second one assumes that there is no prior information about the preference of each constituent objectives and in this case, we use multi-objective genetic algorithm to obtain non-dominating front (Pareto front). A novel genetic encoding model accounting for both routing and spectrum assignment has been employed.

### 3.1 Introduction

Algorithm is undoubtedly central component of optical networks [29, 30]. Indeed, it involves all phases of a network from designing step, planning to operating one. As the network is evolving to replace electronic parts by optic counterpart [31, 32], a number of challenges arise and thus, adds more complexities on algorithm aspect. Clearly, it has been shown that a good set of algorithms lead to better network utilization, even optimal one which translate to considerable gain in capital and operation revenue [33]. Conversely, poor algorithms could under-utilize the resources and consequently, not realize full benefits. Well-designed algorithms are therefore importantly needed. There are a number of criteria and requirements as well in designing algorithm such as complexities, running time, and scalability. Depending on the phase of the network, some criteria could be of more priority than others [9, 34]

Historically and still currently deployed, the optical network is based on wavelength-routed network (WDM) with fixed grid plan which is characterized by identical spectrum spacing distance among channels. For example, in backbone network, the nominal center frequencies are 50 *GHz* equally spaced. Regarding to algorithmic aspect, extensive research activities have been carried out for this type of network covering comprehensively all issues from static to dynamic operation [34], from single to multiple objective scenerio [35] and constitute an important research topic not only from optical network community but also from operation research [29, 30]. Typical problems are addressed including routing and wavelength assignment, traffic grooming and resilience issues [34]. To a great extent, the success of WDM network could be somehow attributed to its efficient algorithms which are the fruit of decades of research [29, 30]. However, there are a number of facts pushing fixed grid WDM networks no longer suitable in the future [36, 37].

The Internet traffic has undergone significant increase during last years with the advent and increasing penetration of new rich-bandwidth services such as video on demand, high definition TV and cloud services. The global IP traffic is forecasted to grow at a compound annual rate (CAGR) of 23% from 2012 to 2017 according to [38]. Transport networks will therefore be severely impacted by such growth. The most concerning point is that with such explosive traffic growth, the network will soon reach the capacity limit of conventional fiber [39] and thus, the efficient usage of fiber spectrum resources are a driving force for research activities on next-generation optical network [36, 37, 40]. With this motivation, WDM network which has been very successful in the past, must be examined to find sources of inefficiency and it has been found that fixed grid scheme based on  $50GHz$  is a main drawback for the evolution of the network to meet future requirements (beyond 100G) [41, 42]. The natural proposal is to remove the current fixed grid one and replace by a finer grid granularity, either 25 GHz or 12.5 GHz or 6.25 GHz, to better match beyond 100 Gb/s era (e.g., 400 Gb/s) plan [43, 44]. There are a large number of research activities justifying the benefits of migrating to flex-grid scheme [26, 45–49]. Besides, significant advances in hardware (flexible optical transponder) [3, 50, 51], software (control plane, management system issue) [52–54] push the perspective of flex-grid more practically. Test-bed and experimental activities has been increasingly reported [55–57]. Apart from extensive research activities from academia, standard bodies are also having on-going activities to incorporate the flex-grid scheme into their specifications [58, 59].

Flex-grid network is characterized by the fact that the spectrum is divided into slices of fixed spectrum bandwidth (e.g., 12.5 GHz or 6.25 GHz [58, 59]) and an optical connection can span elastically to a number of slices as it actually needs. This permeates the supporting from sub-wavelength capacity to super-channel efficiently. Being notably different from WDM network, well-established algorithms for WDM network can not be directly applied to this type of network. In fact, due to finer granularity and elastic scheme, more complex problem appears in flex-grid network and therefore putting more requirements on algorithm aspect.

In an analogy to the importance of routing and wavelength assignment(RWA) [60] in traditional fixed-grid wavelength-route optical network, routing and spectrum assignment(RSA) is a crucial task for planning and operating network with elastic spectrum spacing. RSA problem involves the finding a route and assigning necessary spectrum slices for a demand. Under no spectrum conversion availability or the network is all-optical/transparent which is a favorable architecture now, the following constraints is associated with RSA problem [61, 62].

- Spectrum continuity along the links of a given routing path means that the set of spectrum slices used must be remained the same in all links of the route.

- Spectrum contiguity for spectrum allocation of a demand means that the set of spectrum slices allocated to a demand must be contiguous.
- Spectrum non-overlapping on each fiber means that each spectrum slice on a fiber must be utilized by maximum one demand only.

Noted that the additional constraint of spectrum contiguity compared to RWA problem. It appears due to the elastic spectrum nature of flex-grid network and the implied condition that there is single path routing for the demand.

Like RWA in WDM network, RSA problem could be addressed at different phase of network. For long-term network planning, which typically occurs before the deployment of a network, there is generally a large set of demands (i.e., estimated traffic) which needs to be processed at once. Since there is presumably sufficient time between planning and provisioning process, the objective of planning phase is to determine optimal strategy for accommodating the demand set. The RSA version in this phase is collectively referred as *static or offline RSA*. Once the network is in-operation, static RSA might be performed periodically/on-request for the incrementally added traffic. In contrast, another version of RSA, called online or real-time RSA, needs to be solved for real-time operation phase. As the services have evolved toward more dynamic, real-time planning could become more common [1]. This is a shift from the past which relied only on static or semi-static planning. In real-time planning, demands are processed one by one and there is little gap time between planning and provisioning. The emphasis is therefore put in timing aspect for the algorithm. In this work, we focus only on static version of RSA problem

As mentioned, static RSA problem arises in the planning phase where set of traffic requests are served at once. In the context of flex-grid or spectrum-sliced network, the traffic requests are expressed in term of number of spectrum slices. The requirement is to find a route and assign spectrum so that all connections are served and to minimize/maximize certain objective functions. Objectives could be either single or multiple one. Typical objectives are considered including spectrum width, congestion level, spectrum link usage, etc. In the literature, most of the works focused on single-objective scenario and the approaches toward this problem comes from integer linear programming and/or heuristic algorithms. For ILP approach, it is classified into two types of formulation depending on whether the routes are pre-calculated or not, referring as node-link [63–65] or link-path formulation [61, 66]. While different ILP version have deal with variants of the RSA problem, the ILP model is nevertheless NP-hard complexity [67, 68] and therefore, it is still intractable for large instances. Decomposition approaches based on column generation has been studied [69, 70] in order to alleviate the complexity. Column generation consists of finding a reduced set of variables (columns) to solve the linear relaxation of the ILP

formulations, providing high quality integer solutions in an efficient way. It could be a promising direction since in WDM network, such techniques has been proven to be quite efficient [9, 71]. On the other front, heuristics, approximate solution techniques can be used to tackle RSA-based problems in a very short running time. There has been numerous heuristic proposed tailoring to different variant of RSA problem, for example in [61, 65, 69, 72]. Despite the superior running time of heuristic approach, its quality of solutions is still a concern. Meta-heuristics allow the improvement of heuristics solutions by adding random factor, allowing escaping from local optima. Some popular meta-heuristic are based on simulated annealing, ant colony, or genetic algorithm [30]

Genetic Algorithm (GA) has been used successfully for a number of optimization problems in WDM networks, particularly the RWA problem [73, 74]. For the multi-objective WDM optimization, it has been also a well-studied topic, [75–79]. Nevertheless, the use of genetic algorithm for RSA problem is currently inadequate in the literature. Few research works have been reported so far. In [80], the authors used GA to search for optimal spectrum ordering which were then used for First-Fit spectrum assignment in dynamic network operation. Multi-population GA were first time proposed in [81] in order to address the trade-off between search performance and algorithm robustness. However, the scenario study was simply limited to dynamic operation where the requested are processed one by one. In [82], the offline RSA with dedicated path protection was addressed and solved with a combination of GA and most slice first ordering of demands. In that paper, demands were first ordered according to groups which are based on number of requested slices (i.e., all demands within the group has the same requested slices) and GA is used to find a good ordering for each group so that when all the groups are concatenated according to most slice first scheme, it could yield optimal spectrum width. Noted that the use of GA was limited to search for good ordering for each group only.

This chapter will serve as a contribution to solve static RSA problem for both single and multi-objective scenario. To that end, its original contribution are highlighted as followed:

- Propose a GA-based heuristic to search for best ordering of demands which could yield (near-) optimal solutions as from ILP model.
- Propose and demonstrate the efficiency of combining heuristic solutions and ILP model to boost the running time performance.
- Propose to exploit the information of constituent objectives to properly set the weight that reflect the preference and demonstrate that optimizing with integrated objective would give better solutions than the one solely considering single objective.

- Propose and study a multi-objective genetic algorithm for solving RSA problem with multi-objectives.

This chapter is organized as followed. The next section, section 3.2, presents our studies about single-objective problem. Within that section, we present integer linear programming formulation based on channel definition which is so far known as very efficient in solving RSA problem. Afterward, we present our proposal on using genetic algorithm together with the detail implementation. Subsequently, the efficiency of GA-based heuristic is demonstrated by comparing with solutions from other heuristic and from integer linear programming. In addition, the efficiency of combining heuristic solutions with ILP model is also investigated. Section 3.3 dedicates on multi-objective optimization of RSA problem. In the first part of this section, the approach based on weighting method will be introduced. The content includes the methodology to set proper weight and a demonstration on the benefit of integrated objective approach being solved with ILP model. The second part of section 3.3 investigates the use of multi-objective genetic algorithm for solving RSA problem. The advantage of this approach is on the achieving of Pareto-front in a very efficient way. Numerical result illustrates the benefits of this approach.

## 3.2 A Single-Objective Problem

A range of objectives could be considered for the routing and spectrum assignment problem. In this section, we recall the traditional objective of interest being investigated for static network dimensioning, that is to minimize the *spectrum width requirement* to support a given set of traffic demands under given physical topology. The importance of such objective is to provide information for network planner about a number of spectrum slices needed to be used, and thereby spectrum-related cost to support a given traffic demands. The problem could be informally stated as follows

*Given a physical topology and a set of demands to be served, find the route and assign spectrum to each demand subject to a number of constraints so that all demands are served and to minimize the spectrum width which is measured in term of number of spectrum slices*

We will deal with that problem by presenting an integer linear programming approach and a GA-based heuristic one in the next parts. As a way to speed up the solving of ILP model, we propose to feed good solutions from heuristics to ILP model.

### 3.2.1 Integer Linear Programming Approach

Integer Linear Programming Approach for Routing and Spectrum Assignment has been extensively studied in the literature [72]. Several authors proposed different versions of formulations regarding to diverse objectives, topology and complexities as well. Being differed from routing and wavelength assignment, the more complexity of routing and spectrum assignment problem lies in the condition of spectrum contiguity for which a set of dedicated variables and constraints must be present to account for.

Authors in [66] proposed an innovative approach to simplify the complexity of problem by appropriate pre-processing phase so as to ensure the contiguity constraint beforehand and thus, the formulation could be simplified in terms of numbers of variables and constraints. Besides, the formulation would be more compact than other proposals [72]. A channel concept being formed by pre-computing set of spectrum contiguous frequency slot was introduced as a means of avoiding explicit and rather cumbersome representation in the formulation. We will present the channel concept and based on that, provide the integer linear programming formulation for RSA problem. The key reference for this part is from [66].

#### 3.2.1.1 Channel Definition

The definition of channels is illustrated through following example. The channel sets are classified according to number of contiguous spectrum slices belong to it. For example, set of channel with 2 slices could be represented as  $C(2)$ . Within this set, there are a number of channel which is numbered and occupies exactly two contiguous spectrum slices as illustrated in figure 3.1. By doing so, the identification of channel automatically implies the contiguity condition and the index of spectrum slices which are belong to it. For illustration in figure 3.1, when referring to second channel,  $c_2$ , belong to set of channel  $C(2)$  with two slices, it is implied that two spectrum slices with index 2 and 3 are used for that channel.

Formally, the definition is as follows. Let us represent  $C(n_d)$  as set of channels pre-defined for demand  $d$  (demand  $d$  requests  $n_d$  slices). Let  $\gamma_{cs}$  be coincidence coefficient, which is equal to 1 if channel  $c \in C$  uses slot  $s \in S$  and 0 otherwise. Then, with proper definition of  $\gamma_{cs}$ , the spectrum contiguity could be hold  $\forall c \in C(d): \forall s_i, s_j : \gamma_{cs_i} = \gamma_{cs_j} = 1, s_i < s_j \Rightarrow \gamma_{cs_k} = 1 \forall s_k \in \{s_i, \dots, s_j\}, \sum_{s \in S} \gamma_{cs} = n_d$ . The number of channel belongs to  $C(n_d)$  is  $|S| - (n_d - 1)$  where  $|S|$  is the total number of spectrum slices and  $n_d$  is the number of slices requested by demand  $d$ .

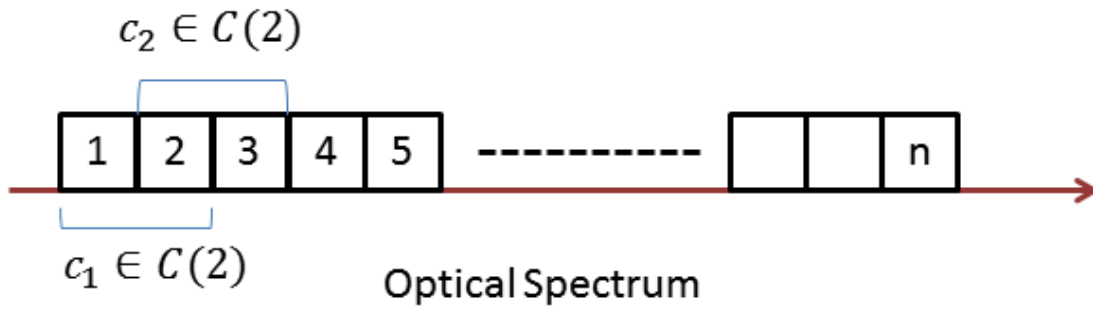


FIGURE 3.1: Channel Concept Illustration

It could be easily verified that the channel computation phase is trivial with polynomial running time and thus, almost no complexity is added in this stage. After computing channel set for all the demand  $d$ , we can re-state the routing and spectrum assignment as the problem of finding a route and a channel to set of traffic demands. Next, we present a link-path integer linear programming formulation based on channel concept. The link path formulation has an advantage of using far less variables and constraints than node-link one thanks to utilizing pre-computed candidate routes.

### 3.2.1.2 Integer Linear Programming Formulation

The integer linear programming formulation takes input from the pre-processing phase. Apart from computing set of channels that were described above, it needs also the calculation of  $k$  candidate paths for each demand  $d$ .

Given Information:

- $G(V, E)$ : Physical topology with  $|V|$  nodes and  $|E|$  links.
- $S$ : Set of available spectrum slices in each fiber.
- $D$ : Set of traffic demands, each demand  $d \in D$  request  $n_d$  slices
- $P_d$ : Set of  $k$  candidate paths for demand  $d \in D$
- $P = \cup_{d \in D} P_d$ : Set of all candidate paths
- $C_d$ : Set of admissible candidate channels for demand  $d \in D$
- $C = \cup_{d \in D} C_d$ : Set of all admissible channels

- $\delta_{pe}$ : constant equals to 1 if path  $p \in P$  uses link  $e \in E$ , 0 otherwise.  $\gamma_{cs}$ : constant equals to 1 if channel  $c \in C$  contains slice  $s \in S$ , 0 otherwise.

Variables:

- $x_{pc} \in \{0, 1\}$ : 1 if channel  $c$  is utilized on path  $p$ , 0 otherwise.
- $y_{es} \in \{0, 1\}$ : 1 if spectrum slice  $s$  is occupied on link  $e$ , 0 otherwise
- $z_s \in \{0, 1\}$ : equal to 1 if slice  $s$  is utilized on any link  $e$ .

The objective function is to:

- Minimize the spectrum width requirements in term of number of spectrum slices

$$\min \sum_{s \in S} z_s \quad (3.1)$$

subject to following constraints:

- The constraint guarantees that all demands are supported by selecting a route and assign a proper channel.

$$\sum_{p \in P_d} \sum_{c \in C_d} x_{pc} = 1 \quad \forall d \in D \quad (3.2)$$

- The constraint ensures that there is no spectrum overlapping by forcing each spectrum slices is utilized by at most one lightpath.

$$\sum_{d \in D} \sum_{p \in P_d} \sum_{c \in C_d} x_{pc} \delta_{pe} \gamma_{cs} = y_{es} \quad \forall e \in E, s \in S \quad (3.3)$$

- The definition of using a slice in network is given by following constraint, that is, a slice is considered as occupied in the network whenever there is a link in which it is occupied.

$$\sum_{e \in E} y_{es} \leq |E| \times z_s \quad \forall s \in S \quad (3.4)$$

### 3.2.2 Genetic Algorithm Approaches

Given the fact that integer linear programming model for RSA problem is NP-hard [67, 68], and thus, in principle, it is not tractable for large-scale instances. Therefore, an alternative approach based on heuristic to find near-optimal solutions are normally utilized as a complement to exact solutions. We present such a heuristic based on genetic algorithm for solving RSA problem. GA



is used to help finding a good (even optimal) ordering of demands to be sequentially served.

GAs concept were firstly coined by Holland [83] inspired by Darwin's law of natural evolution. The basic idea behind GAs is to mimic the natural mechanism by starting with initial population of chromosomes (individual) representing candidate solutions of the problem and applying genetic operators to evolve the population until the found solution meets some criteria. Crossover and mutation are typically used genetic operators where the former one combines, in certain ways, selected solutions to generate new solutions for next-generation of population and the latter alters the value of genes in random fashion aiming at avoiding the convergence of the solution to a local optima. The quality of solution is measured by fitness function, which could be the same or related to the objective of problem. In applying genetic algorithm to solve any problem, the first and foremost important task is to find a good encoding of the solution. Hereafter, we present the detail steps of using GAs for solving RSA problem.

### 3.2.2.1 GA details

Given physical topology  $G(V, E)$ , set of traffic demands  $D$ , and  $k$  candidate paths for each demand  $d \in D$ , we want to find such a good ordering of demands so as to be sequentially served by the algorithm described in fitness function leading to minimization of spectrum width requirement.

- **Genetic Encoding:** A solution to the problem is encoded in each chromosome (individual). In this version of genetic encoding, the individual represents a permutation of demands and hence its length is equal to the number of demands. The value of each gene is the demand id to be served sequentially according to the location of the gene. For example in the figure 3.2, demand 2 is served first and then demand 4, and so on.

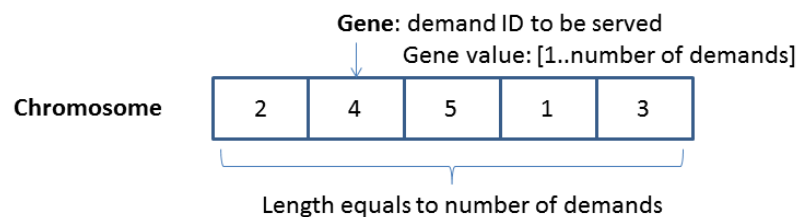


FIGURE 3.2: Genetic Encoding for GA-1

- **Population Initialization:** This process generates a number of initial chromosomes. Each chromosome here is random permutation vector with the length equivalent to number of demands. The number of generated individual is equal to the population size  $P_{size}$
- **Fitness Function:** For each individual, we have an ordered demands to be served. The serving of each demand under the spectrum continuity, spectrum contiguity and non-overlapping condition is performed as follows.

We represent the spectrum availability in each link  $e \in E$  by a vector  $u_e$  with the size equal to the number of spectrum slices  $S$ . Each element in the vector represent the availability of the spectrum slice, and element  $i$  equals to 1 if the slice  $i$  is available and 0 if it is occupied.

$$\overline{u}_e = (u_{e1}, u_{e2}, \dots, u_{e|S|}) \quad (3.5)$$

For a path  $p$ , we can calculate the spectrum availability vector for that path by performing AND operation for all the spectrum availability vector of links comprising the path.

$$\overline{U}_p = \cap_{e \in p} \overline{u}_e \quad (3.6)$$

For each demand  $d$  requesting  $n_d$  slices, we first evaluate the spectrum availability vectors of all  $k$  candidate path and then search the first possible placement of  $n_d$  contiguous slices. The path with the lowest indexed starting slice is selected. Afterward, we update the spectrum availability of the links constituting the selected path. After serving all demands in the chromosome, we evaluate this solution with fitness function as  $F = \max f(\overline{u}_e)$  where  $f(\cdot)$  is the function that returns the index of the last used slices on spectrum availability vector  $\overline{u}_e$ . It is noticed that the fitness value is equal to the objective value.

- **Natural Selection:** This process involves the keeping of fittest solutions to the next generation according to the selection rate  $X_{rate}$ . The solutions are ranked by their fitness value and only  $X_{rate} \times P_{size}$  best individuals are selected to continue while the rest is discarded from the population.
- **Crossover:** This step selects the parents and perform crossover operation to produce offsprings. We use random pairing technique to randomly select parent from mating pool produced after natural selection process. Then, we opt for single-point crossover [84] to produce offsprings. The single-point crossover for permutation problem works as follows. First, a random gene position is selected for parent chromosome. Then, the offsprings are created in such a way that the first part of offspring chromosome comes from one parent and the rest is completed by genes from the other parent not used in offspring yet. Figure 3.3 gives an example for this process. By doing so, the offspring produced are guaranteed to be valid (i.e., a permutation of demands-without replication).

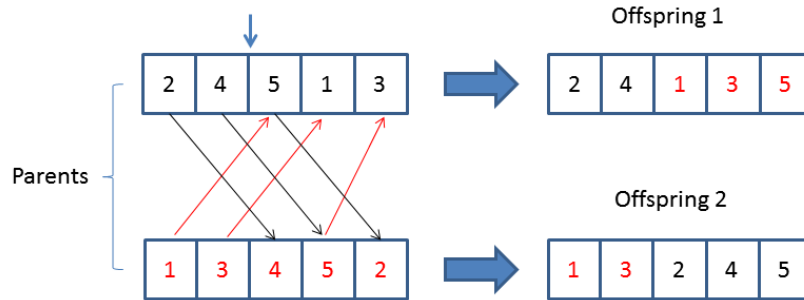


FIGURE 3.3: Single-point Crossover for GA-1

- **Mutation** The mutation operation is performed by firstly randomly selecting two gene position within each chromosome and exchanging their values. Figure 3.4 illustrates this operation. Noted that the chromosome after mutation is still valid one (i.e., no replication of any demand). The number of mutation operation is settled by mutation rate

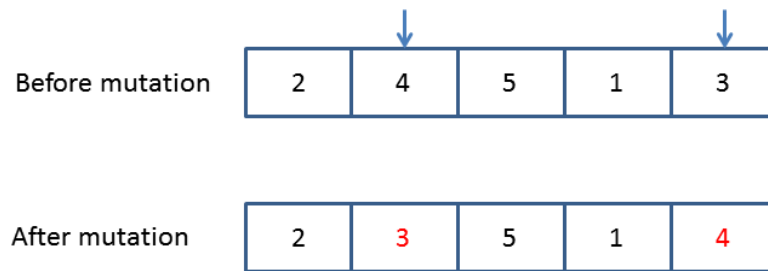


FIGURE 3.4: Mutation Operation for GA-1

- **Stopping Criteria** There are a number of criteria for terminating the algorithm. Typically, it could be the time limitation or a threshold for the best found individual, or alternatively the maximum number of evolution generation. In this work, we consider the maximum number of generation as stopping criteria.

### 3.2.3 Numerical Results and Performance Comparison

This section present numerical results regarding to the performance of GA-based heuristic and the efficiency of warm-start ILP model with heuristic solutions.

#### 3.2.3.1 Simulation Framework

We perform the study over two random topologies, as in figure 3.5, differing in each other by the number of nodes and links. The characteristic of the topologies are summarized in table 3.1

TABLE 3.1: Topology Characteristic

Parameters	Topo 1	Topo 2
Number of Nodes	6	8
Number of Links	18	32
Average nodal degree	3	4
Min nodal degree	2	2
Max nodal degree	4	6

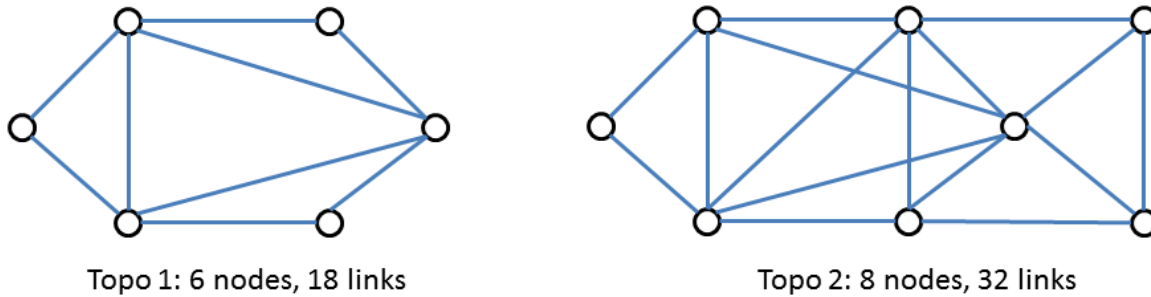


FIGURE 3.5: Network Topologies under Study

The traffic is randomly generated between node pairs in the network and any-to-any. The amount of traffic between each node pair is a random integer within [1..5] spectrum slices. The simulation of each result point is averaged over 20 instances if not mentioned otherwise. Candidate paths are found by using Yen's algorithm [85, 86]

As a reference algorithm, we choose MSF (Most Slices First), a typical reference algorithm for benchmarking purpose. MSF is a sequential heuristic algorithm for RSA where demands are ordered according to their number of requested spectrum slices and demands with highest number of slices is served first. The serving of each demand follows the same procedure as were described in fitness function of GA procedure. More information about this heuristic could be found in [62]

The GA and MSF procedures are implemented in Matlab. The modeling of integer linear programming formulation is carried out in Matlab, and is solved by IBM ILOG CPLEX v.12.4 with academic version [27]. The evaluation is performed on an Intel i7 3.3GHz, 16GB RAM computer.

GA implemented parameters and methods are summarized in table tab: GA Info

TABLE 3.2: GA component parameters

Parameters or Operator	Value
Population size $P_{size}$	chromosome length $\times 2$
Crossover rate $X_{rate}$	0.5
Mutation rate $\mu$	0.05
Maximum number of generations $G$	{50, 200}
Mating selection	random pairing
Crossover scheme	single-point

### 3.2.3.2 Performance Evaluation of GA solutions

We firstly evaluate the quality of GA-based solution by comparing to the solutions obtained from solving ILP formulation in small-scale scenario (i.e., low value of  $k$ ) and the solutions from MSF approach. The focus of comparison is on the objective value ( $\phi$ ) and running time ( $T$ ). The ILP formulation was solved by setting  $|S| = 50$  which is large enough to accommodate all the traffic in the worst case. The stopping condition for GA is set to 50 and 200 generations.

TABLE 3.3: Performance Comparison

Network	k	MSF		GA-50		GA-200		ILP	
		$\phi$	T (s)	$\phi$	T (s)	$\phi$	T (s)	$\phi$	T (s)
Topo1	2	13.15	0.04	10.75	8.50	10.65	33.58	10.55	196.63
	3	12.75	0.06	10.75	12.25	10.65	48.29	10.55	489.12
Topo2	2	15.65	0.09	13.25	29.63	13.15	116.76	12.6	2746
	3	14.4	0.16	12.65	41.79	12.55	164.71	12.15	-

Table 3.3 present the results for small-scale scenario by limiting to low value of  $k$  (i.e.,  $k=2$  and 3). We consider two results for GA corresponding to different number of generations. For topology 2 with  $k = 3$ , due to the complexity of ILP, it has not reached the optimal solutions (i.e., with respect to link-path formulation) for 4 out of 20 instances after two hours and so, we make an average over 16 cases of optimality. It is clearly shown that GA outperform MSF and indeed, it achieves the optimal solutions in most of the cases. For example, with topology 1 and  $k = 3$ , the GA-50 achieves the optimal result for 16 times out of 20 while GA-200 could be better, reaching optimally 18 out of 20 instances. The more generation the GAs run, the better the solution is in general. However, it comes at an expenses of running time which grows linearly with number of generations. MSF solutions were reported to not reach any optimal solution, and indeed, MSF solutions has quite large optimality gap. For example, with topology 2 at  $k = 2$ , the optimality gap is roughly 20%. Regarding to the running time, MSF solutions are able to be obtained within less than a second and it is scalable quite well with more complex topology and more candidate paths. Conversely, ILP solutions, as expected, takes a significant time for running and as the size of the problem increases, the running time could become extremely high. As

the case of topology 2 with  $k = 3$ , it is not able to solve some instances within two hours. GA solutions are relatively time-efficient since the running time is significantly lower than ILP solution.

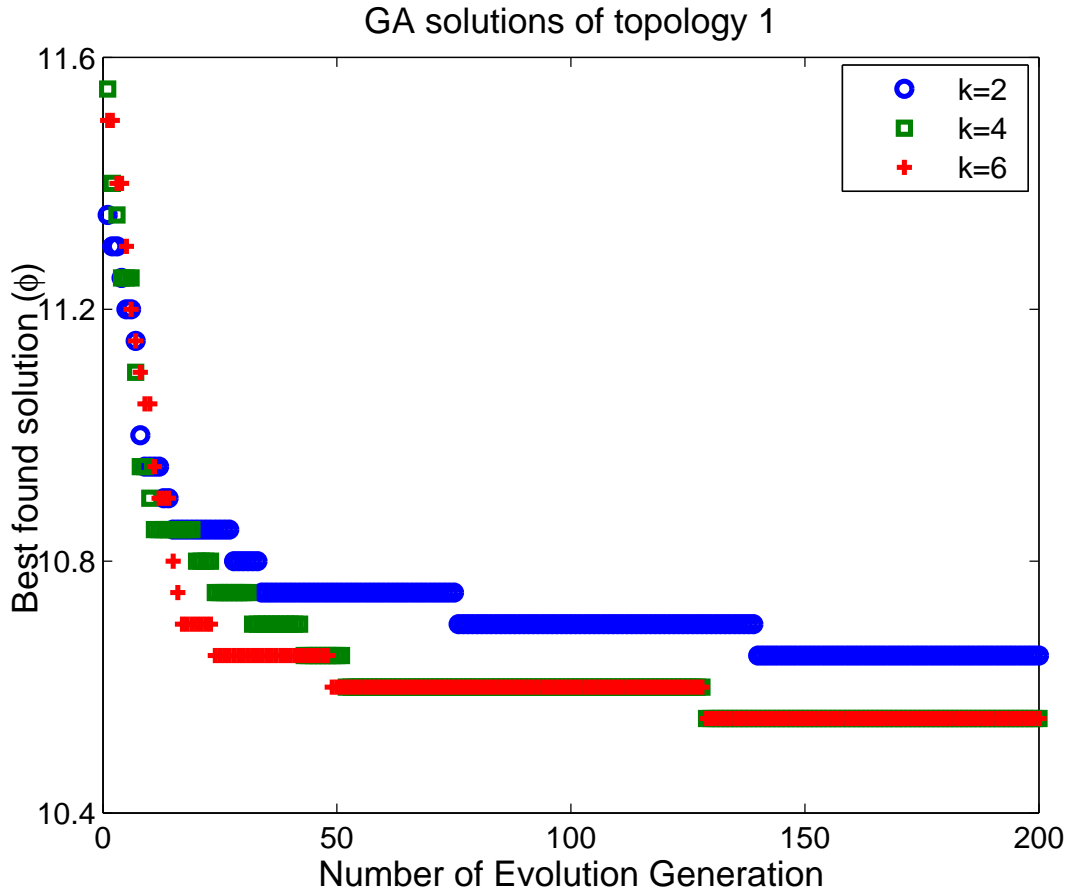


FIGURE 3.6: GA solutions as function of generations-topology 1

Figure 3.6 shows the quality of GA solutions with respect to number of generations and at different value of  $k$  for topology 1. It is clearly seen that GA-based solution achieves good convergence rate. After around 30 generations, a significant improvement compared to initial solutions has been realized. For the impact of  $k$  to the objective value, moving from  $k = 2$  to  $k = 4$  clearly leads to better solution, an improvement of approximately 1%. However, as  $k$  continue increasing, from 4 to 6, there is almost no benefits with respect to objective value. This is due to the fact that topology 1 has small number of nodes and node degree, and thus, impact of having many candidate paths is negligible. With that observation, we could conclude that with  $k = 4$ , the algorithm reach the optimal value of objective  $\phi$ .

Similarly, Figure 3.7 shows the results of GA solutions as an evolution over generations at different value of  $k$  for topology 2. It is clear that the value of  $\phi$  for topology 2 is higher than topology

1 due to a growing number of traffic demands (which is proportional to a square of number of nodes). It is also noted that for the case of topology 2, it needs more generations of running to be practically considered to be convergent. Compared to around 30 generations for topology 1, the value for topology 2 is around 50 generations. It could be explained by noticing that the search space in the case of topology 2 is bigger than topology 1 because there are more demands and thus, the chromosome length is longer. The figure also shows the impact of  $k$  in improving the objective  $\phi$ . The objective value is considerably improved by increasing  $k$  from 2 to 6, an improvement of 5%. We experimented that as candidate paths are more than 6, it becomes not necessary since there is almost no change in objective value. Therefore, it is concluded that at  $k = 6$ , optimal solution is found.

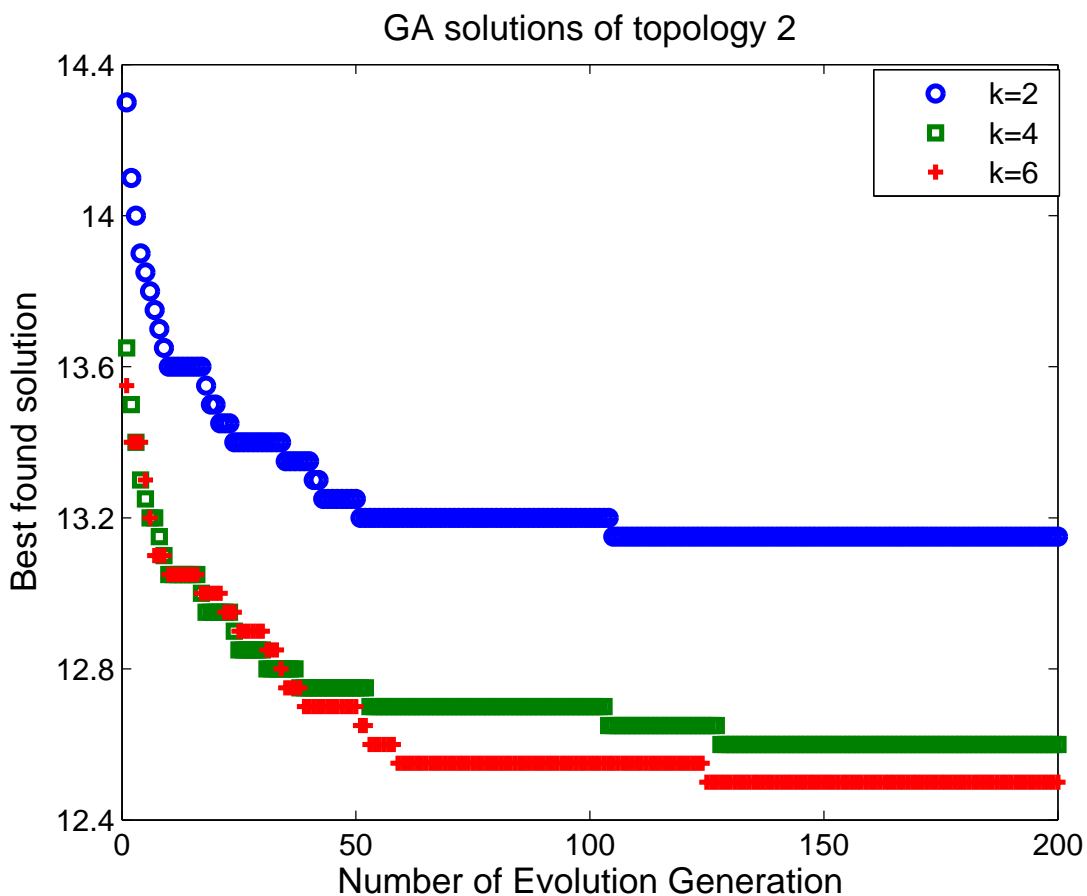


FIGURE 3.7: GA solutions as function of generations-topology 2

Figure 3.8 presents the impact of  $k$  to the running time of GAs for two topologies. We report here the running time when GAs is stopped at 100 generations. As expected, the running time grows almost linearly with the increasing of candidate paths  $k$  due to the processing in fitness evaluation. Besides, it is important to consider that the size of chromosome has a significant impact on running time. For the study case, the topology 1 has 30 demands and topology 2 has 56 demands, and noted that the running time of topology 2 is more than three times higher

than topology 1.

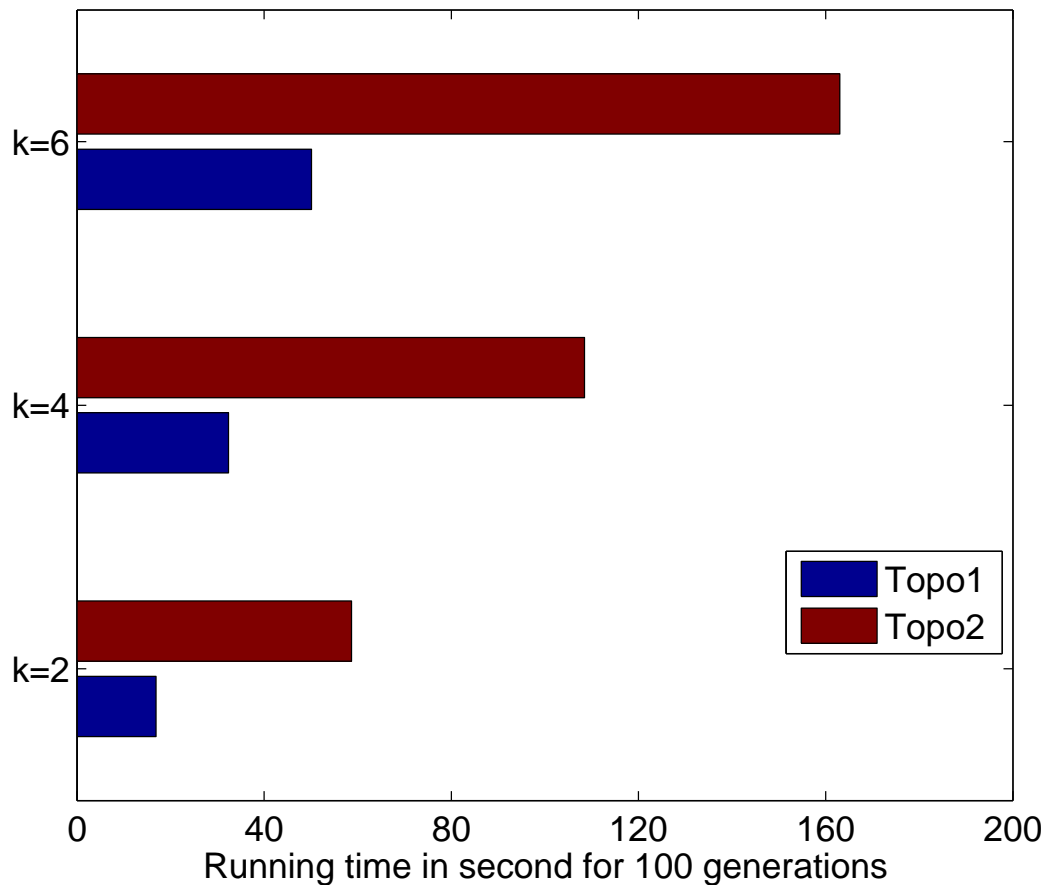


FIGURE 3.8: Running of GA solutions for 100 generations

### 3.2.3.3 Efficiency of Warm-start with heuristic solutions

It is clear that for solving this type of RSA problem with ILP model, the setting of upper-bound  $S$  is critically important to the running time. Also, we observe that it is very likely to take a considerable amount of time, depending on the problem, for optimization solver to find good solutions (i.e., comparable to solutions from heuristics) with its own heuristic techniques. Despite the fact that the solver is equipped with advanced heuristic techniques, it is still quite general and blind to the characteristic of the problem. Recent activities in operation research community suggested the possibility of boosting performance for integer linear programming with efficient heuristic [87]. The result in this part investigates the efficiency of feeding heuristic solutions to warm-start the solving of integer linear programming model.



For benchmarking, we compare the running of three ILP options. The first one is the traditional option when  $S$  is blindly set or based on worst-case to be sure that it could meet the most demanding scenario. Here we set  $S = 50$  as it is proven to work well in most demanding scenario [62, 66]. The second and third option is where  $S$  is set by the objective value found from MSF and GA approach. Moreover, the solutions from MSF and GA (the routing and spectrum assignment for each demand) are also provided to ILP model as a warm-start point. The second and third options are differed by the fact that the GA solutions are better than MSF one and thus, favorably tighten the ILP model. In this study, ILP-GA is when GA solution is found after 50 generations and fed to ILP model.

TABLE 3.4: Running time Comparison

Network	$k$	$T_{ILP}(s)$ with $ S  = 50$	$T_{ILP-MSF}(s)$	$T_{ILP-GA}(s)$
Topo1	2	196.63	0.26	0.08
	3	489.12	0.28	0.08
	4	1211.20	0.28	0.12

In the first scenario, we test in small-scale scenario (topo 1 with low value of  $k$ ) where original ILP model is solvable within 2 hours of running. Table 3.4 presents the results. It is clear that as  $k$  increases, the running time of traditional ILP model grows significantly as expected due to the non-polynomial proliferation of variables and constraints. The benefits of providing good bounds and initial start are demonstrated by very low running time for ILP model which are fed by MSF and GA solutions. The results are very encouraging since the ILP-MSF and ILP-GA model could be solved in less than one second compared to order of hundred seconds as for original ILP model. Noted that in several cases, the objective value found from GA is already optimal and as matter of fact, the solver needs simply performing very less amount of processing in order to ensure the optimality. The added value from running ILP-GA even with "optimal" solution being fed is the confirmation of optimality which is not mathematically proven by simply using GA.

TABLE 3.5: Optimality Comparison

Network	$k$	ILP with $ S  = 50$	ILP-MSF		ILP-GA	
		$\alpha$	$\alpha$	$T(s)$	$\alpha$	$T(s)$
Topo2	4	$\frac{11}{20}$	$\frac{20}{20}$	12.5	$\frac{20}{20}$	2.9
	6	$\frac{7}{20}$	$\frac{20}{20}$	20.5	$\frac{20}{20}$	5.1
	10	$\frac{1}{20}$	$\frac{20}{20}$	52.2	$\frac{20}{20}$	25.2

In the second scenario, we perform study on topology 2 (more complex) and larger values of  $k$  (i.e.,  $k = 4, 6, 10$ ) where traditional ILP model is not solvable for certain instances within 2 hours. The table 3.5 presents the results of the capability of finding the optimal results (parameter  $\alpha$ ) with different ILP models under a limited time. It is shown that as  $k$  increases, the capability of the solver to find optimal point within 2 hours is considerably reduced for traditional ILP

model. However, when armed with MSF and GA solutions, all the instances are solvable and more encouragingly, the running time is still very low, e.g., a magnitude of ten seconds. It is noted that the running time of ILP-GA is better than ILP-MSF for all the studied cases. This is quite intuitive since GA solutions are proven to be better than MSF solutions and thus, it tightens the bound better for ILP model, leading to a reduced search space.

### 3.3 A Multi-Objectives Problem

We now turn our attention to the multi-objective problem. Many real-world problems require the simultaneous optimization of a number of objectives. This is collectively known as multi-objective optimization. Very often, in those problems, a situation in which certain of the required objectives may be in conflict with one another. For example, in the network design with both minimizing the spectrum link usage and congestion level. As the minimization of congestion level is achieved by spreading the traffic to diverse routes (normally longer routes) which inherently causes increase of spectrum link usage. A reduction of spectrum link usage, on the other hand, means that demands simply takes the shortest routes which potentially causes bottle-neck congestion.

Extensive studies have been carried out in multi-objective optimization. Basically, there are two approaches [88]. The first one, quite straightforward, is to weight each objectives and add them together to form a single scalar one (integrated one) to be optimized. The optimal solution is obtained by solving the single-objective problem. Clearly, the challenge with this method is to know how to properly determine the value of weight that incorporate the preference information. The second approach is preferred where there is no prior preference information on constituent objects and therefore, a set of solutions in the form of non-dominating front are desired. On the non-dominating front, all the solutions are equally optimal.

In this section, we will consider the multi-objective RSA problem trying to minimize both spectrum link usage and congestion level. Clearly, the extension to more than two objectives are quite straightforward. We investigate the problem from two perspectives. In the first one, we assume that there is information about the priority of constituent objective, and therefore we propose a method to properly set the weight that reflect such preference. For the second perspective, all objectives are equally important (i.e., without any prior preference), we employ the multi-objective genetic algorithm which is based on fast non-dominated sorting (NSGA-II) to find the best non-dominating front.

### 3.3.1 Weighting Method with Integer Linear Programming

#### 3.3.1.1 Joint Spectrum Link and Congestion Level Optimization

We introduce ILP formulation for multi-objective RSA problem, jointly minimizing spectrum usage and congestion level. The path-link formulation adopting channel assignment, as described in [66], is used here thanks to its provenly efficient computational time and also its compact form. The study presented here was reported in [89].

Given information:

- $G(V, E)$ : A graph represents physical network topology where  $V$  is the set of nodes and  $E$  is the set of links.
- $S$ : Set of available spectrum slices in each fiber. The number of slices is  $|S|$
- $D$ : Set of traffic demands, each demand  $d \in D$  is represented by a tuple  $(s_d, r_d, n_d)$  where  $s_d$  and  $r_d$  are respectively the source and destination nodes of the request, and  $n_d$  is the number of requested spectrum slices.
- $P_d$ : Set of  $k$  candidate path which are pre-calculated for demand  $d \in D$
- $P = \cup_{d \in D} P_d$ : Set of all candidate paths
- $C_d$ : Set of admissible candidate channels for demand  $d \in D$  (i.e., set of channel have  $n_d$  contiguous slices)  
 $C = \cup_{d \in D} C_d$ : Set of all admissible channels
- $\delta_{pe}$ : constant equals to 1 if path  $p \in P$  uses link  $e \in E$ , 0 otherwise.
- $\gamma_{cs}$ : constant equals to 1 if channel  $c \in C$  contains slice  $s \in S$ , 0 otherwise.
- $\mathbf{w} = (\alpha, \beta)$ : weight vector indicates the importance of each constituent objective

#### Variables

- $x_{pc} \in \{0, 1\}$ : 1 if channel  $c$  is utilized on path  $p$ , 0 otherwise.
- $y_{es} \in \{0, 1\}$ : 1 if spectrum slice  $s$  is occupied on link  $e$ , 0 otherwise
- $G$ : positive integer, defines the overall usage of spectrum link
- $F$ : positive integer, defines the congestion level of the network

#### Objective

$$\text{Minimize } f_{int} = \alpha G + \beta F \quad (3.7)$$

subject to following constraints:

$$\sum_{p \in P_d} \sum_{c \in C_d} x_{pc} = 1 \quad \forall d \in D \quad (3.8)$$

$$\sum_{d \in D} \sum_{p \in P_d} \sum_{c \in C_d} x_{pc} \delta_{pe} \gamma_{cs} = y_{es} \quad \forall e \in E, s \in S \quad (3.9)$$

$$\sum_{e \in E} \sum_{s \in S} y_{es} = G \quad (3.10)$$

$$\sum_{s \in S} y_{es} \leq F \quad \forall e \in E \quad (3.11)$$

The integrated objective function  $f_{int}$  consists of two weighted terms. The first term  $G$  represents the spectrum usage and the second term  $F$  represents the congestion level. Constraint 3.8 guarantees that all demands are supported by selecting a route from a set of pre-defined paths and assign a proper channel. Constraint 3.9 ensures that there is no spectrum overlapping on each link by imposing a condition that each spectrum slice on a fiber link is utilized by at most one demand. Constraint 3.10 and 3.11 gives the definition of  $G$  and  $F$ , respectively.

### 3.3.1.2 Analysis on Impact of Weight Vector

The weight vector identifies the importance of each constituent objective. We will analyze the priority of each objective depending on the weight vector values. Noted that  $0 \leq G \leq |E||S|$  and  $0 \leq F \leq |S|$  and the minimum change in  $G$  and  $F$  is a unit. We consider three cases:

- $\frac{\alpha}{\beta} > |S|$ : Assume that there is a minimum increase, a unit, in  $G$ , and an arbitrary change over  $F$  (e.g., from  $F$  to  $F^*$ ). The overall variation on integrated objective is  $\delta = \alpha + \beta(F^* - F)$ . Noted that  $-|S| \leq F^* - F \leq |S|$  and  $\alpha > \beta|S|$ , hence  $\delta > 0$ . Thus, a minimum increase in  $G$  causes an increase in integrated function despite any variation of  $F$ . This implies that the minimization of  $f_{int}$  is to firstly minimize  $G$  and then to minimize  $F$ , or in other words,  $G$  is prioritized in this case.
- $\frac{\alpha}{\beta} < \frac{1}{|E||S|}$ : Similarly, we consider a unit increase in  $F$  and an arbitrary change in  $G$  (e.g., from  $G$  to  $G^*$ ). The integrated objective variation is therefore  $\delta = \beta + \alpha(G^* - G) > 0$  since  $-|E||S| \leq G^* - G \leq |E||S|$  and  $\beta > \alpha|E||S|$ . This implies that the minimization of  $f_{int}$  is to firstly minimize  $F$  and then to minimize  $G$ . In other words,  $F$  is prioritized in this scenario.

- $\frac{1}{|E||S|} < \frac{\alpha}{\beta} < |S|$ : There is no definitive conclusion on priority of each constituent objective in this case. Intuitively, it is observed that the priority on  $G$  is highest for  $\frac{\alpha}{\beta} > |S|$  and becomes lowest when  $\frac{\alpha}{\beta} < \frac{1}{|E||S|}$ . Conversely,  $F$  is at highest priority if  $\frac{\alpha}{\beta} < \frac{1}{|E||S|}$  and at lowest one if  $\frac{\alpha}{\beta} > |S|$

### 3.3.1.3 Numerical Results

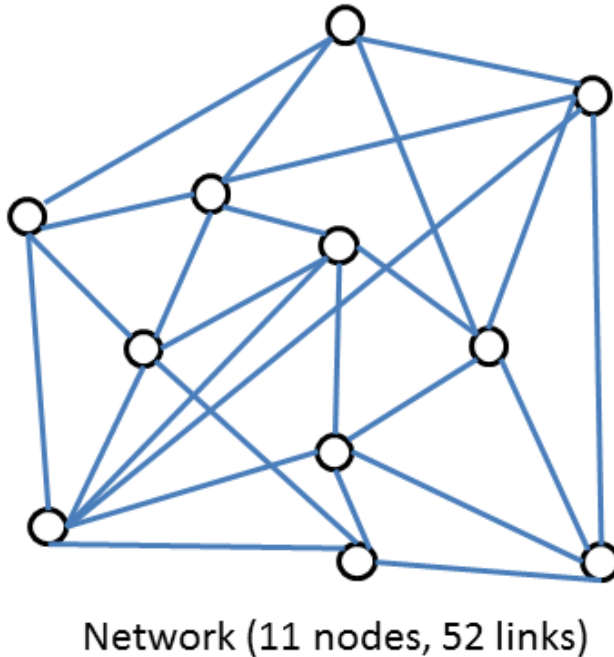


FIGURE 3.9: COST 239 topology

We numerically illustrate the impact of weight vector on integrated objective function and compare integrated approach to single-objective ones. Four designs, denoted as *SpecL*, *CongL*, *IntSpecL*, and *IntCongL*, are considered corresponding to weight vector  $\mathbf{w} = (1, 0), (0, 1), (|S| + 1, 1), (1, |E||S| + 1)$  respectively. The first two weight vectors correspond to single-objective minimization of spectrum link and congestion level and the last two weight vectors represent integrated objective with priority on spectrum link and congestion level respectively. COST239 topology (11 nodes, 52 links as in figure) is used as a case study. We assume  $|P_d| = 5$  and being the shortest paths, number of spectrum slices per fiber link  $|S| = 12$ . The source and destination of demands are randomly generated and the number of requested slices per demand,  $n_d$ , is uniformly distributed among  $\{1, 2, 3\}$ . Seven increasing traffic loads are generated ranging from a total load of 20 to 140 spectrum slices in a step of 20 slices. Each simulation point per load is averaged over 20 instances with the same total load. Optimal results are collected by solving ILP formulation with CPLEX in default setting

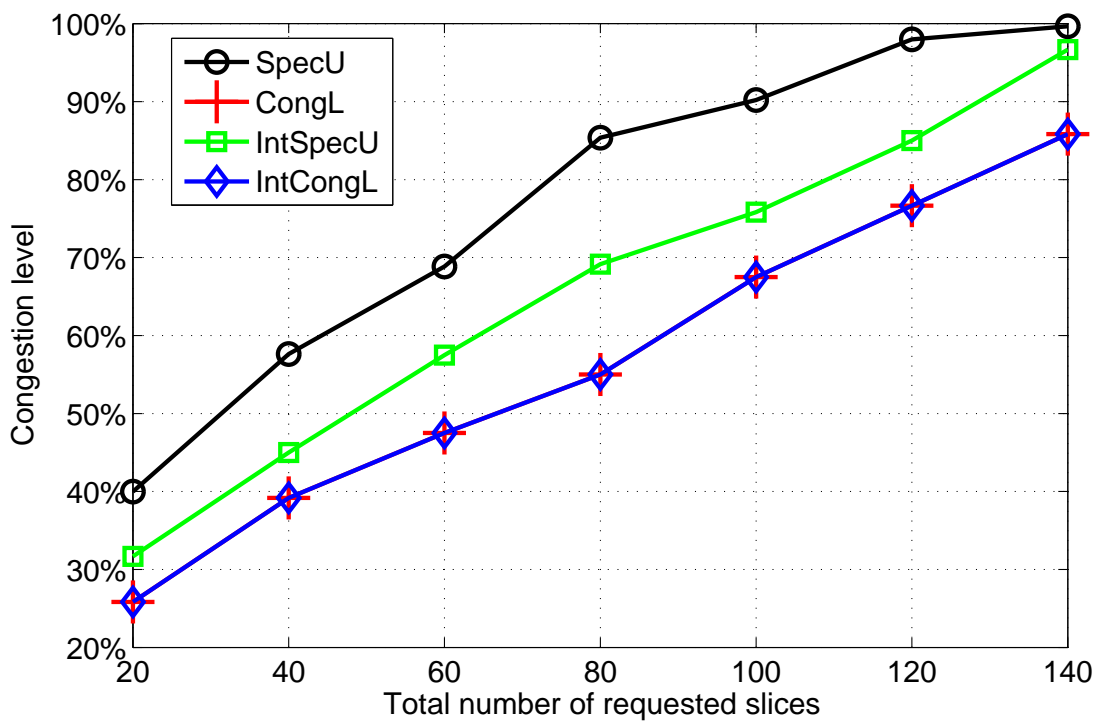


FIGURE 3.10: Congestion level vs. Traffic load

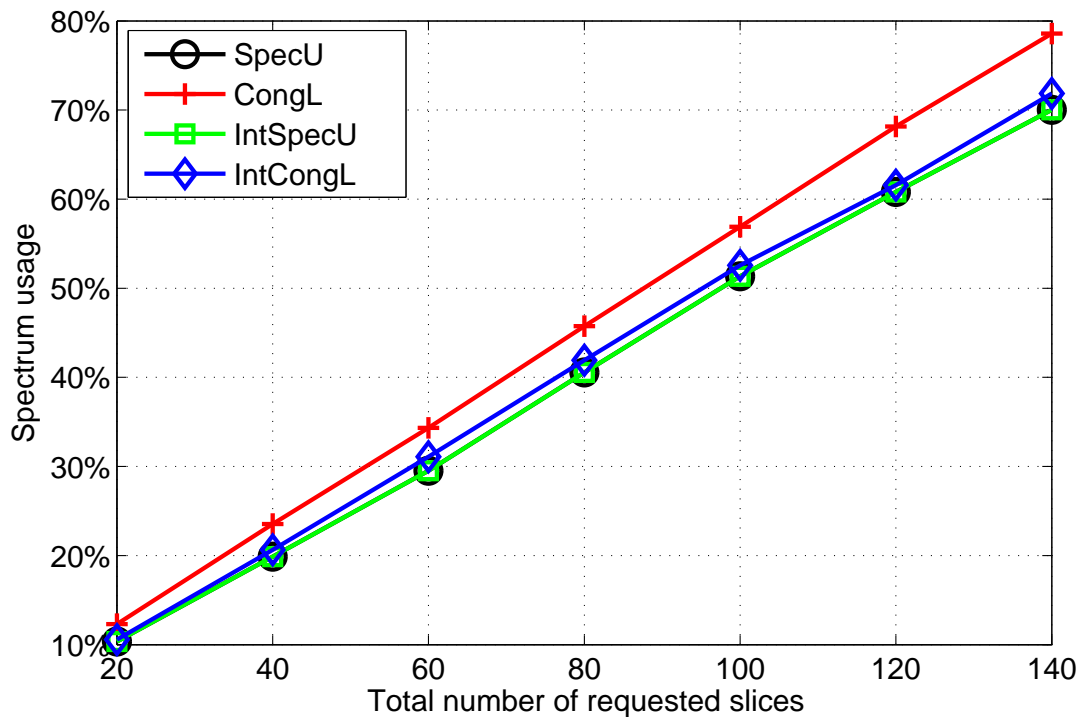


FIGURE 3.11: Spectrum usage vs. Traffic load

Figure 3.10 compares the congestion level (normalized to number of spectrum slices per fiber)

of four designs as the total traffic load increases. It is observed that the *CongL* and *IntCongL* achieve the best performance and coincide with each other. This corresponds to the analysis that minimizing integrated objective function with congestion level priority also leads to minimizing congestion level as a single-objective. Additionally, *SpecU* has the worst performance while *IntSpecU* has an improvement compared to *SpecU* and that improvement is evident at low and medium traffic load (i.e., when network congestion level has not reached maximum).

Figure 3.11 shows the spectrum usage (normalized to the total spectrum link) comparison among four designs with respect to traffic load. We can see that both *SpecU* and *IntSpecU* attain the best efficiency. This again validates the analysis on priority that minimizing integrated objective function with spectrum usage priority simultaneously brings to minimizing spectrum usage as a single-objective. In addition, *IntCongL* has a slightly lower performance compared to optimality (i.e., given by *SpecU* and *IntSpecU*) and *CongL* causes highest spectrum usage.

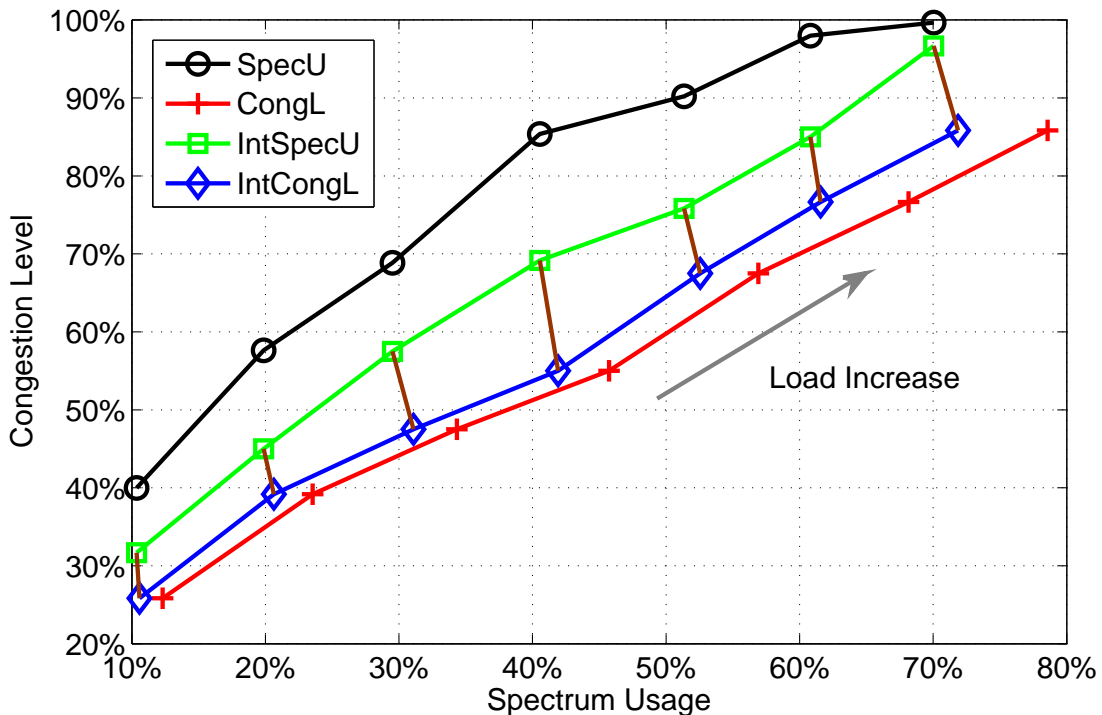


FIGURE 3.12: Congestion level vs. Spectrum Usage

Figure 3.12 illustrates the relation between two metrics, spectrum usage and congestion level, of four designs. It is clear from the figure that as the traffic increases, both congestion level and spectrum usage rise up in all designs. It is also shown that while *CongL* and *IntCongL* achieve best performance for minimizing congestion level, it nevertheless requires more resources than *SpecU* and *IntSpecU*. Conversely, *SpecU* and *IntSpecU* perform best for minimizing resources usage, yet incurring a higher congestion level than *CongL* and *IntCongL* design. It is highlighted that *IntCongL* always consume less spectrum usage than *CongL* while achieving

the same optimal congestion level. Similarly, *IntSpecU* leads to lower congestion level than *SpecU* while guaranteeing same optimal spectrum usage.

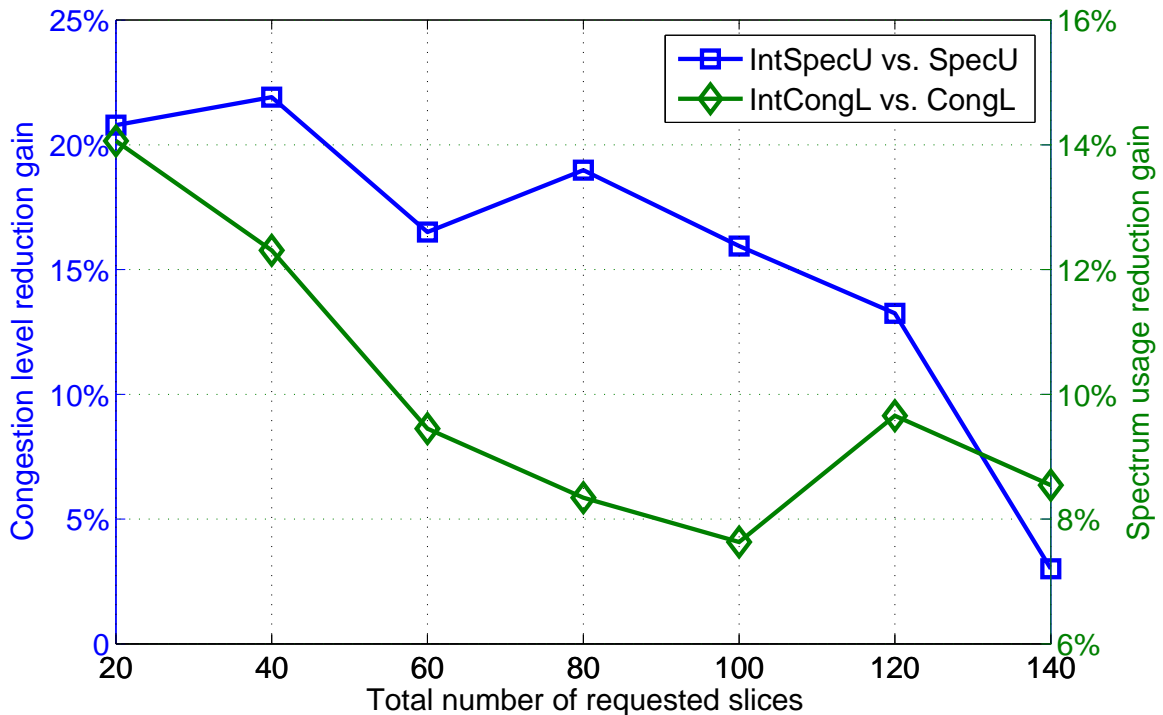


FIGURE 3.13: Relative gain of integrated objective approach

Finally, the relative gain of integrated objective over single-objective is shown in Figure 3.13. The comparison is drawn between *IntSpecU* versus *SpecU* in term of congestion level reduction and *IntCongL* versus *CongL* in term of spectrum usage reduction. It is clear from the figure that for all range of traffic, designs with integrated objective, *IntSpecU* and *IntCongL*, always outperform *SpecU* and *CongL* respectively. In this case study, a maximum gain of 20% in reducing spectrum usage could be attained by *IntCongL* compared with *CongL* while *IntSpecU* also achieves maximum 22% gain in reducing congestion level than its single-objective counterpart *SpecU*. Thus, by simultaneously optimizing multiple objectives and appropriately setting  $\mathbf{w}$ , better solutions than a traditional single-objective approach could be obtained.

### 3.3.2 Multi-objective Genetic Algorithm Approach

The feature of genetic algorithm which is based on the evolution of a population of solutions is well-suited for multiple objective optimization when there is no further information about the priority of each objective. In this case, there is in general no single best solution. Instead, there are set of solutions, known as Pareto-optimal solutions or non-dominated solutions. Without additional information, all these solutions are equally satisfactory. The goal of optimization in



this case is to find as many of these solutions as possible. Before going to the details of genetic algorithm approach, we introduce the concept of dominance and Pareto front which sets the basis for the study.

### 3.3.2.1 Pareto front and Dominance Concept

This part provides definition on domination concept and Pareto front for solutions in multi-objective problem. Without loss of generality, we consider the minimization of two objectives ( $f_1$  and  $f_2$ ) and all are equally important.

A solution to the problem could be represented by vector  $\mathbf{x}$  in the design space. The evaluation of two objective functions on  $\mathbf{x}$  produces corresponding objective values  $\mathbf{f}(\mathbf{x}) = (f_1, f_2)$  in the objective space.

For comparing two solutions  $x_1$  and  $x_2$ , a dominance concept is defined. In multi-objective optimization, Pareto criteria is mostly used. It is stated as followed:

- An objective vector  $\mathbf{f}_1$  is said to dominate another objective vector  $\mathbf{f}_2$  if no component of  $\mathbf{f}_1$  is greater than the corresponding component of  $\mathbf{f}_2$  and at least one component is strictly smaller.
- The solution  $\mathbf{x}_1$  dominates  $\mathbf{x}_2$  if  $\mathbf{f}_1 = \mathbf{f}(\mathbf{x}_1)$  dominates  $\mathbf{f}_2 = \mathbf{f}(\mathbf{x}_2)$
- All non-dominated solutions are the optimal solutions of the problem, i.e., solutions which are not dominated by any others. The set of these solutions is named Pareto set while its corresponding objective values is named Pareto front.

The purpose of multiobjective optimization genetic algorithm is to search for non-dominated solutions which is very close to real Pareto set.

### 3.3.2.2 Multi-objective Genetic Algorithm Implementation

We present the multi-objective RSA problem and its associated genetic algorithm model. We consider the RSA problem of spectrum-sliced optical network to support many request of different granularities simultaneously (known as multi-commodity flow problem). Each request has many possible routings and each routing has several choices of spectrum assignment. The network

design problem is to minimize the spectrum width requirement in number of slices to support all requests and to minimize the overall spectrum link usage.

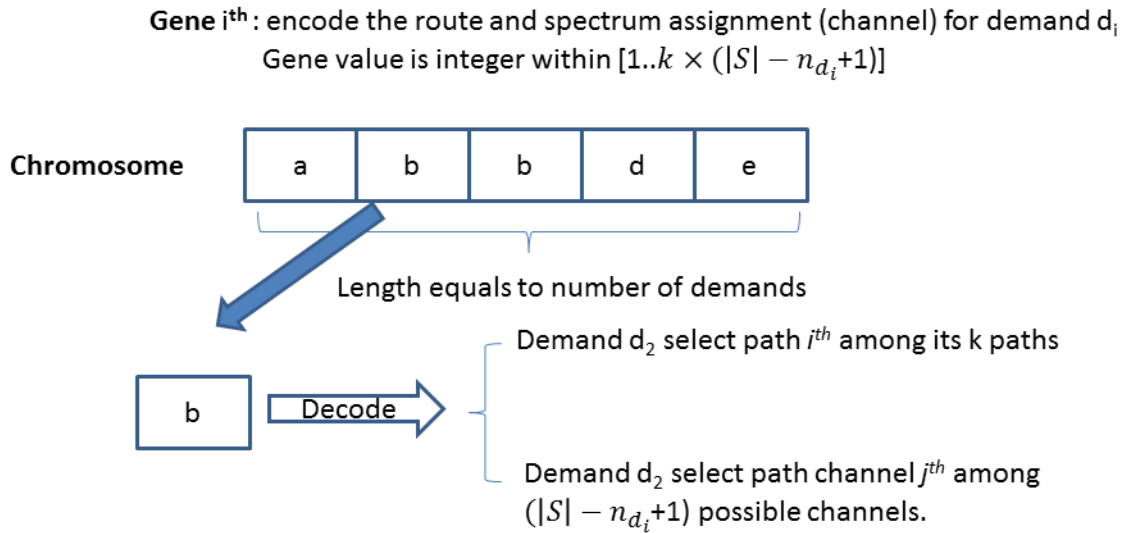


FIGURE 3.14: Genetic Encoding for Routing and Spectrum Assignment Problem

**Genetic Encoding** Given the set of demands which has been numbered ( $d_i$ ) to indicate the order of serving, each chromosome represents the serving of those demands by selecting a route and assigning a channel to each demand. Thus, the chromosome length is equal to total number of demands and the value of each gene encodes the route and spectrum assignment for the demand being represented. Figure 3.14 provides the illustration for the genetic encoding process. Assuming demand  $d_i$  requests  $n_{d_i}$  and there are  $k$  candidate paths, the number of possible ways for routing and spectrum assignment would be:  $k \times (|S| - n_{d_i} + 1)$ . By assigning a positive integer value within the range  $[1..k \times (|S| - n_{d_i} + 1)]$  for gene  $i^{\text{th}}$ , it is possible to decode that value to bring about which route and channel is selected by the demand. The decoding procedure is described algorithm 3. It is noticed that the serving of demand in such way satisfies the spectrum contiguity and the spectrum continuity constraint while the spectrum non-overlapping is not guaranteed. However, it is always possible to discard solutions that violates spectrum non-overlapping by assigning a very high value of objective functions to them. We opt for that option in this study.

**Algorithm 3** Chromosome Decode Procedure**INPUT:** Chromosome, Demand set  $D$ , number of candidate path  $k$ , Spectrum set  $S$ **OUTPUT:** Path and channel assignment for each demand  $d \in D$ 


---

```

for  $d_i \in D$  do

    if  $\text{rem}(\text{chromosome}(i), |S| - n_{d_i} + 1) == 0$  then
        path id for  $d_i = \frac{\text{chromosome}(i)}{|S| - n_{d_i} + 1}$            # rem: remainder after division
        channel id for  $d_i = |S| - n_{d_i} + 1$ 
    else
        path id for  $d_i = \lfloor \frac{\text{chromosome}(i)}{|S| - n_{d_i} + 1} \rfloor + 1$ 
        channel id for  $d_i = \text{rem}(\text{chromosome}(i), |S| - n_{d_i} + 1)$ 
    end if
end for

```

---

**Objective functions** There are two objectives associated to each chromosome. The first objective,  $f_1$ , is the spectrum width indicating the maximum slice indexed used in the network and the second objective,  $f_2$  is the total spectrum link usage. The algorithm 4 describe the evaluation procedure. Given a chromosome, the route and channel for each demand are calculated. After serving each demand sequentially, the spectrum availability vector of each link is updated. Whenever the serving of demand violates the spectrum non-overlapping condition, the procedure returns the very high value for both objectives indicating the discard of those solution. Otherwise, all demands are served and the objectives  $f_1$  and  $f_2$  are evaluated by performing simple calculation on spectrum availability vector of all links  $u_e$ .

**Algorithm 4** Objectives Evaluation**INPUT:** Chromosome, Demand set  $D$ , Spectrum set  $S$ **OUTPUT:**  $f_1$  and  $f_2$ 


---

```

for  $d_i \in D$  do
    Decode  $\text{chromosome}(i)$  into path id and channel id for demand  $d_i$ 
    Update the spectrum availability vector for each link  $u_e$  after serving demand  $d_i$ 

    if Spectrum Overlapping == True then
         $f_1 = Inf$ 
         $f_2 = Inf$ 
        RETURN
    end if
end for

 $f_1$  = maximum index of utilized slice for all links
 $f_2$  = arithmetic summation of spectrum availability vector of all links

```

---

**Crossover** For producing offsprings from parents, we use arithmetic scheme which linearly combine two parent chromosome vectors on a gene basis. By doing so, the valid range for each gene of the chromosome is preserved. Besides, in order to guarantee integer requirement for produced gene value, an upper rounding and/or lower rounding need to be performed.

$$offspring1 = \lceil \alpha * Parent1 + (1 - \alpha) * Parent2 \rceil \quad (3.12)$$

$$offspring2 = \lfloor (1 - \alpha) * Parent1 + \alpha * Parent2 \rfloor \quad (3.13)$$

**Mutation** The mutation operator is performed in this case by firstly locating the position of gene to be mutated and secondly, generating different random value within the range of this gene to be a new value.

For a multi-objective genetic algorithm procedure, a variant of NSGA-II [88, 90], the so-called controlled elitist genetic algorithm is used. The difference between elitist version controlled elitist one lies in the fact that the former one only consider the fitness value (rank) to evaluate the solutions whereas the latter one, apart from fitness value, also take into account diversity aspect of solutions. By doing so, the diversity of population is improved, which leads to a better convergence to an optimal Pareto front. The steps of the procedure could be described as follows:

### Fast Non-dominated Sorting Genetic Algorithm

Step 1) Initialization:

- Generate an initial population with  $P_{size}$  random chromosome vectors  $\mathbf{x}_i$  ( $i=1..P_{size}$ )
- *The initial population is sorted into categories (rank) on the basis of non-dominance. Each solution is assigned a fitness value equal to its non-dominance rank (i.e., rank 1 is the best)*

Step 2) Update:

- A mating pool is formed by selecting the best solutions from the population based on their ranks. In case of having to choose among solutions of the same rank, the crowding distance of the solutions belonging to that front is calculated and those individuals with higher value of crowding distance are preferred so as to favor the diversity.
- Generate offspring solutions by performing crossover operation and mutation.

- Combine all the new solutions with parent solutions to form new population.
- *Sort the newly formed population into categories (rank) according to their relationship of dominance*

Step 3) Stopping Criterion: If the stopping criterion is reached, then stop and output the set of non-dominated solutions, otherwise, continue step 2. The stopping criteria here is based on maximum number of generations.

### 3.3.2.3 Numerical Results

We perform the study on COST239 topology (11 nodes and 52 links). The traffic is generated randomly between node pairs and within the range [1..10] such that the total traffic number of requested slices is 200. Table 3.6 shows the used traffic matrix for study. The NSGA-II is implemented by making use of available Matlab built-in function from Global Optimization toolbox with some modification [90]

TABLE 3.6: Traffic Matrix

	1	2	3	4	5	6	7	8	9	10	11
1	0	9	0	0	2	2	0	0	0	0	0
2	0	0	3	9	9	10	0	0	0	0	0
3	0	0	0	0	0	0	0	3	0	3	0
4	2	0	5	0	8	1	0	0	0	0	0
5	0	0	0	0	0	0	0	4	0	0	0
6	0	0	0	0	0	0	0	4	0	9	6
7	0	0	0	10	0	0	0	0	0	0	0
8	0	5	0	0	0	0	9	0	0	0	0
9	7	4	3	0	7	6	0	7	0	3	0
10	0	0	8	7	0	3	9	0	0	0	2
11	0	10	0	1	1	0	3	0	0	0	0

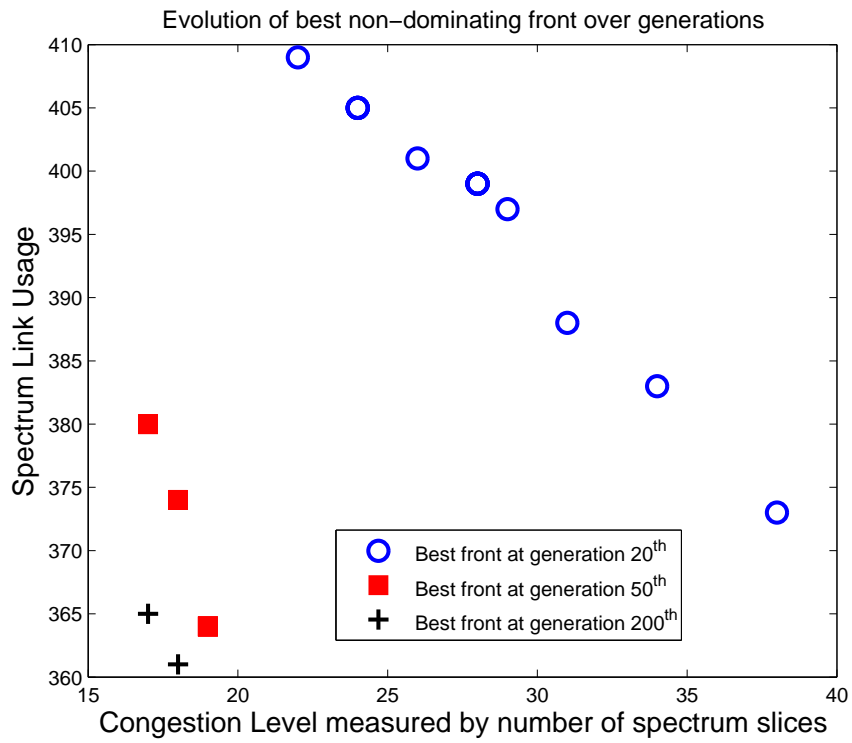


FIGURE 3.15: Best found non-dominated front

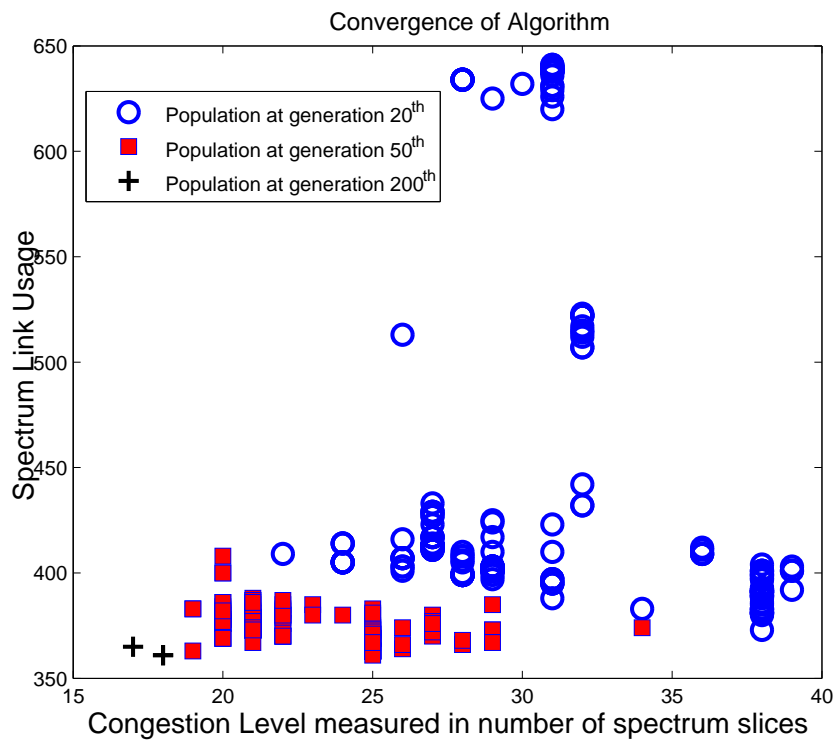


FIGURE 3.16: Population Evolution

Figure 3.15 shows the best front found over different generations. In this experiment, it is found that after around 200 generation, the best found front does not show much of an improvement. Therefore, it could be implied that the front at 200 generation is converged to optimal one (Pareto-front). There are two different optimal points on the Pareto front clearly demonstrating the trade-off between two objectives.

Figure 3.16 presents the evolution of population at different generations. It is shown that set of solutions are quite diversely distributed at low evolution generation. As the generation increases, the population demonstrate a good convergence as it moves to better value for both objectives. At generation of 200, the whole population is converged to the Pareto-front, which consists of two different points as shown in the figure 3.16.

### 3.4 Chapter Conclusion

In this chapter, the static routing and spectrum assignment has been studied for both single and multi-objective scenario.

Firstly, a single-objective RSA with respect to spectrum width optimization has been considered. Based on the fact that ILP model is not scalable for large-scale model, we proposed the efficient heuristic based on the application of genetic algorithm. The proposed GA encoded the ordering of demands as chromosome and made use of its evolution to search for best ordering of demands. The extensive simulation results showed that the proposed heuristic based on GA achieved the optimal solutions in most of the cases and outperformed typical heuristic in literature. To boost the running time performance of ILP model, we proposed to use very good heuristic solutions to set the upper-bound on the objective and the warm-start point for ILP model. Since the heuristic is already very close to optimal one, the running time for ILP model in this way, has been significantly reduced. Moreover, this approach also allowed the improved probability of achieving optimality in a given time period compared to solving ILP model separately.

Secondly, a multi-objective RSA with respect to congestion level and spectrum link usage has been investigated. We approached the problem from two perspective. In the first one, when the priority of any objective is given, we provided a methodology to set the weight vector that reflect such priority. By doing so, we transformed the multi-objective optimization into an optimization problem with integrated objective function. By solving the corresponding ILP model of different designs, either single objective function or integrated objective, we demonstrated that by taking into account both objectives into integrated one, the better results could be achieved compared

to having only one objective in the objective function. In the second perspective, when there is no priori information about the priority of objectives, we utilized multi-objective genetic algorithm based on NSGA-II to search for non-dominated front (Pareto front). The algorithm was able to find the Pareto front in a very efficient time and demonstrated a good convergence rate.



## Chapter 4

# Network-side Path Protection in OFDM-based network

Optical orthogonal frequency-division multiplexing (OFDM) has been gaining a lot of interest thanks to its superior feature of high spectral efficiency and flexibilities. This has therefore paved the way for elastic optical network based on OFDM technology, the so-called OFDM-based optical network. The key enabler in such network is OFDM transponder, being armed with advanced digital signal processing which offers adaptation capabilities by customizing modulation format and bandwidth transmission. Dimensioning optical network taking into account adaptive operation of OFDM technology poses new challenges as the selection of transmission parameters is now needed to tailor to each individual request rather than decided by worst-case design as in traditional fixed WDM network. In this chapter, we propose to exploit the modulation-adaptive operation of OFDM transponder to be used in network-side protection. The idea is inspired by the observation that in reach-diverse network, the transmission margin between working path and protection path of a connection might be large enough, and thus, different modulation format could be used, rather than a common one based on the worse condition (i.e., longer route). We formulate the survivable network design for both dedicated path and shared path protection, and perform a case study on realistic COST239 topology to draw a comparison among three cases differing in degree of freedoms, namely, *i)SCSF*: same modulation format and spectrum assignment for working and protection path is enforced *ii)DCSF*: same modulation format yet allowing different spectrum assignment for working and protection path *iii)DCDF*: different modulation format and different spectrum assignment between working and protection path is allowed. The study is considered in two scenarios. The first one is called un-capacitated where all demands are accepted and the comparison metric is based on spectrum width requirement and transponder power consumption. The second scenario is capacitated one where the resources is limited, causing not all demands are served and thus, blocking traffic metric is considered.

## 4.1 Introduction

The increasing penetration of rich-bandwidth services such as video on demand, high definition TV and cloud computing are accelerating the traffic growth in transport network. With such growth, the existing transmission systems have started to approach the capacity limit of conventional fiber, which is collectively known as fiber capacity crunch [7, 39]. While lightning up new fibers emerges as intuitive solution, there is no improvement in economic and energy aspect of this scaling. Introducing flexibilities to optical layer has been well-discussed recently to improve efficiency of optical network and thereby postpone the need of deploying/lightning up new fibers pairs. The key concept toward flexibility is to remove the fixed grid and replace it by flexible-grid architecture [36, 37, 49]

Flex-grid optical network could be realized by both single-carrier [91, 92] or multi-carrier solution [47]. The former one is based on the availability of multiple fixed WDM transponder profiles (e.g., transponders at different bit-rate/ baud-rate and/or different modulation formats) or tunable ones [93, 94]. It is clear that the more availability of transponder profiles, the more adaptation capability the network could provide. However, the downside of this solution lies in the fact that utilizing multiple transponder profiles, likely with different technologies, could causes link engineering challenges and management issues. Multi-carrier approach based on OFDM technology avoid such problems and furthermore, enable the supporting of the so-called software-defined transmission. The motivation for optical OFDM technology is its superior high spectral efficiency and excellent adaptation features [46, 48]. Thanks to that, OFDM solution is promising candidate to go beyond 100G era in such an efficient way [95]. Besides, the elastic bandwidth feature and modulation format agility of OFDM transponder paves the way for adaptive spectrum allocation according to end-to-end physical condition of optical path, which is known as distance-adaptive spectrum allocation [26]. Moreover, the digital signal processing at both receiver and transmitter enables the rapid (re)configuration of most transmission properties (e.g., bandwidth, modulation format) in response to network condition variation. Dimensioning a OFDM-based network taking into account such adaptation opportunities poses new challenges since the selection of transmission parameters is now needed to tailor to each individual request rather than decided by worst-case design as in traditional fixed WDM network. The problem becomes therefore not only concerns of routing and spectrum assignment but also the modulation format selection. [62, 96]

Ensuring survivability against failure becomes crucial for network dimensioning process because of the fact that the society is entering information era and thus, any loss of information could cause significant impact. Among survivability scheme, path protection has been favored for

transparent network since the protection route and capacity is identified in advance, and independently of failure location which is not easily monitored in transparent architecture [1]. Path protection in OFDM-based network needs to be investigated carefully to fully capture opportunities from adaptation capabilities of OFDM technology. There are some works in literature addressing this problem differently. Authors in [82] studied the static dedicated path protection by proposing mixed integer linear programming and heuristic approach, emphasizing on algorithmic aspect. In the same context of dedicated protection, [97] investigated the energy gain thanks to the adaptation of transmission parameter on protection path to traffic variation. It was found out that the highest gain is realized in elastic OFDM-based network. A different strategies for energy saving was studied in [98] by considering heterogeneous protection requirements instead of full duplication (1+1) and it turned out that OFDM-based network benefited most in term of energy saving from this strategy compared to mixed line rate or single-line rate system. Shared-path protection was addressed in [99] for dynamic scenario and benchmarked with dedicated one. To improve the efficiency of shared path protection in dynamic scenario, [100] proposed different heuristics taking into account fragmentation and shareability metrics. For static scenario, [101, 102] formulated the shared path protection in mixed integer linear programming and quantified the spectrum gain compared to dedicated one. A similar scenario was presented in [103] with further consideration on whether the resource on failure-affected paths are still utilized (stub release) or not (without stub release) and an interesting result was come out that there is almost no difference with respect to spectrum width metric. An interesting research line is on bandwidth squeezing so as to maximize the recovery bit-rate under the limited network capacity. It has been addressed in [104–106]. A related perspective is on multipath provisioning and/or multipath protection. Authors in [107, 108] performed extensive studies on both static and dynamic scenario to demonstrate the spectrum-related benefits of multipath provisioning scheme compared to single-path one. The benefits come from the natural resilience of multipath provisioning when a failure occurs on one of the connection’s paths, traffic carried on the other paths is not affected. Despite of clearly shown benefits, the implementation would be an issue since either multiple transponders needs to be employed for a connection or an advanced one based on sliceable bandwidth variable transponder must be used.

A point of particular interest that have been rarely mentioned in literature for survivable OFDM-based network is the fact that the transmission condition of working path and protection path of a connection might be different enough to use different modulation format efficiently and thereby exhibits promising benefits. In [109], we presented preliminary study on this idea in a dedicated scenario. In this chapter, we aim to extend the works by studying the dimensioning of OFDM-based network with network-side protection for both dedicated and shared scenario. We compare the three operation modes differing in degree of freedom between working and protection mode, namely, *i)SCSF*: same modulation format and channel are enforced for working

and protection path of a connection *ii)DCSF*: same modulation yet different channel assignment is allowed and *iii)DCDF*: modulation format and channel assignment could be different. The study is considered in two scenarios. The first one is called un-capacitated where all demands are accepted and the comparison metric is based on spectrum width requirement and transponder power consumption. The second scenario is capacitated one where the resources is limited causing not all demands are served and thus, blocking probability metric is considered. The original contribution is highlighted as followed:

- Propose a framework to dimension OFDM-based network with network-side protection considering the possibility of different operation between working and protection path.
- Investigate the impact of spectrum efficiency, transponder power consumption and blocking probability as the reconfiguration of OFDM transponder is utilized between working and protection mode.

This chapter is organized as followed. The next section, section 4.2, present the modulation-adaptive operation of OFDM transponder in network-side protection. Within that section, we details the concept of network-side protection together with assumption on a CO-OFDM transponder (coherent optical transponder) about optical reach and power consumption model. We also gives an example illustrating the benefit of new scheme compared to traditional consideration in literature. Section 4.3 provides a study on uncapacitated scenario where all the demands are accepted. We formulate the survivable network design for both dedicated and shared scenario in mixed integer linear programming with the objective of minimizing spectrum width requirement. Afterward, we perform a case study on realistic COST239 topology to investigate the impact of allowing the reconfiguration between working and protection mode. Section 4.4 is dedicated to survivable network design for capacitated context where the fiber capacity is limited and thus, not all the demands are accepted. A different objective is adopted, accounting for minimizing blocking capacity. We provides mixed integer linear programming formulation for this context considering dedicated and shared scheme. A numerical result on the COST239 topology is also provided highlighting the benefits of our proposal on exploiting the transmission difference between working and protection path. The final section is left for words of conclusion.

## 4.2 Modulation-adaptive Operation for Network-side Protection with CO-OFDM transponder

This section details the proposal on the exploiting the transmission margin between working and protection path by modulation-adaptive operation of CO-OFDM transponders in network-side protection. It starts with introduction on network-side protection, highlighting its advantage of

single transponder usage. Afterward, brief introduction about OFDM transmission is presented together with relevant assumption on CO-OFDM transponders. Finally, an illustrative example demonstrates the network-side protection with CO-OFDM transponder is given together with detailed analysis on potential benefits.

### 4.2.1 Network-side Protection

Most of the information in this part is presented based on reference [1]

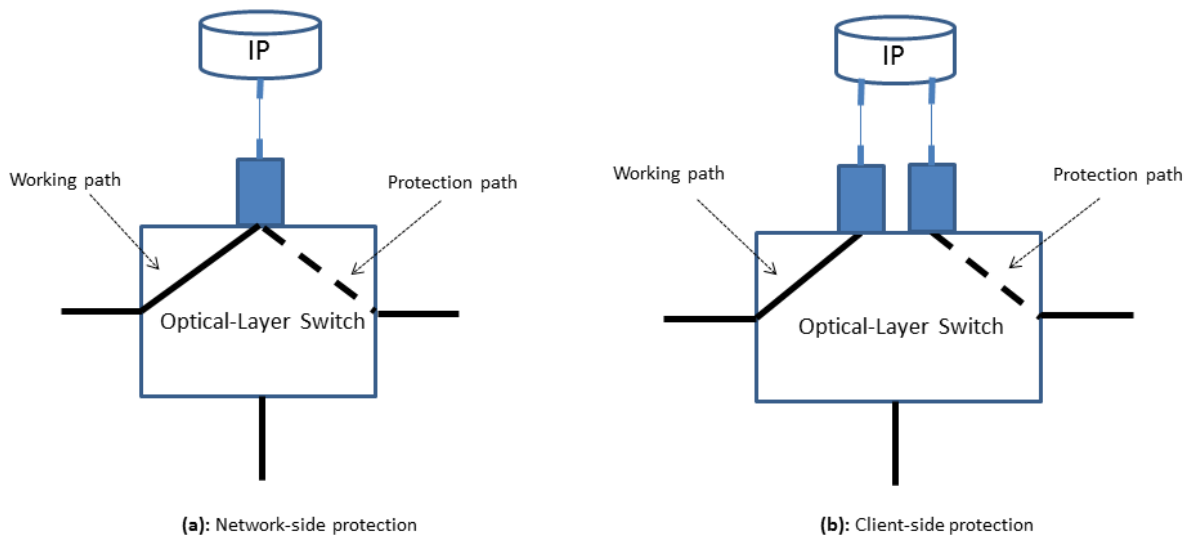


FIGURE 4.1: Comparison of Network-side and Client-side Protection

Network-side protection refers to the case where the optical side (network side of a transponder) is in charge of triggering the protection mechanism once the failure happens. This is to be differentiated from client-side protection where the client decides how to counteract failure events. That difference is translated to dissimilar requirements for redundant equipments at connection endpoints and network design aspect. Figure 4.1 illustrates the configurations supporting network-side scheme (a) and client-side one (b). It is noted that both type of protection can be operated in a dedicated or shared mode.

For the client-side protection in dedicated mode, two transponders are utilized for one connection in order to send/receive two copies of the signal to the optical layer over two disjoint routes. The advantage of the scheme is that in addition to provide resilience to link failure, it could also provides protection against hardware failures at endpoints (e.g., transponder, client-port

failure). Clearly, it comes at almost doubling the hardware cost.

In contrast, the network-side protection utilizes single transponder for a connection, and thereby save transponder cost. Let's consider the 1:1 protection, in the normal working condition (i.e., no link failure), the transponder is directed to the working path. Upon the detection of failure event, the optical-layer switch is reconfigured to re-direct the transponder to the protection path which is link-disjoint to working path. This scheme could also be operated in 1+1 protection if the switch supports multicast capability. In that case, the signal is sent/received simultaneously over working and protection path. Due to the fact that single transponder is utilized, the scheme is vulnerable to hardware failures at endpoint (e.g., transponder).

We focus on network-side scheme since it is cost-efficient compared to client-side and also, we address the link failure only. In the past with fixed WDM technologies, one of the disadvantage of network-side compared to client-side is the complexity in network design and thus, possibly exposed to inefficient spectrum utilization. For example, with fixed transponder, and in either dedicated (1+1 or 1:1) or shared protection (1:N), the same wavelength must be kept for both working and protection path while for client-side, there is no such constraint since two different transponders are utilized. With the availability of flexible transponder (e.g., optical OFDM transponder) where a number of transmission properties could be tuned easily and rapidly, it opens up new opportunity for network-side protection operating in 1:1 or 1:N mode where the signal is not sent/received simultaneously for working and protection path. Such opportunity comes from the fact that different transmission properties (e.g, modulation format, spectrum assignment) could be efficiently exploited for the working and backup path by a single transponder.

## 4.2.2 CO-OFDM Transponder Assumption

### 4.2.2.1 OFDM transmission

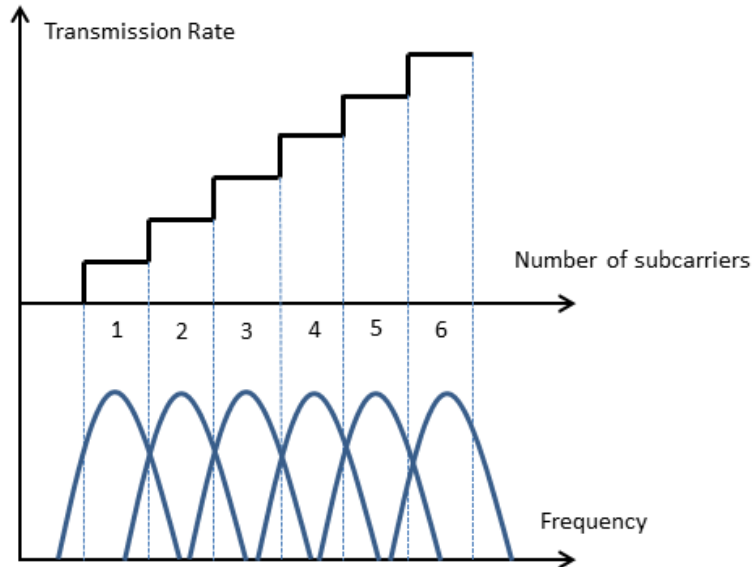


FIGURE 4.2: Adaptive-rate/bandwidth transmission by varying number of subcarriers

OFDM is a special class of multi-carrier modulation scheme where a high-speed data stream is transmitted by splitting into multiple lower-rate streams. Each lower-rate stream is modulated onto a separated channel, referred as subcarrier. The advantage of OFDM transmission is the fact that adjacent subcarriers could be overlapped in spectrum domain thanks to its orthogonality. Orthogonality property results from the fact that all sub-carriers are in-phase with frequency spacing being equal to the baud rate. The promising of OFDM in optical communication has been extensively investigated and reinforced by both theoretical and experimental studies [45, 48] highlighting its superior spectral efficiency, flexibility, and tolerance impairments. The application of OFDM in optical communication could be realized either in electrical or optical. The former one are called electrical OFDM where subcarriers are electrically modulated offering ultra-fine sub-wavelength capacity while the later one are called optical OFDM where a comb of frequency-locked subcarriers are conventionally modulated at the baud rate of the subcarrier spacing [47]. In this work, we focus on optical OFDM solution.

In term of flexibility, the introduction of optical OFDM brings a new concept to optical network, the so-called elastic or flexible optical network. Optical OFDM technology enables the tailoring of data-rate and/or bandwidth requirement to each client, and thus allowing significant saving of spectrum and a more efficient operation compared to traditional WDM technologies. Figure

4.2 illustrates the elastic bandwidth operation of optical OFDM transmission by controlling the number of subcarriers. The additional flexibility given by OFDM is the capability of controlling modulation format per subcarrier. The selection of modulation level for subcarrier is decided by the bit-rate requirement and the route length. The next part will address that dependency.

#### 4.2.2.2 Optical Reach Assumption

The optical reach of a transponder is not only dependent on modulation format, but also on the bit-rate. Some studies neglected the dependence of reach on the operation bit-rate and just focused on the impact of modulation format [62, 97] in order for simplification. In this study, the accurate model for OFDM transponder employing polarization multiplexing for different modulation format from [110] are referred. Based on that work, authors in [111] derived an empirical formulation calculating the transmission rate for different bit-rates as a function of spectral efficiency.

$$L = 145.741 + (n - 14.0344) \times (60.2196 \times \ln(BR) - 465.82) \quad (4.1)$$

where  $L$  is in  $km$ ,  $n$  in  $bit/s/Hz$  and bit rate ( $BR$ ) in  $Gb/s$



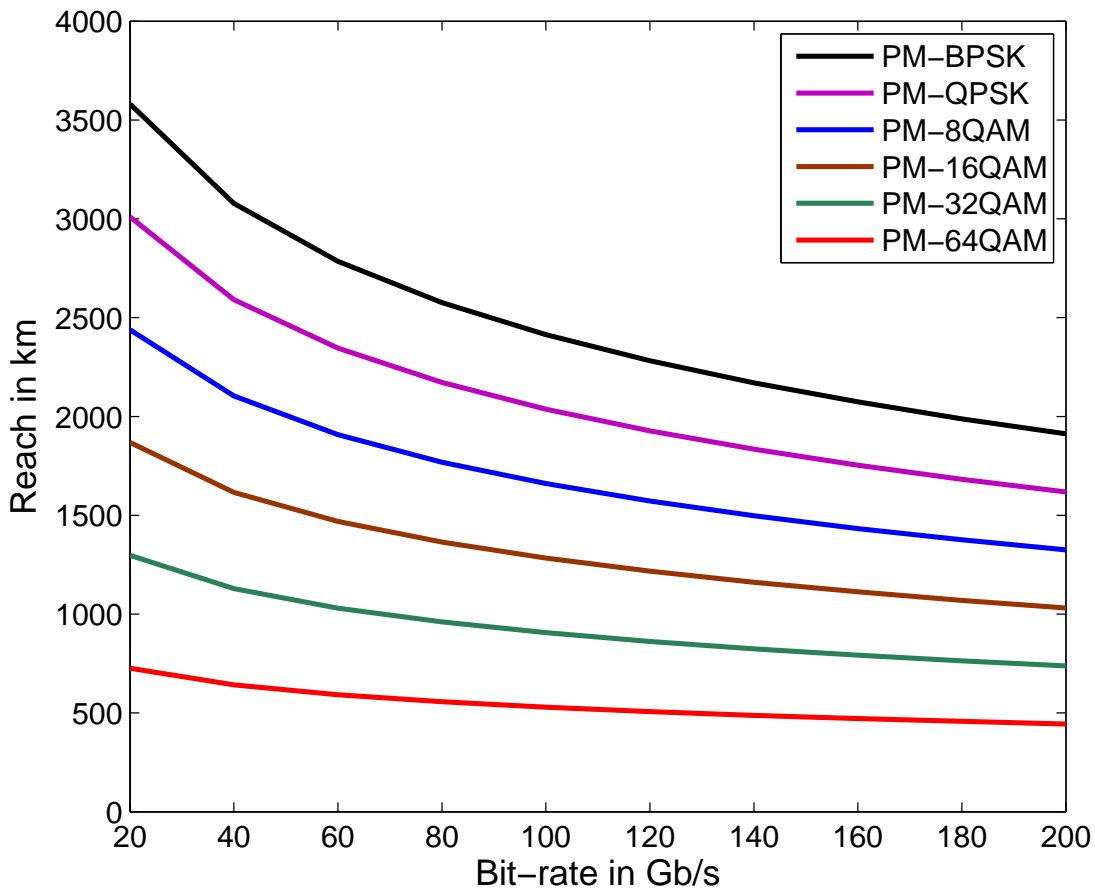


FIGURE 4.3: Optical reach versus bit-rate, modulation formats

Figure 4.3 illustrates the optical reach as a function of bit-rate for different modulation formats. It is clear to see that apart from modulation format, the effect of bit-rate variation impacts considerably the optical reach.

#### 4.2.2.3 Power Consumption Assumption

Due to the current commercial unavailability of OFDM transponders, several assumptions have been made to estimate values regarding to power consumption and overall cost. We consider optical OFDM transponder (to be differentiated from electrical one). In [4, 47, 97], the power consumption of such transponder is evaluated based on power consumption per active subcarrier. This is based on the observation that at the optical OFDM receiver the all-optical FFT (Fast Fourier Transform) module separates the subcarriers which are then processed independently by an equal number of coherent receivers. The extraction of power consumption per subcarrier is obtained from values for WDM transponder operating at corresponding rates. We adopt here the empirical formula from [4] to estimate the power consumption of CO-OFDM transponder.

$$PC_{CO-OFDM}(W) = 1.683 \times TR(\text{Gb/s}) + 91.333 \quad (4.2)$$

where  $TR$  is the bit-rate operation on a subcarrier which in turn is dependent on the subcarrier granularity in  $GHz$  and modulation level. Table 4.1 show the power consumption value for different modulation formats

TABLE 4.1: Power Consumption of a CO-OFDM transponder for different modulation formats [4]

Modulation Format	Subcarrier Bit-rate (Gb/s)	Power Consumption (W)
BPSK	12.5	112.374
QPSK	25	133.416
8QAM	37.5	154.457
16QAM	50	175.498
32QAM	62.5	196.539
64QAM	75	217.581

It is noted that the formula is evaluated on a subcarrier basis and therefore, for the transponder utilizing more than one subcarrier, its power consumption is simply a corresponding multiple of a value for one subcarrier. It should also be highlighted that the turning on of a subcarrier requires much more power consumption than increasing the modulation level for a subcarrier. For example, a request of 50 Gb/s could be served either by two subcarriers using BPSK or one subcarrier using 16QAM modulation format. It is clear that the latter option, utilizing one subcarrier, significantly save the power consumption.

### 4.2.3 Modulation-adaptive Operation for Network-side Protection

This section illustrates the usage of CO-OFDM transponder in modulation-adaptive mode for network-side protection. We consider for both dedicated and shared protection cases and highlight the difference in our proposal compared to previous works in the literature. Let us consider an example in figure 4.4 where there are two lightpath requests A and B with their corresponding working and backup paths.

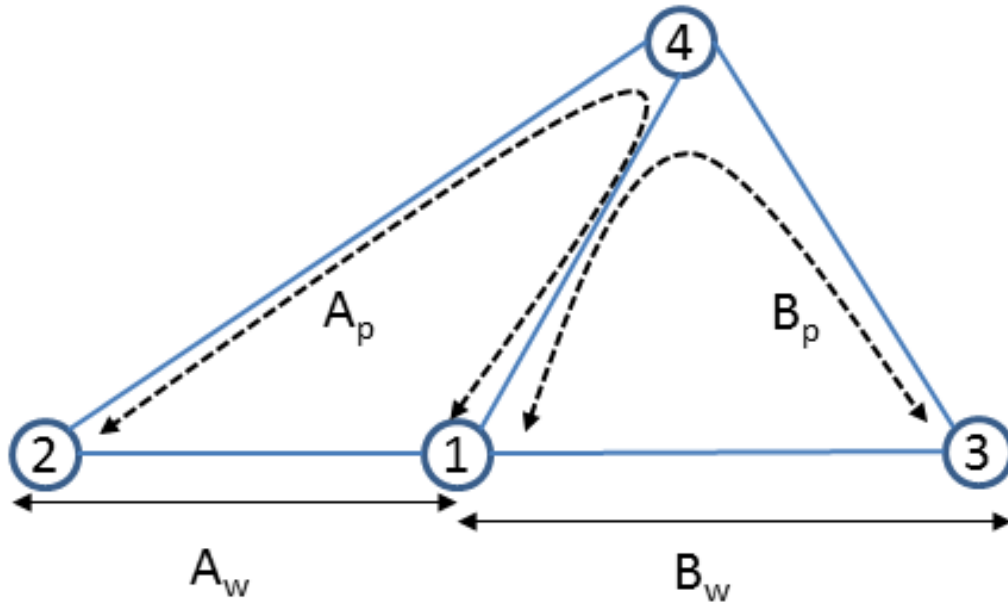


FIGURE 4.4: Exemplary network topology with two requests A and B

#### 4.2.3.1 Dedicated Path Protection Scenario

Let's focus on dedicated path protection scenario. Dedicated protection here refers to the case 1:1 where there is dedicated reserved spectrum for the backup path. Considering lightpath A and assume that modulation format 16QAM is assumed to be robust enough to operate on working path while, in the protection path, due to longer distance, QPSK must be used to overcome higher impairments (distance-adaptive modulation). Figure 4.5 shows the node architecture at node 1 for lightpath A in network-side protection. As highlighted in the previous part, there is only one transponder needed in conjunction with bandwidth-variable switch for this protection mode. Under the normal working mode, the transponder is directed to the working path and if the working path fails (e.g., link failure), the switch is reconfigured to direct the same transponder to the protection path. With the reconfiguration capability of OFDM transponder, it opens up opportunity to adjust transmission parameters (e.g., modulation format) in response to the changing of the route from working to protection.

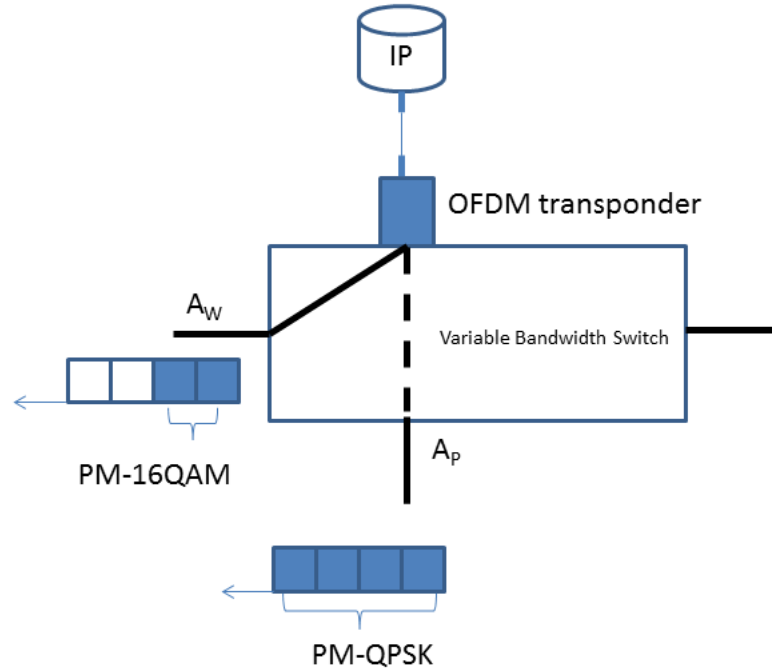


FIGURE 4.5: Node 1 architecture in dedicated protection - focus on request A

Previous works in literature considered the survivable network design with OFDM transponder neglected the capability of switching modulation format between working and protection path and therefore performed dimension (selection of modulation format) based on worse path condition (e.g., longer route). In the context of this example, modulation format QPSK would be used for both routes and thus, it consumes 4 spectrum slices on each route. Different from that, we propose to exploit the reconfiguration capability of OFDM transponder to tailor the most efficient modulation format to working route and backup route of a connection. The benefit of our proposal is envisioned to be important. Clearly, it is the saving of spectrum slices and thus, improve the spectral efficiency. In this example, with our proposal, the lightpath A consumes only two spectrum slices for the working path rather than four spectrum slices in the previous works. Besides, as the consequence of saving spectrum slices for working path, less power consumption is expected for CO-OFDM transponder. On the other hand, the saving of spectrum slices helps to better accommodate the traffic and in the case of limited capacity, the higher throughput could be foreseen for our approach compared to current works in the literature.

## 4.2.3.2 Shared Path Protection Scenario

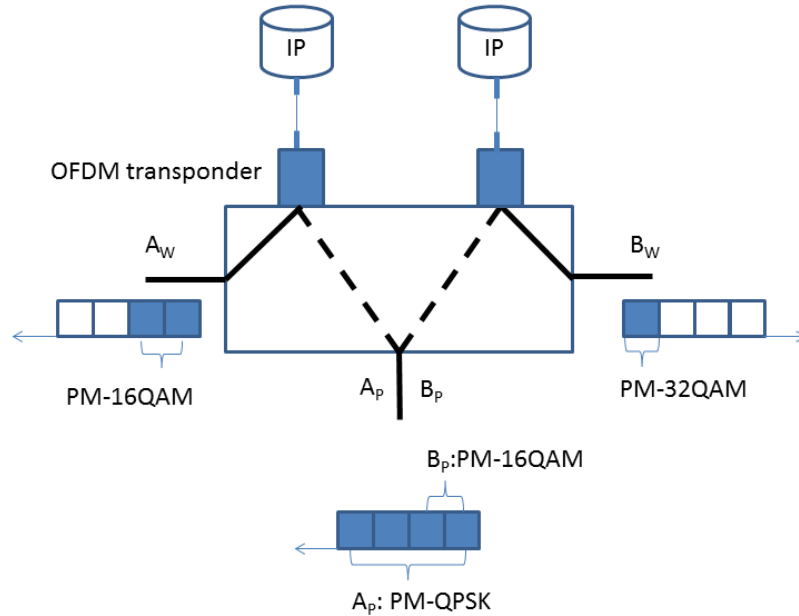


FIGURE 4.6: Node 1 architecture in shared protection

We turn the attention to the shared path protection scenario. It should be noted that shared path protection here refers to the *spectrum sharing* on backup routes whose working paths are not simultaneously failed by one failure event. The transponder is still dedicated to each connection as illustrated in figure 4.6. We highlight the difference between dedicated and shared protection, between our proposal and current works in literature.

Together with lightpath A, we consider lightpath B with assumption that modulation format 32QAM is best used for working path and modulation format 16QAM is most spectrum-efficient for protection path. Since the working paths of A and B are not failed simultaneously for any single link failure, and their backup routes has common link (e.g., link 1-4), the spectrum sharing on link 1-4 could be realized. Thus, different from dedicated protection where a total amount of at least six (four for A and two for B, possibly with guard band) spectrum slices are needed on link 1-4, in shared protection there is a need for four slices as clearly shown in figure 4.6. It would therefore be expected that the shared path protection achieves better spectral efficiency than dedicated path protection. Besides, similar to dedicated path protection, in shared path protection, it is possible to tailor the most spectrum-efficient modulation format independently to the working and backup route for each connection. Thus, benefits mentioned in dedicated protection part would be still hold for shared case.

### 4.3 Survivable Network Design for Uncapacitated Scenario

This section presents the formulation for survivable OFDM-based network design with dedicated and shared path protection. The protection scheme aims at ensuring the full connection availability against any single-link (fiber) failure. Given the physical network topology, a set of traffic demands, we want to find a route, modulation format, and assign spectrum for working and protection path of each demand so as to minimize the spectrum width required in the network. For ease of computation, we pre-calculate  $k$  candidate cycles containing working and backup path for each demand. Given the function that relates the length of the path, bit-rate operation to feasible modulation formats, the feasibility of each cycle for demand  $d$  is also pre-evaluated. The spectrum assignment is performed based on channel concept from [66]

#### 4.3.1 Dedicated Path Protection Formulation

Given Input:

- $G(V, E)$ : Physical topology with  $|V|$  nodes and  $|E|$  links
- $S$ : Set of available spectrum slices in each fiber
- $D$ : Set of static traffic demands, indexed by  $d$ . Each demand  $d \in D$  requires  $t_d$  Gbps.
- $R^d$ : Set of  $k$  candidate cycles for node pair belongs to demand  $d \in D$
- $R = \cup_{d \in D} R^d$ : Set of all cycles for all node pairs in the networks
- $M$ : Set of available modulation formats
- $\alpha_r^d$ : 1 if cycle  $r \in R$  is feasible for demand  $d \in D$ , 0 otherwise. The cycle of demand  $d$  is considered to be feasible if there is at least one feasible modulation format for working and backup path to carry demand  $d$
- $m_{rw}^d$ : highest-order modulation format for working path of feasible cycle  $r \in R$  for demand  $d \in D$
- $m_{rb}^d$ : highest-order modulation format for backup path of feasible cycle  $r \in R$  for demand  $d \in D$
- $C_{rw}^d$ : set of admissible candidate channels for working path of cycle  $r \in R^d$
- $C_{rb}^d$ : set of admissible candidate channels for backup path of cycle  $r \in R^d$
- $C = \cup_{r \in R} (C_{rw} \cup C_{rb})$
- $\beta_{cs}$ : 1 if channel  $c \in C$  contains slice  $s \in S$ , 0 otherwise

- $\delta_{rwe}$ : 1 if working path of cycle  $r \in R$  contains link  $e \in E$ , 0 otherwise
- $\delta_{rbe}$ : 1 if backup path of cycle  $r \in R$  contains link  $e \in E$ , 0 otherwise
- $pc(m, |c|)$ : a function that relates CO-OFDM transponder power consumption to operated modulation format  $m \in M$  and number of utilized slices  $|c|$  (sub-carriers).

Variables:

- $x_{rc}^d \in \{0, 1\}$ : Boolean variable equals to 1 if demand  $d$  is served by selecting cycle  $r \in R$  and a channel  $c \in C$  for working path
- $y_{rc}^d \in \{0, 1\}$ : Boolean variable equals to 1 if demand  $d$  is served by selecting cycle  $r \in R$  and a channel  $c \in C$  for protection path
- $z_{es} \in \{0, 1\}$ : Boolean variable equals to 1 if spectrum slices  $s \in S$  is occupied in link  $e \in E$
- $z_s \in \{0, 1\}$ : Boolean variable equals to 1 if spectrum slices  $s \in S$  is used in a network

Objective: Minimize the total number of spectrum slices to serve all the demands

- Minimize

$$\text{Minimize } \phi = \sum_{s \in S} z_s \quad (4.3)$$

Subject to following constraints

- All demands must be satisfied by selecting its route and channel for working path

$$\sum_{r \in R^d} \sum_{c \in C_{rw}^d} \alpha_r^d x_{rc}^d = 1 \quad \forall d \in D \quad (4.4)$$

- No overlap spectrum constraint: Each spectrum slice on link is used by at most one lightpath

$$\sum_{d \in D} \sum_{r \in R^d} \alpha_r^d \left( \sum_{c \in C_{rw}^d} x_{rc}^d \delta_{rwe} \beta_{cs} + \sum_{c \in C_{rb}^d} y_{rc}^d \delta_{rbe} \beta_{cs} \right) = z_{es} \quad \forall e \in E, s \in S \quad (4.5)$$

- The definition of using a spectrum slice in the network: A spectrum slice is considered to be used if it is occupied in any link of the network.

$$\sum_{e \in E} z_{es} \leq |E| z_s \quad \forall s \in S \quad (4.6)$$

The coherence between the working and backup path: three cases are considered

- SCSF: Same channel and same modulation format is forced between working and protection path ( $m_{rw}^d \equiv m_{rb}^d$  and  $C_{rw}^d \equiv C_{rb}^d$ )

$$x_{rc}^d = y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1, \forall c \in C_{rw}^d (C_{rb}^d) \quad (4.7)$$

- DCSF: Different channel is allowed between working and backup path while the same modulation format is forced ( $m_{rw}^d \equiv m_{rb}^d$  and  $C_{rw}^d \equiv C_{rb}^d$ )

$$\sum_{c \in C_{rw}^d} x_{rc}^d = \sum_{c \in C_{rb}^d} y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1 \quad (4.8)$$

- DCDF: Different channel and different modulation format are allowed between working and backup path. Noted in this case, in general,  $m_{rw}^d \neq m_{rb}^d$  and  $C_{rw}^d \neq C_{rb}^d$

$$\sum_{c \in C_{rw}^d} x_{rc}^d = \sum_{c \in C_{rb}^d} y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1 \quad (4.9)$$

- The transponder power consumption is evaluated based on working path operation

$$P = \sum_{d \in D} \sum_{r \in R^d} \sum_{c \in C_{rw}^d} \alpha_r^d x_{rc}^d p_c(m_{rw}^d, |c|) \quad (4.10)$$

### 4.3.2 Shared Path Protection Formulation

For the shared path protection formulation, apart from given input for dedicated path formulation, we need following additional input:

Additional Input:

- $F$ : Set of events (normal working and failure events),  $F = \{f_0, f_1, f_2, \dots, f_{nlink}\}$  where  $f_0$  refers to normal working case and  $f_i$  ( $i=1$ :number of links) refers to single-link failure event.
- $\theta_{rf}^d$ : 1 if working path of cycle  $r$  belongs to demand  $d$  is affected by event  $f \in F$

Variables: The same set of variables could be used for shared path protection. We re-write here for ease of checking.

- $x_{rc}^d$ : Boolean variable equals to 1 if demand  $d$  is served by selecting cycle  $r \in R$  and a channel  $c \in C$  for working path



- $y_{rc}^d$ : Boolean variable equals to 1 if demand  $d$  is served by selecting cycle  $r \in R$  and a channel  $c \in C$  for protection path
- $z_{es}$ : Boolean variable equals to 1 if spectrum slices  $s \in S$  is occupied in link  $e \in E$
- $z_s$ : Boolean variable equals to 1 if spectrum slices  $s \in S$  is used in the network

Objective: Minimize the total number of spectrum slices to serve all the demands

- Minimize

$$\text{Minimize } \phi = \sum_{s \in S} z_s \quad (4.11)$$

Subject to following constraints

- All demands must be satisfied by selecting its route and channel for working path

$$\sum_{r \in R^d} \sum_{c \in C_{rw}^d} \alpha_r^d x_{rc}^d = 1 \quad \forall d \in D \quad (4.12)$$

- No overlap spectrum constraint: Each spectrum slice on link is used by at most one lightpath under any event (normal working and failure events). Different from dedicated protection, this constraint allows the sharing of spectrum slices for backup connections provided that their working paths are not affected simultaneously by a single failure event  $f \in F$ .

$$\sum_{d \in D} \sum_{r \in R^d} \alpha_r^d \left( \sum_{c \in C_{rw}^d} \theta_{rf}^d x_{rc}^d \delta_{rwe} \beta_{cs} + \sum_{c \in C_{rb}^d} (1 - \theta_{rf}^d) y_{rc}^d \delta_{rbe} \beta_{cs} \right) \leq z_{es} \quad \forall e \in E, \forall s \in S, \forall f \in F \quad (4.13)$$

- The definition of using a spectrum slice in the network

$$\sum_{e \in E} z_{es} \leq |E| z_s \quad \forall s \in S \quad (4.14)$$

The coherence between the working and backup path: three cases are considered

- SCSF: Same channel and same modulation format is forced between working and protection path ( $m_{rw}^d \equiv m_{rb}^d$  and  $C_{rw}^d \equiv C_{rb}^d$ )

$$x_{rc}^d = y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1, \forall c \in C_{rw}^d \quad (4.15)$$

- DCSF: Different channel is allowed between working and backup path while the same modulation format is forced ( $m_{rw}^d \equiv m_{rb}^d$  and  $C_{rw}^d \equiv C_{rb}^d$ )

$$\sum_{c \in C_{rw}^d} x_{rc}^d = \sum_{c \in C_{rb}^d} y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1 \quad (4.16)$$

- DCDF: Different channels and different modulation formats are allowed between working and backup path

$$\sum_{c \in C_{rw}^d} x_{rc}^d = \sum_{c \in C_{rb}^d} y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1 \quad (4.17)$$

- The transponder power consumption is evaluated based on working path operation

$$P = \sum_{d \in D} \sum_{r \in R^d} \sum_{c \in C_{rw}^d} \alpha_r^d x_{rc}^d p_c(m_{rw}^d, |c|) \quad (4.18)$$

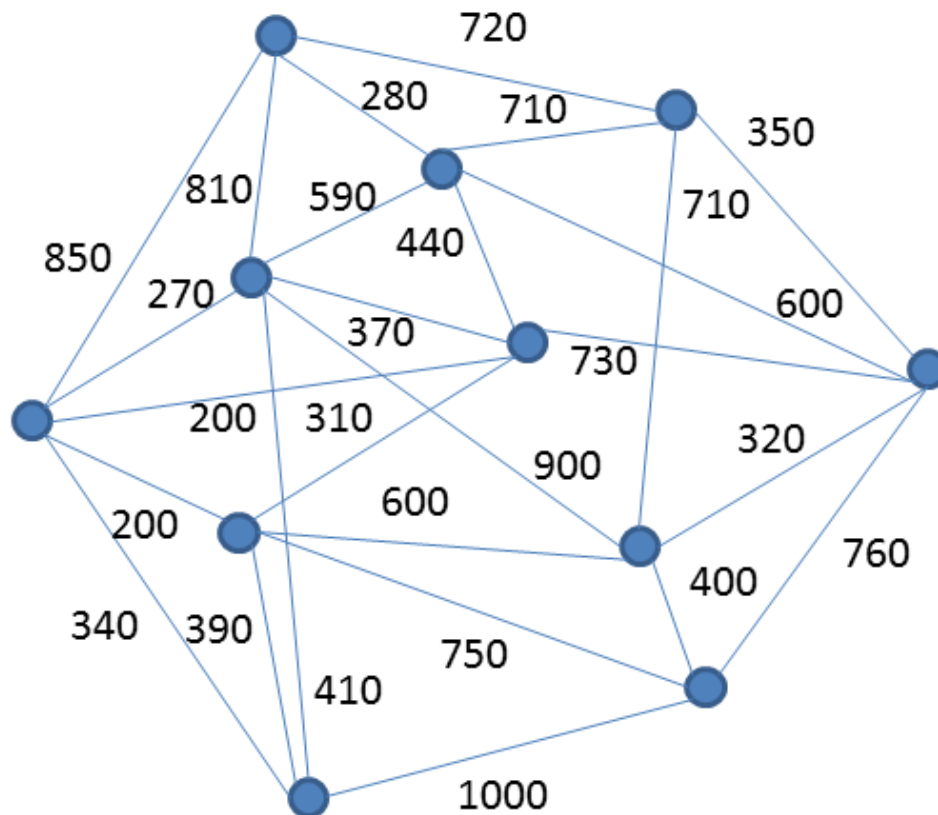
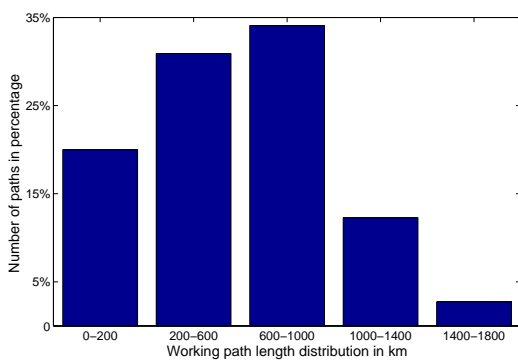
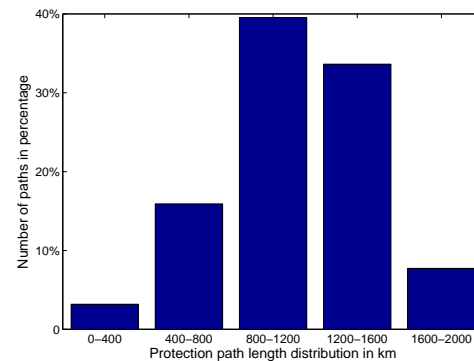
### 4.3.3 Numerical Results

We perform a case study on realistic COST239 topology (11 nodes and 52 bi-directional links) 4.7. The general characteristic of topology is summarized in table 4.2

TABLE 4.2: Topology Characteristic

Parameters	Value
Number of Nodes	11
Number of Links	52
Average nodal degree	4.7
Min link length	200 km
Max link length	1000 km

To illustrate the transmission distance difference between the working and protection path in COST239 topology, figures 4.10 and 4.11 shows their length distribution at  $k = 4$ . All cycles are found based on shortest overall length [112]. It is clear that protection length is considerably higher than working length and indeed, the average difference is found to be more than 500 km. The associated transmission margin corresponding to length difference could be exploited for efficient spectrum allocation.

FIGURE 4.7: COST239 topology with distances in *km*FIGURE 4.8: Working length distribution with  $k = 4$ FIGURE 4.9: Protection length distribution with  $k = 4$ 

The parameters for simulation are: spectrum slice granularity  $B = 5$  GHz, number of candidate cycles  $k = 4$ , and six polarized multiplexing modulation format are considered, namely, PM-BPSK, PM-QPSK, PM-8QAM, PM-16QAM, PM-32QAM. The source and destination of demands are randomly generated and the traffic per demand is randomly generated between 40 Gbps and 200 Gbps with a step of 40 Gbps. Five types of traffic matrix being different in total number of connections are generated. For each type, there are 10 traffic instances and thus, the

result for each simulation point is averaged over 10 instances. The formulated ILP was modeled with Matlab and solved with CPLEX academic version. To speed up the solving process, a warm-start implementation was applied. We implemented a simple heuristic to find initial solution and good bound  $|S|$  for SCSF case. For solving DCSF case, the best found solution from SCSF case was fed into DCSF as an initial solution. Similarly, for solving DCDF case, the simple heuristic was run first to provide initial solutions and upper bound to solver. The maximum running time for each simulation point was 4 hours, and the simulation is performed on an Intel i7 3.3GHz, 16GB RAM computer.

We present two sets of results. The first one is about the objective value-spectrum width requirement. The second one is about transponder power consumption. We pick up the best found solution returned from solver to evaluate the corresponding transponder power consumption. It is noticed that the figure is calculated based on the operation of working path only.

Table 4.3 shows the result for dedicated scenario. As the number of connections between node-pair increases, the total needed spectrum slices to support also grows. The impact of introducing adaptation between working and protection path is evident for all range of traffic. It is clear that the more degree of freedom in reconfiguration, the better result is observed. Compared to SCSF, DCSF could provide gain up to 5%, as the constraint of same spectrum assignment for working and protection path is relaxed. However, the dimensioning in DCSF case is still based on the worse condition of either working or protection path. By introducing modulation format adaptation in DCDF, an appreciable spectrum saving could be realized as the required spectrum slices is tailored to each path of a connection separately. Indeed, in this case study, DCDF outperforms both SCSF and DCDF. The maximum gain compared to SCSF is up to 21% as observed.

TABLE 4.3: Spectrum Width Requirement for Dedicated Case

Number of Connections	20	30	40	50	60
SCSF	14.8	19.4	22.1	23.8	24.5
DCSF	14.3	19.1	21.1	23.2	23.9
DCDF	12.1	16.9	17	18.4	19.6
Max difference DCSF vs. SCSF: 5%					
Max difference DCDF vs. SCSF: 21%					

The result for the shared case is summarized in table 4.4. It is evident that by introducing sharing opportunity, the spectrum width dimension is decreased. For example, SCSF case is down to 9% while DCDF is decreased to 8% compared to dedicated one. Different from dedicated case, in the shared case, DCSF shows moderate gain compared to SCSF, being maximum 2%. DCDF,

on the other hand, exhibits lowest spectrum requirement, reaching a gain of up to 19% compared to SCSF.

TABLE 4.4: Spectrum Width Requirement for Shared Case

Number of Connections	20	30	40	50	60
SCSF	14.6	18.4	20.4	21.6	22.5
DCSF	14.3	18	19.9	21.1	22.2
DCDF	12	15.6	16.1	18.3	19
Max difference DCSF vs. SCSF: 2%					
Max difference DCSF vs. SCSF: 19%					

We turn our attention to transponder power consumption comparison. We plot the result of DCSF and DCDF normalized to SCSF for both dedicated and shared case. A same trend is observed for both cases. DCSF consumes almost the same power like SCSF since the same modulation format is utilized for both working and protection path like in SCSF. Differently, the benefits of using more efficient modulation format for working path in DCDF features considerable power consumption gain. The actual gain is dependent on the traffic and relatively consistent over a wide range of traffic. In this study, a gain of up to 18% could be observed for DCDF case compared to SCSF. A notice in the result is that the absolute value for each operation mode (i.e., SCSF, DCSF, DCDF) are almost comparable in dedicated and shared cases. This could be attributed to observation that for almost all demands, the same modulation format and cycles are selected for a demand either in dedicated or shared case.

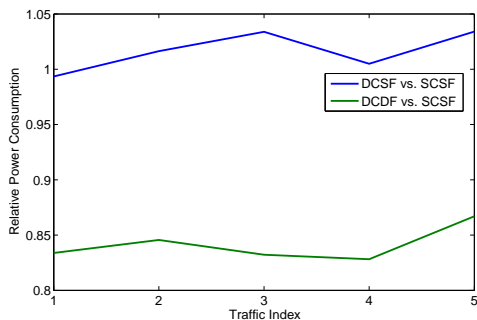


FIGURE 4.10: Dedicated Protection Comparison

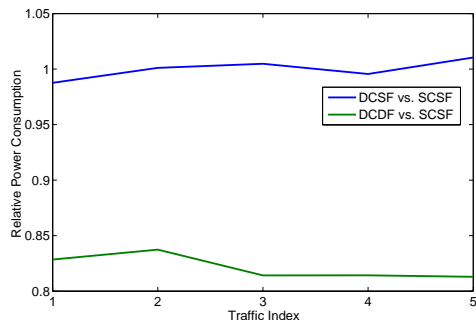


FIGURE 4.11: Shared Protection Comparison

## 4.4 Survivable Network Design for Capacitated Scenario

This section presents the formulation for dedicated and shared path protection in the case of the fiber link capacity is limited and thus, not all the demands are served. Given the physical network topology, a set of traffic demands, we want to find whether a demand is served or not and if a demand is served, on which modulation format, routes and spectrum assignment it is for working and protection path. The objective is to minimize the un-served traffic. We use

path-link formulation where  $k$  candidate cycles containing working and backup path for each demand are pre-calculated. The feasibility of each cycle for demand  $d$  is also pre-evaluated. The spectrum assignment is performed based on channel concept from [66].

#### 4.4.1 Dedicated Path Protection

Given Input:

- $G(V, E)$ : Physical topology with  $|V|$  nodes and  $|E|$  links
- $S$ : Set of available spectrum slices in each fiber
- $D$ : Set of static traffic demands, indexed by  $d$ . Each demand  $d$  request  $t_d$  Gbps
- $R^d$ : Set of  $k$  candidate cycles for node pair belongs to demand  $d \in D$
- $R = \cup_{d \in D} R^d$ : Set of all cycles
- $M$ : Set of available modulation formats
- $\alpha_r^d$ : 1 if cycle  $r \in R$  is feasible for demand  $d \in D$ , 0 otherwise. The cycle of demand  $d$  is considered to be feasible if there is at least one feasible modulation format for working and backup path to carry demand  $d$
- $m_{rw}^d$ : highest-order modulation format for working path of feasible cycle  $r \in R$  for demand  $d \in D$
- $m_{rb}^d$ : highest-order modulation format for backup path of feasible cycle  $r \in R$  for demand  $d \in D$
- $C_{rw}^d$ : set of admissible candidate channels for working path of cycle  $r \in R^d$
- $C_{rb}^d$ : set of admissible candidate channels for backup path of cycle  $r \in R^d$
- $\beta_{cs}$ : 1 if channel  $c \in C$  contains slice  $s \in S$ , 0 otherwise
- $\delta_{rwe}$ : 1 if working path of cycle  $r \in R$  contains link  $e \in E$ , 0 otherwise
- $\delta_{rbe}$ : 1 if backup path of cycle  $r \in R$  contains link  $e \in E$ , 0 otherwise

Variables:

- $v_d \in \{0, 1\}$ : Boolean variable equals to 1 if demand  $d$  is rejected and 0, otherwise
- $x_{rc}^d \in \{0, 1\}$ : Boolean variable equals to 1 if demand  $d$  is served by selecting cycle  $r \in R$  and a channel  $c \in C$  for working path

- $y_{rc}^d \in \{0, 1\}$ : Boolean variable equals to 1 if demand  $d$  is served by selecting cycle  $r \in R$  and a channel  $c \in C$  for protection path

Objective:

- Minimize the un-served traffic (Maximize the throughput)

$$\text{Minimize } \phi = \sum_{d \in D} v_d t_d \quad (4.19)$$

Subject to following constraints

- All demands must be either supported or rejected (rejected due to spectrum-related constraints)

$$\sum_{r \in R^d} \sum_{c \in C_{rw}^d} \alpha_r^d x_{rc}^d + v_d = 1 \quad \forall d \in D \quad (4.20)$$

- No overlap spectrum constraint: Each spectrum slice on link is used by at most one lightpath

$$\sum_{d \in D} \sum_{r \in R^d} \alpha_r^d \left( \sum_{c \in C_{rw}^d} x_{rc}^d \delta_{rwe} \beta_{cs} + \sum_{c \in C_{rb}^d} y_{rc}^d \delta_{rbe} \beta_{cs} \right) \leq 1 \quad \forall e \in E, s \in S \quad (4.21)$$

The coherence between the working and backup path: three cases are considered

- SCSF: Same channel and same modulation format is forced between working and protection path ( $m_{rw}^d \equiv m_{rb}^d$  and  $C_{rw}^d \equiv C_{rb}^d$ )

$$x_{rc}^d = y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1, \forall c \in C_{rw}^d (C_{rb}^d) \quad (4.22)$$

- DCSF: Different channel is allowed between working and backup path while the same modulation format is forced ( $m_{rw}^d \equiv m_{rb}^d$  and  $C_{rw}^d \equiv C_{rb}^d$ )

$$\sum_{c \in C_{rw}^d} x_{rc}^d = \sum_{c \in C_{rb}^d} y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1 \quad (4.23)$$

- DCDF: Different channel and different modulation format are allowed between working and backup path

$$\sum_{c \in C_{rw}^d} x_{rc}^d = \sum_{c \in C_{rb}^d} y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1 \quad (4.24)$$

### 4.4.2 Shared Path Protection Formulation

For the shared path protection formulation in capacitated context, apart from given input for dedicated path formulation, we need following additional input:

Additional Input:

- $F$ : Set of events (normal working and failure events),  $F = \{f_o, f_1, f_2, \dots, f_{nlink}\}$  where  $f_o$  refers to normal working case and  $f_i$  ( $i=1$ :number of links) refers to single-link failure event.
- $\theta_{rf}^d$ : 1 if working path of cycle  $r$  belongs to demand  $d$  is affected by event  $f \in F$

Variables: The same set of variables could be used for shared path protection. We re-write here for ease of following.

- $v_d \in \{0, 1\}$ : Boolean variable equals to 1 if demand  $d$  is rejected and 0, otherwise
- $x_{rc}^d \in \{0, 1\}$ : Boolean variable equals to 1 if demand  $d$  is served by selecting cycle  $r \in R$  and a channel  $c \in C$  for working path
- $y_{rc}^d \in \{0, 1\}$ : Boolean variable equals to 1 if demand  $d$  is served by selecting cycle  $r \in R$  and a channel  $c \in C$  for protection path

Objective:

- Minimize the un-served traffic (Maximize the throughput)

$$\text{Minimize } \phi = \sum_{d \in D} v_d t_d \quad (4.25)$$

Subject to following constraints

- All demands must be either supported or rejected (due to spectrum-related constraints)

$$\sum_{r \in R^d} \sum_{c \in C_{rw}^d} \alpha_r^d x_{rc}^d + v_d = 1 \quad \forall d \in D \quad (4.26)$$

- No overlap spectrum constraint: Each spectrum slice on link is used by at most one lightpath under any event (normal working and failure events). The sharing

$$\sum_{d \in D} \sum_{r \in R^d} \alpha_r^d \left( \sum_{c \in C_{rw}^d} \theta_{rf}^d x_{rc}^d \delta_{rwe} \beta_{cs} + \sum_{c \in C_{rb}^d} (1 - \theta_{rf}^d) y_{rc}^d \delta_{rbe} \beta_{cs} \right) \leq 1 \quad \forall e \in E, \forall s \in S, \forall f \in F \quad (4.27)$$



The coherence between the working and backup path: three cases are considered

- SCSF: Same channel and same modulation format is forced between working and protection path ( $m_{rw}^d \equiv m_{rb}^d$  and  $C_{rw}^d \equiv C_{rb}^d$ )

$$x_{rc}^d = y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1, \forall c \in C_{rw}^d \quad (4.28)$$

- DCSF: Different channel is allowed between working and backup path while the same modulation format is forced ( $m_{rb}^d \equiv m_{rb}^d$  and  $C_{rw}^d \equiv C_{rb}^d$ )

$$\sum_{c \in C_{rw}^d} x_{rc}^d = \sum_{c \in C_{rb}^d} y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1 \quad (4.29)$$

- DCDF: Different channel and different modulation format are allowed between working and backup path

$$\sum_{c \in C_{rw}^d} x_{rc}^d = \sum_{c \in C_{rb}^d} y_{rc}^d \quad \forall d \in D, r \in R^d : \alpha_r^d = 1 \quad (4.30)$$

### 4.4.3 Numerical Results

We perform a case study on COST239 topology in a similar context like uncapacitated section. The difference is that the number of spectrum slices per fiber is limited to 10, which is known that it could cause certain blocking. The metric for comparison here is blocking ratio, which is evaluated as the ratio of blocking traffic to overall traffic. Table 4.5 presents the result for dedicated case with  $k = 4$ . DCDF is found to achieve lowest blocking ratio. Compared to SCSF, DCDF could decrease blocking traffic more than 6.93% thanks to its adaptation capability.

TABLE 4.5: Blocking ratio for dedicated protection at  $k = 4$

Operation Mode	Number of Connections				
	20	30	40	50	60
SCSF	16.69%	22.06%	24.97%	26.25%	34.31%
DCSF	16.12%	21.85%	23.98%	25.06%	32.67%
DCDF	9.97%	16.10%	18.04%	19.77%	29.76%
Max difference DCSF vs. SCSF: 1.64%					
Max difference DCDF vs. SCSF: 6.93%					

Table 4.6 presents the result for shared case with  $k = 4$ . It is noticed that the shared protection case offers lower probability ratio than in dedicated one thanks to the better accommodation of traffic by enabling sharing opportunity. As expected, DCDF outperforms the others in achieving the best blocking ratio. The difference between SCSF and DCDF is up to 6.41% in this study.

TABLE 4.6: Blocking ratio for shared protection at  $k = 4$ 

Operation Mode	Number of Connections				
	20	30	40	50	60
SCSF	14.53%	18.61%	20.43%	22.70%	29.56%
DCSF	14.53%	18.36%	20.14%	22.41%	29.09%
DCDF	8.12%	12.54%	14.86%	16.28%	23.00%
Max difference DCSF vs. SCSF: 0.46%					
Max difference DCDF vs. SCSF: 6.41%					

Finally, we show the result at different values of  $k$  to see the impact of introducing more candidate cycles as in table 4.7 for dedicated case and table 4.8 for shared case. Since the running time grows significantly with high value of  $k$ , we just keep a few values of  $k$  for consideration. It is observed that in general, the increasing of  $k$  leads to lower blocking ratio.

TABLE 4.7: Impact of  $k$  - number of candidate cycles - dedicated mode

Operation Mode	k	Number of Connections				
		20	30	40	50	60
SCSF	2	20.54%	21.91%	28.66%	30.40%	37.99%
	6	13.92%	19.25%	21.88%	26.14%	32.51%
DCSF	2	20.20%	20.86%	26.88%	29.27%	36.24%
	6	13.92%	19.25%	21.21%	25.04%	30.85%
DCDF	2	15.80%	20.20%	24.61%	26.26%	32.30%
	6	7.45%	15.65%	17.31%	19.77%	29.26%

TABLE 4.8: Impact of  $k$  - number of candidate cycles - shared mode

Operation Mode	k	Number of Connections				
		20	30	40	50	60
SCSF	2	18.14%	18.75%	22.65%	25.20%	30.77%
	6	10.73%	16.51%	18.34%	22.31%	27.33%
DCSF	2	17.68%	18.75%	22.01%	24.78%	30.46%
	6	10.73%	16.25%	17.71%	22.17%	26.86%
DCDF	2	12.37%	16.21%	17.04%	18.99%	25.82%
	6	7.16%	12.49%	14.22%	15.99%	22.96%

## 4.5 Conclusion

In this chapter, the dimensioning of OFDM-based network with path protection has been considered. We proposed to exploit the transmission margin between working and protection path for a more efficient operation. The reconfiguration of CO-OFDM transponder has been utilized to select the most spectrum-efficient modulation format for working and protection route of a connection in network-side scheme. The advantage of this operation was discussed in terms of spectrum-efficiency, transponder power consumption, blocking ratio in different scenarios.

We formulated the network dimensioning for both dedicated path and shared path protection in uncapacitated and capacitated scenario. In the former scenario, we draw a comparison on spectrum width requirement and transponder power consumption between three cases differing in flexibility between working and protection mode, namely, SCSF, DCSF and DCDF. In a case study on realistic COST239 topolog, we found out that DCDF outperforms significantly SCSF and DCSF in term of spectrum efficiency and energy consumption. The limited flexibility enabled by DCSF provided marginal gain in term of spectrum efficiency compared to SCSF while the transponder power remains almost the same. For the capacitated scenario, the benefit of introducing adaptation in DCDF was again confirmed by the capability of reducing significantly blocking ratio compared to traditional operation in literature SCSF and DCSF.

Based on this study, we would therefore conclude that exploiting the different channel condition of working and backup route in OFDM-based network brings promising benefits. The case study showed that significant gain in term of spectrum efficiency, power consumption, blocking ratio was achieved. Of course, the actual gains would be highly dependent on topology and traffic scenario.

## Chapter 5

# Conclusions and Future Works

### 5.1 Conclusions

The explosive growth of Internet traffic driven by proliferation of broadband services necessitate for a paradigm change in transport network. Introducing flexibility into optical layer has been considered as a guiding direction for cost and energy-efficient network. The traditional fixed network paradigm is therefore migrating to flexible one where a number of transmission parameters could be tuned and adapted to various network conditions. Network resilience problems in this new paradigm are interesting topic and nevertheless it is inadequately addressed. On the other front, the role of algorithm in optical network has been of particular importance as the network becomes more complex and more flexible. In this context, the thesis was an attempt to study some aspects relating to network resilience in flexible optical networks and the algorithm aspect of solving routing and spectrum assignment in flex-grid network.

The first chapter briefly introduced about research context, framework and the motivations. It also reported main achievements and contribution of the thesis. Besides, an overview of background information involving the basic of optical transport network, network optimization techniques involving the content of the thesis has also been introduced.

In chapter 2, we have examined the novel rate-adaptive operation of multi-line transponder for efficient protection. In our proposal, MLR transponder is utilized in such a way that at nominal mode, it operates at lower rate and when there is failure, it could be tuned to higher rate temporarily to carry protection traffic. Such rate variation is realized by modulation format change with the same baud-rate, and hence same channel spacing. We have performed a survivable network design with opaque architecture for both dedicated and shared protection. The

design was formulated as integer linear programming with the objective of minimizing overall flow allocation. As a case study, we considered the comparison between network design with SLR 100G and the other one with both SLR 100G and MLR 100/200G. The simulation was extensively carried out over 100 traffic matrices and different network topologies. Impact in term of transponder count, cost and power consumption has been addressed. It was shown that the new protection schemes with MLR transponder could be cost efficient than traditional one if MLR excess cost is less than 85% for the shared case and less than 90% for the dedicated case. From energy point of view, the proposal operation of MLR could achieve up to more than 30% gain when excess power consumption  $\beta = 0$ , and more than 15% when  $\beta = 50\%$  for both dedicated and shared case. It was emphasized that the actual gain is highly dependent on the network topology and traffic matrices.

Chapter 3 was dedicated to investigate routing and spectrum assignment, a crucial problem arising in flex-grid network. We performed studies for both single objective and multiple objective scenario. For single objective case, we presented a novel algorithm based on genetic algorithm to find good ordering of demands. We performed numerical study on different topologies to demonstrate the efficiency of the proposal compared to exact approach based on integer linear programming and other heuristic. It was found out that our algorithm could achieve optimal solutions in most cases while demonstrating a short running time. Besides, we proposed to collaboratively use heuristic solutions and integer linear programming approach to improve the running time of the solver and the capability of finding optimal solutions in a given time slot. The numerical result showed significant reduction of running time. Compared to solving time of traditional way in a matter of hours, the new approach exploiting this collaboration solves the problem in a matters of second. Furthermore, for problems which is known not be able to solve in two hours, the new approach is able to solve it within a magnitude of ten seconds. Generally, the better the solution is fed into solver, the shorter the running time it takes. For the multi-objective scenarios, we approached from two perspectives, depending on whether the preference is given priori or not. In the first perspective, we analyzed the weight vector to properly set such that the preference is reflected by that setting. It was shown that by solving the problem with such integrated objective, better solutions could be found than simply considering single objective. When there is no preference of any objective, we utilized multi-objective genetic algorithm based on NSGA-II to find a Pareto front. We performed a case study demonstrating the efficient convergence of the algorithm.

Chapter 4 focused on path protection in OFDM-based network. We addressed the transmission margin difference between working and protection path in reach-diverse network and proposed to exploit it for modulation-adaptive operation in network-side protection. The reconfiguration capability of CO-OFDM transponder was utilized for such operation. We formulated the static

network design process considering dedicated and shared path protection. A case study on realistic COST239 topology was performed to examine the impact of spectrum width requirement, transponder power consumption and blocking capacity. It was found out that the modulation-adaptive operation could achieve advantageous performance compared to the previous solutions in literature. In our studies, the spectrum width could be reduced to 20% and transponder power consumption gain is around 15% for uncapacitated case while in the capacitated case, a reduction of more than 6% of blocking capacity could be achieved.

## 5.2 Future works

Within the scope the thesis, we have investigated a number of interesting problems in flexible optical network. Nevertheless, this is large topic and the concept of flexible network is still evolving as more degree of freedom are introduced to networks and diverse options are available. For example, with the advances in technologies, a recently proposed transponder is capable of multi-flow operation with single transponder [113]. The introduction of such devices with more degree of freedom leverage new opportunities for efficient operation of network and opens up several related network design problems with new challenges. For the further promising activities directly related to the content presented in this thesis, we would like to highlight following points:

Firstly, in chapter 2, the concept of rate-adaptive operation could be extended to translucent and transparent network. Certainly, there are challenges in formulation as the wavelength assignment must be taken into account and the rate-adaptive operation of multi-line rate transponder gives rise to the separation of working and protection in the formulation. Finding efficient heuristic is therefore needed for such problems. Besides, a transponder scheme of more than two line-rates is also worth for further studies regarding to how to best utilize it for efficient protection.

For chapter 3 dealing with routing and spectrum assignment problem, there are several nice activities deserving further investigation from algorithmic perspective. One possibility is to make use of other advanced evolutionary algorithms (bio-inspired algorithm) such as firefly, artificial bee colony algorithms in combination with high-performance computing techniques (e.g., parallelization) to explore the efficiency of such algorithms. The key aspect is to find a efficient encoding scheme for the problem. In the study of chapter 3, we limited the encoding to find a good orders of demand. However, it is possible to encode other factors such as routing and spectrum assignment as well. Of course, it would come at the increased complexity and advanced repairing techniques is needed to ensure constraint satisfaction. From architectural point of view, the routing and spectrum assignment problem in translucent network is also interesting topic

for future activity. Since the regeneration is taken into account, multiple objectives should be considered, e.g., minimizing spectrum usage and regeneration. From computing perspective, the research direction of combining integer linear programming with efficient heuristic to improve the running time and memory issues with linear programming solver is a promising topic for further works. A possible extended work is to run heuristic and linear programming solvers in parallel and exchange information collaboratively or a multi-start feeding for the solvers.

The idea of chapter 4 on the modulation-adaptive operation of OFDM transponder in network-side protection could be further elaborated in dynamic scenario. It would be expected that interesting result will come out since the fragmentation issue must be taken into account for efficient operation. Of equal interest, it is useful to conduct a study on the sharing opportunity and adaptation scheme in client-side protection. The emphasis in that context is not only single-link failure but also transponder protection consideration. In [114], we had preliminary study on the spectrum-efficiency of adaptive forward error correction in network planning. Since the work is still in its infancy, we did not report it here. In a broader context, one could introduce forward error correction code-adaptive operation for network-side protection and exploit transmission margin difference for efficient code rate adaptation. With a relevant cost and energy model of different code-rate, one could perform a network design to study impact of introducing such operation in network-side protection compared to previous consideration. The combination of both modulation format and code-rate adaptation would be of particular interest since the adaptation is expected to be finer than simply introducing either modulation or code-rate. In chapter 4, we limited the study to transparent architecture and hence, it would be interesting to re-conduct the work in translucent operation. The impact of having regeneration certainly poses new challenges in the network design. We also limited to one connection per request (i.e., one transponder for a bi-directional request) and hence, the allowed maximum bit-rate is limited by the length of connection. One could therefore consider the network design supporting the parallel connections for a request. In such scenario, the large request could be split into multiple parallel connections.

# Appendix A

## Thesis Publications

The following publication has been done during the time-span of thesis. Most of the works are directly involved to the content of the thesis.

H. Dao Thanh, M. Morvan, P. Gravey, *On the interest of multi-line rate transponder for energy-efficient protection.*, ICOCN 2012-International Conference on Optical Communication and Networks, 28-30 November 2012, Pattaya, Thailand.

H. Dao Thanh, M. Morvan, P. Gravey, F. Cugini, I. Cerutti, *On the spectrum-efficiency of transparent optical transport network design with variable-rate forward error correction codes.*, ICACT 2014-International Conference on Advanced Communication Technology, 16-19 February 2014, PyeongChang, Korea.

H. Dao Thanh, M. Morvan, P. Gravey, *On the routing and spectrum assignment with multiple objectives.* PS 2014-Photonic in Switching, 13-16 July 2014, San Diego, United States.

P. Gravey, H. Dao Thanh, M. Morvan, *On the advantages of CO-OFDM transponder in network-side protection.* PS 2014-Photonic in Switching, 13-16 July 2014, San Diego, United States.

H. Dao Thanh, M. Morvan, P. Gravey, *On the usage of flexible transponder in survivable transparent flex-grid optical network.* CSNDSP 2014-International Symposium on Communication Networks and Digital Signal Processing, 23-25 July 2014, Manchester, United Kingdom.



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La croissance explosive du trafic Internet, de par la prolifération des services à large bande, nécessite un changement de paradigme dans le réseau de transport. L'introduction de la flexibilité dans la couche optique a été considérée comme axe privilégié pour améliorer le coût du réseau et l'efficacité énergétique. Il s'agit à partir du réseau à grille de multiplexage fixe traditionnel de migrer vers une grille flexible où un certain nombre de paramètres de transmission pourront être réglés et adaptés à diverses conditions de réseau. Ce changement de paradigme exploite clairement de nouvelles possibilités pour résoudre des problèmes très importants comme la résilience ou la conception du réseau. Par ailleurs, comme le réseau devient plus flexible avec un nombre croissant de degrés de liberté, et par conséquent plus complexe, le rôle des algorithmes dans la conception, l'exploitation et la gestion du réseau a une importance primordiale. Ainsi, il est nécessaire de disposer d'algorithmes efficaces permettant non seulement d'obtenir le meilleur usage des ressources, mais aussi de répondre à des exigences strictes en termes de temps d'exécution et de passage à l'échelle. Dans ce contexte, les travaux réalisés dans la thèse présentent des nouveaux systèmes de protection reposant sur l'adaptation de transpondeurs flexibles et de nouveaux algorithmes pour résoudre le problème de routage et d'allocation du spectre en considérant les deux cas mono- et multi-objectifs. Les nouvelles contributions scientifiques sont présentées dans les trois chapitres suivants :

Dans le chapitre 2, le changement de débit de transpondeurs à débit variable est exploité en tant que mécanisme de protection. Ce nouveau mécanisme est comparé à l'approche traditionnelle. Une méthode de dimensionnement d'un réseau protégé, avec une protection à la fois dédiée et partagée est proposée et étudiée par le biais de simulations détaillées afin d'étudier l'impact de l'introduction de ces nouveaux systèmes de protection en terme de nombre de transpondeurs, de coût et de consommation d'énergie.

Le chapitre 3 est consacré à des algorithmes pour résoudre le problème de routage et d'allocation du spectre. Dans le cas mono-objectif, un nouvel algorithme basé sur un algorithme génétique est proposé et comparé avec d'autres heuristiques ainsi que des solutions optimales obtenues à partir de la formulation exacte. L'approche proposée inclut également le recours à un « démarrage à chaud » des solveurs pour aboutir rapidement à de bonnes solutions avec les algorithmes heuristiques. Ensuite, le cas multi-objectifs est examiné en distinguant deux scénarios selon l'existence ou non d'un objectif préféré.

Le chapitre 4 se concentre sur la protection de chemin dans un réseau utilisant la transmission OFDM optique et un nouveau schéma de modulation adaptative. Le schéma de protection s'appuie sur la capacité de reconfiguration du transpondeur OFDM capable de travailler, pour un même débit, avec différents formats de modulation et largeurs spectrales. Ceci permet, par conséquent, une allocation de fréquences différente pour les chemins de travail et de protection (celle-ci étant effectuée uniquement côté réseau). Le dimensionnement de réseau selon ce nouveau schéma, avec protection de chemin dédiée et partagée, est effectué et comparé avec l'approche conventionnelle pour démontrer l'intérêt de cette nouvelle approche de point de vue de l'efficacité spectrale et de la consommation électrique.

**Mots-clés :** Réseaux Optiques, Optimisation des réseaux, Transpondeurs flexibles

The explosive growth of Internet traffic driven by proliferation of broadband services necessitates for a paradigm change in transport network. Introducing flexibility into optical layer has been considered as a guiding direction for improving network cost and energy efficiency. The traditional fixed network paradigm is therefore migrating to flexible one where a number of transmission parameters could be tuned and adapted to various network conditions. This changing paradigm clearly leverages new opportunities for addressing the very important problem, resiliency, in network design. On the other front, as the network becomes more flexible with an increasing number of degree of freedom, and consequently more complex, the role of algorithm in designing, operating and managing network has turned into of paramount importance when efficient algorithms are sought to achieve not just best use of resources but also to meet stricter requirement on running time and scalability issues. In this context, the works carried out in the thesis presents new protection schemes enabled by adaptive operation of flexible transponders, and new algorithms for solving the routing and spectrum assignment considering both single and multi-objective cases. Novel scientific contributions are presented into three following chapters:

In chapter 2, the rate-adaptive operation with multi-line rate transponder for efficient protection is presented and benchmarked with traditional approach. The survivable network design with both dedicated and shared protection is formulated and investigated over extensive simulations to study the impact of introducing such new protection schemes in term of transponder count, cost and power consumption.

Chapter 3 is dedicated to algorithms for solving the routing and spectrum assignment. In single-objective case, the novel algorithm based on genetic algorithm is proposed and benchmarked with other heuristics as well optimal solutions obtained from exact formulation. The contribution also includes the proposing of feeding good solutions from heuristic algorithms to warm-start the solvers. Afterwards, the multi-objective cases are examined extensively considering two scenarios whether or not the objective preferences is taken into account.

Chapter 4 focuses on path protection in OFDM-based network considering novel scheme based on modulation-adaptive operation. The scheme is enabled by the reconfiguration capability of OFDM transponder to work at different modulation formats and consequently different spectrum assignments for the working and protection path in network-side protection. The dimensioning of network with both dedicated and shared path protection considering this new scheme is performed and examined in compared with conventional approach to demonstrate the spectrum and power consumption efficiency.

**Keywords :** Optical network, Network optimization, Flexible transponders