Mechanisms for Efficient Inter-domain Traffic Distribution
To Aldona, my wife and my children
Many people have helped me in my work on this dissertation over the last four years, and I would like to thank all of them. There are also a few people I want to thank in particular. First of all, I would like to express my gratitude towards my supervisor, Professor Andrzej Jajszczyk for his understanding, valuable comments, advice and constant support. I am sure that without Professor Jajszczyk’s broad vision and patience, this PhD dissertation would not have been possible.

I would also like to express my sincere gratitude to Krzysztof Wajda for his support and help in many areas of my work. His experience of an older colleague has been and remains a very important influence on my work and life.

I have been very fortunate to work with Piotr Cholda. His remarks concerning the Least Cost Routing concept and many other issues contributed significantly to the improvement of my results. It is a pleasure to work with him.

My work on this dissertation would not have been possible without the patience, support and love of my family. I would like to thank my wife Aldona and our children Natalia, Michal, Damian, Karol, and Maria. They deserve my deepest appreciation.
Abstract

The dissertation proposes a comprehensive approach to joint cost and performance optimization in the inter-carrier context. The research was performed for three types of proposals, which take into account cost, performance parameters and resilience aspects related to the inter-domain environment. The general mathematical formulation for the optimization problem is given together with mathematical models for four types of tariffs. Generally speaking, finding a solution for such an optimization problem could be very difficult, especially if the number of involved discrete (binary) variables is large. Thus, in order to find the solution, some heuristic algorithms are proposed. The proposed heuristics can be grouped in three sets: algorithms with a greedy-based approach, algorithms using simulated annealing and evolutionary algorithms.

Apart from cost, some performance parameters were considered in the developed optimization models and algorithms. Measurements were taken in order to collect data related to the length of AS-path and latencies (used as indicators of QoS). Some novel heuristics which optimize QoS parameters with imposed cost-constraints are also proposed to find the solution.

The third part of mechanisms consist of reliability optimization algorithms and an evaluation of their performance. The goal of these algorithms is to find the distribution of the traffic which has to be sent in requested directions to assure the required level of resilience.

Mechanisms for efficient inter-domain traffic distribution are evaluated by scenario experiments run on a proprietary software written in C++.

The set of mechanisms proposed and studied in the thesis, called Least Cost Routing (LCR) solution, form a framework which helps to optimize connections between telecommunication operators by minimizing costs for served demands and maximizing an efficient use of the existing network infrastructure. By using the results of the proposed algorithms, the routing strategy can be executed more
efficiently by incorporating the knowledge of the connection cost with network conditions. Utilizing the LCR solution can also reduce time needed to analyze a huge number of alternatives and help carriers make decisions regarding new agreements with other carriers within a dynamic framework.

As the LCR solution proposed in the dissertation is rather general, it can be applied to many scenarios within current network technologies related to inter-domain traffic engineering. The results can be used in a BGP context to build routing tables by setting up values of ‘local preference’ parameters based on suggested inter-domain traffic distribution; the capacity and traffic can be then expressed in, e.g., Mbit/s. VoIP providers can use the proposed solution to choose other providers offering connectivity; the parameters and constraints will be related to the number of connections. In the context of mobile operators, the number of minutes can be used as the traffic volume. Other possible application areas include MPLS and optical networks with paths, wavelengths or fibers.

**Keywords:** Least Cost Routing, inter-domain traffic optimization, cost optimization, traffic engineering, Quality of Service, Quality of Recovery, BGP
Streszczenie

W rozprawie zaproponowano mechanizmy umożliwiające wyznaczenie efektywnego rozpyłu ruchu międzyoperatorskiego. Badania przeprowadzono dla trzech typów mechanizmów, które biorą kolejno pod uwagę koszt, parametry jakościowe oraz parametry niezawodnościowe w procesie wyznaczania tras dla rozważanego ruchu. Zaproponowano model matematyczny postawionego problemu oraz modele matematyczne czterech typów taryf stosowanych w rozliczeniach międzyoperatorskich. W ogólnym przypadku rozwiązanie analizowanego problemu optymalizacyjnego byłoby utrudnione, szczególnie w sytuacji gdy liczba zmiennych binarnych byłaby duża.

W celu znalezienia rozwiązania problemu dotyczącego efektywnego wyboru tras rozpyłu ruchu międzyoperatorskiego zaproponowano zatem algorytmy heurystyczne. Część algorytmów w trakcie wyznaczania rozwiązania optymalizuje koszt, niektóre zaś oprócz kosztu uwzględniają także wymagania jakościowe lub niezawodnościowe. Wśród zaproponowanych oraz przebadanych algorytmów biorących pod uwagę koszt przesłania ruchu znajdują się algorytmy stosujące podejście zachłanne, jak również algorytmy genetyczne oraz algorytmy symulowanego wyżarzania. W rozprawie zamieszczono również wyniki obrazujące działanie opisanych algorytmów.

Druga część rozprawy zawiera modele optymalizacyjne oraz heurystyki, które biorą pod uwagę parametry jakościowe w procesie wyznaczania tras. W celu zbierania danych dotyczących długości ścieżek AS-path (liczby skoków traktowanych jako systemy autonomiczne) oraz opóźnień na tych ścieżkach (parametry traktowane w pracy jako wskaźniki jakości) przeprowadzono odpowiednie pomiary. W celu rozwiązania postawionego problemu zaproponowano heurystyki, które umożliwiają optymalizację parametrów jakościowych z równoczesnym ograniczeniem dotyczącym kosztów ruchu międzyoperatorskiego.

Modele optymalizacyjne oraz algorytmy uwzględniające niezawodność w pro-
Streszczenie
ciesie rozpływu ruchu międzyoperatorskiego stanowią trzecią część zaproponowanych mechanizmów. Celem zaproponowanych rozwiązań jest znalezienie takich tras dla ruchu międzyoperatorskiego, które zapewnią wymagany poziom niezawodności. W celu oceny zaproponowanych mechanizmów umożliwiających efektywny rozpływ ruchu międzyoperatorskiego przeprowadzono badania przy pomocy programu napisanego w języku C++, w którym zostały zaimplementowane badane algorytmy.

Zaproponowane i przeanalizowane w rozprawie rozwiązanie LCR (Least Cost Routing) umożliwia optymalizację kosztów ruchu wychodzącego operatora. Zastosowanie rozwiązania LCR ułatwia operatorowi podjęcie decyzji, którymi ścieżkami będzie przesyłany ruch na określone kierunki. W konsekwencji rozwiązanie LCR prowadzi nie tylko do wyboru najtańszej drogi, ale znajduje najlepsze rozwiązanie uwzględniając zależności między ceną a jakością. Wybór taki zapewnia użytkownikowi większą elastyczność wyboru tras. Rozwiązanie LCR umożliwia również skrócenie czasu koniecznego do analizy dużej liczby możliwości wynikającej z proponowanych przez partnerów taryf oraz pomaga w powzięciu decyzji dotyczących nawiązania nowych umów biznesowych pomiędzy operatorami w dynamicznym środowisku.

Zaproponowane w rozprawie rozwiązanie LCR nie zależy od protokołów i metod stosowanych w środowisku międzyoperatorskim do inżynierii ruchu. Wyniki działania rozwiązania LCR mogą zatem być zastosowane w wielu technikach sieciowych, w których podejmuje się decyzję o wyborze trasy. Naturalnym miejscem zastosowania rozwiązania LCR umożliwiającego zbudowanie tablicy rutingu jest protokół międzydomenowy BGP. W tym przypadku wyniki działania rozwiązania LCR wprost mogą być przełożone na wartość parametru ‘local preference’, który decyduje o wyborze trasy na dany kierunek. W kontekście protokołu BGP przepływność łączy oraz wielkość przenoszonego ruchu może być wyrażona, np. w Mbit/s. Operatorzy VoIP mogą zastosować zaproponowane rozwiązanie do wyboru innych operatorów oferujących połączenia; parametry i ograniczenia będą się wówczas odnosić np. do liczby połączeń. W przypadku operatorów komórkowych liczba minut może być użyta jako miara wielkości ruchu. Technika MPLS oraz sieci optyczne posługujące się pojęciami ścieżek, stanowią kolejny potencjalny obszar zastosowań rozważanego rozwiązania LCR.

Słowa kluczowe: LCR, optymalizacja ruchu międzydomenowego, optymalizacja kosztów, inżynieria ruchu, QoS, QoR, BGP
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and background

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<tr>
<td>AS</td>
<td>Autonomous System</td>
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<td>ASBR</td>
<td>Autonomous System Border Router</td>
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<td>BGP</td>
<td>Border Gateway Protocol</td>
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<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<td>eBGP</td>
<td>external BGP</td>
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<td>EWMA</td>
<td>Exponentially Weighted Moving Average</td>
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<td>GAP</td>
<td>Generalized Assignment Problem</td>
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<td>Internet Access Provider</td>
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<td>IETF</td>
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<td>IGP</td>
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<td>IntServ</td>
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<td>ITU-T</td>
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<td>PoP</td>
<td>Point of Presence</td>
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<td>QoR</td>
<td>Quality of Recovery</td>
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</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
<td></td>
</tr>
<tr>
<td>RIB</td>
<td>Routing Information Base</td>
<td></td>
</tr>
<tr>
<td>RTT</td>
<td>Round-Trip Time</td>
<td></td>
</tr>
<tr>
<td>SES</td>
<td>Single Egress Selection</td>
<td></td>
</tr>
<tr>
<td>SLA</td>
<td>Service Level Agreement</td>
<td></td>
</tr>
<tr>
<td>SLS</td>
<td>Service Level Specification</td>
<td></td>
</tr>
<tr>
<td>SNMP</td>
<td>Simple Network Management Protocol</td>
<td></td>
</tr>
<tr>
<td>TE</td>
<td>Traffic Engineering</td>
<td></td>
</tr>
<tr>
<td>TIE</td>
<td>Tunable Interdomain Egress</td>
<td></td>
</tr>
<tr>
<td>TM</td>
<td>Traffic Matrix</td>
<td></td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
<td></td>
</tr>
<tr>
<td>VPN</td>
<td>Virtual Private Network</td>
<td></td>
</tr>
</tbody>
</table>
Part I

Introduction and background
Introduction

In a multi-domain environment, possibly combining incumbent and virtual network operators (VNO), service providers and operators who want to send traffic to certain destinations outside their networks have many possibilities to choose routes offered by various connectivity providers. Since an important element of an operation budget is the interconnection cost, the critical problem is to route traffic through the cheapest routes in order to control OpEx (Operational Expenditure). Apart of the cost, Quality of Service (QoS) parameters very often play a significant role in the total routing strategy. There are also some other factors that have to be taken into account while looking for a solution which will guarantee an efficient distribution of the inter-domain traffic. Moreover, the constraints related to the physical network, that is capacity constraints, and the tariff limits are also some of the factors that have to be considered while determining the paths for the traffic flows. The operators have different types of charging agreements, they also offer different destinations for the traffic. What is more, a higher offered quality of the path to a given destination will most often result in a higher price. The operator has to decide how the relation between cost and performance in its network should look like.

However, very often, operators make manual changes in the routing policies without a good understanding of the effects on the traffic flows or the impact on other domains.

The Least Cost Routing approach, considered in the thesis, refers to the prob-
lem of optimizing connections between telecommunication operators by minimizing cost for served demands and maximizing efficient usage of the existing network infrastructure. The usage of the LCR solution can also shorten time needed to analyze a huge number of alternatives and help a carrier make decisions considering new agreements with other carriers within a dynamic framework. The results of the proposed solution help also the carrier to track which traffic routes generate the highest revenues.

It has to be stressed that the considered problem is of the optimization character with a defined objective function and a set of constraints. In the first phase, the efficient inter-domain traffic distribution is determined. In the second phase, at the control plane level, traffic engineering techniques should be used to build the routing table based on the results obtained from the LCR solution. The methods used in the LCR system can also be used together with online inter-domain traffic engineering techniques. To determine the online traffic flow assignment a real-time monitoring should be implemented. Traffic predictors to forecast traffic for a short time interval (e.g., minutes) should be applied and then algorithms implemented in the LCR solution should be run in a quasi-offline manner to produce solutions in a short timescale.

1.1 Scope and thesis

This dissertation proposes mechanisms for efficient distribution of inter-domain traffic. The new solutions are described in details and implemented in a purposely developed C++ software. The performed analysis show their usefulness as well as their advantages and drawbacks.

The following thesis of this dissertation has been formulated and proved:

*It is possible to efficiently distribute the inter-domain traffic using moderately complex algorithms.*

The proposed algorithms were intended to be simple and not to require a high computational complexity as the computation time was one of the significant constraints. This aim was achieved for all the proposed solutions.

1.2 Publications

Some of the results presented in the dissertation were published in six conference papers and one journal text. The list of relevant publications is as follows:

1.2 Publications

GLOBECOM 2006, 27 November-1 December, San Francisco, California, USA.


1.3 Structure of the dissertation

The dissertation is composed of four parts. The introduction, thesis and the theoretical background for the research is presented in the first part (Chapters 1-3). In Chapter 2, the taxonomy and classification of interconnections and inter-domain TE concepts are given. Chapter 3 provides an overview of the literature related to the research on inter-domain traffic engineering issues. The most important papers and books which cover the inter-domain traffic optimization issues are briefly reviewed.

A general connection model for the LCR problem, mathematical optimization models and heuristic algorithms for efficient inter-domain traffic distribution are given in the second part (Chapters 4-6). Chapter 4 presents the connection model considered in the thesis. This model is presented from the point of view of an operator who wants to optimize its inter-domain traffic. In Chapter 5 the mathematical optimization models for the analyzed LCR problem are given. The presented models take into account a few different tariffs used in the business agreements between the operators. Mechanisms and heuristic algorithms for assuring the optimal inter-domain traffic distribution are proposed in Chapter 6.

The results of the numerical analysis are presented in the third part of the dissertation (Chapters 7-8). The problem of route selection in a multi-homed stub network to optimize transit cost and paths performance offered by an operator to its customers is presented in Chapter 7. We provided some QoS optimization models together with heuristic algorithms to solve the problem. As the indicators of the QoS related to interconnections and routes offered by interconnected partners we consider the length of AS-path (Autonomous System) and latency experienced on that path as measured by the round-trip time ($RTT$). The measured values of the QoS parameters are provided and explained. The results of numerical experiments considering algorithms which take into account QoS parameters and the analysis of the results are also included. On the other hand, in Chapter 8 the LCR solution which takes into account the resilience issue is described. The presented algorithms help to optimize connections between telecommunication operators by minimizing cost for served demands and maximizing efficient use of the existing network infrastructure guaranteeing a required level of reliability at the same time. The proposed algorithms have been verified by a number of numerical experiments. The numerical results and their analysis have also been provided. The mechanisms proposed for inter-domain traffic distribution may be successfully implemented in operator networks and allow for ensuring short times for finding optimized paths for inter-domain traffic.

The fourth part of the dissertation contains Chapter 9 that summarizes the research presented in the dissertation and gives some practical recommendations for network operators.
This chapter presents a brief introduction and preliminary background information. The Internet is basically a hierarchy made up of stub networks, mid-level networks, and Internet backbones that provides global connectivity. The Internet is divided into autonomous systems (ASes) that exchange reachability information using the Border Gateway Protocol (BGP). To control traffic routing across multiple domains, Internet Service Providers (ISPs) apply traffic engineering (TE) techniques to achieve load balancing over inter-domain resources and/or to minimize transit cost.

The structure of the Internet is presented in Chapter 2.1. The results of the Internet topology analysis are provided in Section 2.2. An overview of the current inter-domain routing protocol is given in Chapter 2.3. A description of inter-domain traffic engineering methods is presented in Chapter 2.4. The economic relations between providers present in the inter-domain environment form Chapter 2.5.
2.1 Internet structure

The Internet is a large decentralized internetwork comprised of more than 64,000 separate administrative domains or Autonomous Systems (ASes) at the time of writing [77]. In [41], an Autonomous System is defined as a connected group of one or more Internet Protocol (IP) prefixes run by one or more network operators which has a single and clearly defined routing policy. Each AS is composed of multiple networks operated under the same authority and, therefore, applies various economic, business, and performance decisions in its routing policy. They form the Internet by interconnecting with each other and exchanging traffic.

The Internet is operated by many Internet Service Providers (ISPs). An ISP is a business or organization that provides an access to the Internet to its customers. It can also offer other related services, such as Internet transit, domain name registration and hosting, etc. End-users generally want to access all other possible end-users, regardless of the network they belong to. To provide such a global connectivity to their users, ISPs must interconnect with each other, creating one large, global entity to share their network infrastructure.

A physical infrastructure through which Internet Service Providers (ISPs) exchange Internet traffic between their networks (Autonomous Systems) is generally called an Internet eXchange Point (IXP) [56]. The primary purpose of an IXP is to allow networks to interconnect directly, via the exchange, rather than through transit networks. Logically, an IXP consists of routers interconnected through a variety of layer-2 (e.g., Ethernet, ATM) and layer-3 (IP routers) mechanisms. A public IXP is owned and operated by a third party and is open to any ISP that wishes to interconnect with other ISPs there. A private IXP is a direct point-to-point interconnection between ISPs [70].

All the domains in the Internet can be classified into two categories: transit domains and stub domains [110]. In the case of the transit domains they offer transit services to other domains (i.e., inter-domain traffic delivery across the Internet). The stub domains, on the other hand, constitute the leaf domains of the AS-level hierarchy. They only send or receive traffic, and do not provide transit services to any other AS. Stub domains can be further classified as single- or multihomed. Multihomed stub domains have connections to more than one transit domain while singlehomed stubs connect to only one transit domain. Some stubs have also links to other stubs. Stub domains currently constitute the majority of the observable ASes in the Internet. A large fraction of the stub ASes are content providers, universities, or enterprise networks.

The domains in the Internet form a hierarchy of Tier-1, Tier-2, and Tier-3 domains. Although there is no formal definition of tiers of networks participating in the Internet, the most common definition of a Tier-1 network is the one that can reach every other network in the Internet without purchasing IP transit or
paying settlements [82]. Due to this definition, all Tier-1 ASes more or less have to peer with each other in order to exchange routing information with other Tier-1 ASes. Therefore, we say that such ASes are in the core of the Internet. Smaller customer ASes are usually the periphery of the Internet graph. The Tier-2 network is defined as a network that peers with some networks, but still purchases IP transit or pays settlements to reach at least some portion of the Internet. In case of the Tier-3 domain, it solely purchases transit from other networks to reach the Internet.

An example of the Internet structure is presented in Fig. 2.1. The business relations between domains forming the hierarchy in the Internet are also presented.

Figure 2.1: Example of Internet structure.

The different types of ASes lead to different types of business relationships between them. There are two main business models between two interconnected
Area of research

ASes: customer-provider (c2p) and peer-to-peer (p2p) [108]. In the customer-provider (c2p) case, domain A pays domain B money for obtaining transit through B network. To charge domain A, domain B should measure the amount of traffic that A sends over its upstream links to B. In case the peer-to-peer (p2p) model is applied, two interconnected ASes share the deployment and maintenance cost for the technical infrastructure that is needed to exchange traffic between neighboring domains. A peering scheme is usually adopted by neighboring ASes in case the amount of traffic they exchange in both directions is balanced. When an exchange participant increases the amount of traffic the renegotiation of the agreement is often performed. Apart from the customer-provider and peer-to-peer models there exist also other less frequent business relationships. One example are siblings where neighboring ASes have a mutual transit agreement. Often the two ASes are merging ISPs or they adopt this scheme to obtain Internet connection backup.

As business agreements frequently are not public information it is very hard or even impossible for an outside part to confirm that a network is not paying settlements of any type. There exists approximately 10 Tier-1 networks. Examples of such networks which are believed to be Tier-1 networks (as they do not have publicly known settlements with any other network) are Level3, Sprint, Qwest, Verizon.

2.2 Internet topology analysis

The section presents the results of the Internet topology analysis. The results related to the type of business relationships between operators are given in Section 2.2.1. Measurement results indicating the details for Tier-3 domains are presented in Section 2.2.2. Tier-2 domains and Tier-1 domains are considered in Section 2.2.3 and Section 2.2.4, respectively.

2.2.1 ISP types

To setup realistic parameters for the LCR software we analyzed the Internet topology based on data obtained from Cyclops [23]. Cyclops is a system that provides ASes a view of how their connectivity is perceived from hundreds of vantage points across the network. It uses real BGP data from thousands of vantage points of Abilene [1], University of Colorado BGPmon [11], Packet Clearing House [75], RIPE-RIS [85] and RouteViews [86]. The publicly available BGP vantage points (VPs) have been heavily used by the research community to build the Internet autonomous system (AS) level topology. The final analyzed topology consisted of 33851 domains as the AS-level Internet topology at the time of measurement (August 12, 2009).
From the point of view of business relationships two types of ASes can be distinguished: transit ASes and stub ASes. Stub ASes have no customers (or client ISPs). In case of transit ASes (which include Tier-1 and Tier-2 providers), they are present in the middle of an AS path to other networks and carry both local and transit traffic. Regarding the business agreements, the transit ASes have customers and can also have providers (the case for Tier-2 ASes).

The heuristic used in Cyclops for determining these agreements is based on the assumption that Tier-1 ASes should have a large transit degree [111]. The results of the performed measurement revealed that within the analyzed topology there is only 14.9% of transit domains (5079 ASes). Among the transit ASes we identified 10 large Tier-1 domains. The results also indicate that stub networks are predominant in the Internet consisting of 84.4% of the analyzed networks (28540 ASes). In the case of 232 ASes (0.7%), it was not possible to determine the type of domain based on the performed measurements.

One of the parameters obtained through the performed measurements is the multihoming degree of the Internet domains. The considered parameter informs us of the number of interconnection links from the given domain to other ASes. In the studied Internet topology, the average degree of the stub domains is equal to 2.7, while in case of Tier-2 transit domains this value is significantly higher and equals to 30.3. As Tier-1 providers offer the global connectivity, it is clear that the degree of such domains should be extremely high. According to the performed research, the average number of partners connected with Tier-1 domains is as large as 1564.

Table 2.1 presents the detailed results related to the degree of the Internet domains (the number of interconnection links) for the stub and Tier-2 domains. The results are also given for unrecognized domains and all analyzed ASes. The results show that more than 28% of the recognized stub networks are connected through only one inter-AS link while the majority of all analyzed domains is connected with 2 partners. There are also some stub domains (574 ASes) connected with more than 10 partners. In the case of Tier-2 domains more than 38% of ASes are connected with more than 10 partners.

Figure 2.2 shows the cumulative distribution function (CDF) for stub and transit ASes. The results for total domain degree distribution which includes unrecognized domains and Tier-1 networks are also presented. In general, these plots share the same basic characteristics and are often referred to as the ‘power-law’ of Internet topology [29].

To provide some initial characterization of the analyzed multi-domain environment, we first examine the commercial relationships in the graph structure. The Internet has a hierarchical structure that is determined by the business agreements between ASes (e.g., provider, customer, peer). However, peering relationship data usually is not publicly available and should be, instead, inferred
Table 2.1: Degree of Internet domains

<table>
<thead>
<tr>
<th>Degree</th>
<th>Stub</th>
<th>Tier-2</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASes</td>
<td>%</td>
<td>ASes</td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>8027</td>
<td>28.1</td>
<td>7</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>13520</td>
<td>47.4</td>
<td>348</td>
<td>6.9</td>
</tr>
<tr>
<td>3</td>
<td>3808</td>
<td>13.3</td>
<td>613</td>
<td>12.1</td>
</tr>
<tr>
<td>4</td>
<td>1312</td>
<td>4.6</td>
<td>544</td>
<td>10.7</td>
</tr>
<tr>
<td>5</td>
<td>543</td>
<td>1.9</td>
<td>452</td>
<td>8.9</td>
</tr>
<tr>
<td>6</td>
<td>271</td>
<td>0.9</td>
<td>327</td>
<td>6.5</td>
</tr>
<tr>
<td>7</td>
<td>186</td>
<td>0.7</td>
<td>274</td>
<td>5.4</td>
</tr>
<tr>
<td>8</td>
<td>132</td>
<td>0.5</td>
<td>222</td>
<td>4.4</td>
</tr>
<tr>
<td>9</td>
<td>87</td>
<td>0.3</td>
<td>171</td>
<td>3.4</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>0.3</td>
<td>151</td>
<td>3.0</td>
</tr>
<tr>
<td>&gt;10</td>
<td>574</td>
<td>2.0</td>
<td>1960</td>
<td>38.7</td>
</tr>
<tr>
<td>Total</td>
<td>28540</td>
<td>100%</td>
<td>5069</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 2.2: Degree distribution of Internet domains.

from the BGP data. The number of domains with known business relations is presented in Table 2.2.

The results indicate that there are almost 85% of domains without customers, i.e., stub domains. A large number of analyzed domains (64.5%) does not have peering agreements while almost 60% ASes have the connection links only with providers. There are also some domains only with peering agreements.
2.2 Internet topology analysis

Table 2.2: Number of business relations

<table>
<thead>
<tr>
<th>Scenario</th>
<th>ASes</th>
<th>%</th>
<th>Scenario</th>
<th>ASes</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>no customers</td>
<td>28540</td>
<td>84.9</td>
<td>only customers</td>
<td>7</td>
<td>0.02</td>
</tr>
<tr>
<td>no providers</td>
<td>973</td>
<td>2.9</td>
<td>only providers</td>
<td>20004</td>
<td>59.5</td>
</tr>
<tr>
<td>no peers</td>
<td>21690</td>
<td>64.5</td>
<td>only peers</td>
<td>952</td>
<td>2.8</td>
</tr>
</tbody>
</table>

2.2.2 Stub domains

The results for stub networks show that customer-provider relations (48849 links) consist of almost 68% of all business relations for stub networks while peering agreements (23527 links) are set up in more than 32% cases.

The algorithm used in Cyclops was not able to infer about the business relations for about 4% of connections. The number of stub domains with at least one not recognized business relation is equal to 1691 ASes (5.9%) while all business agreements have been properly recognized for 26849 ASes (94.1%).

The results indicate that 70.1% stub domains have only transit agreements while only peering relation has been setup in 3.3% of stub networks. Both business relations are present in 26.6% of stub ASes.

Table 2.3 shows the distribution of provider-customer (p2c) and peering (p2p) links for stub ASes considered in the analysis. The results indicate that almost 43% of stub networks have only one provider while the multihomed ASes consist of 57% of the analyzed stub networks. Moreover, roughly 99.3% of all stub ASes have 5 or less interconnection links. In addition, 2÷5 multihomed ASes comprise about 54.4% of multihomed domains. Thus, ASes with degree 6 or more consist of a small fraction of multi-homed ASes.

Table 2.3: Stub domains: distribution of p2c and p2p links

<table>
<thead>
<tr>
<th>Links</th>
<th>p2c links</th>
<th>p2p links</th>
<th>Any relation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASes</td>
<td>%</td>
<td>ASes</td>
</tr>
<tr>
<td>0</td>
<td>952</td>
<td>3.3</td>
<td>20004</td>
</tr>
<tr>
<td>1</td>
<td>12023</td>
<td>42.2</td>
<td>6113</td>
</tr>
<tr>
<td>2</td>
<td>11913</td>
<td>41.7</td>
<td>1049</td>
</tr>
<tr>
<td>3</td>
<td>2558</td>
<td>9.0</td>
<td>331</td>
</tr>
<tr>
<td>4</td>
<td>667</td>
<td>2.3</td>
<td>173</td>
</tr>
<tr>
<td>5</td>
<td>230</td>
<td>0.8</td>
<td>134</td>
</tr>
<tr>
<td>&gt;5</td>
<td>197</td>
<td>0.7</td>
<td>736</td>
</tr>
<tr>
<td>Total</td>
<td>28540</td>
<td>100%</td>
<td>28540</td>
</tr>
</tbody>
</table>

Figure 2.3 presents the results for stub networks showing the cumulative dis-
2. Area of research

The distribution function (CDF) of business relations for providers and peers. The CDF function is also given for the total number of business relations which also includes not inferred agreements. In the case of stub domains the average numbers of providers and peers are equal to 1.71 and 0.85, respectively.

![CDF of business relations](image)

Figure 2.3: Stub domains: CDF of business relations.

### 2.2.3 Tier-2 transit domains

Table 2.4 shows the distribution of provider, peer and customer links for transit Tier-2 ASes determined in the performed measurement.

The results indicate that 33.3% of Tier-2 networks do not have peering agreements with other domains. Most Tier-2 ASes (31.8%) are connected to 2 providers. On the other hand, as much as 40% Tier-2 domains have only one customer. In 17.3% of ASes only one peering agreement was set up. However, at the same time more than 38% of domains have more than 10 interconnection links. In the case of Tier-2 transit domains the average numbers of providers, peers, and customers are equal to 2.76, 16.17, and 9.8, respectively.

![CDF of business relations](image)

Figure 2.4: Tier-2 transit domains: CDF of business relations.

The CDF function is also given for the total number of business relations which also includes not inferred agreements.
Table 2.4: Transit domains: Degree distribution of business relations

<table>
<thead>
<tr>
<th>Partners</th>
<th>Providers %</th>
<th>Peers %</th>
<th>Customers %</th>
<th>Any relations %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.2</td>
<td>33.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>24.1</td>
<td>17.3</td>
<td>40.0</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>31.8</td>
<td>9.5</td>
<td>16.6</td>
<td>6.9</td>
</tr>
<tr>
<td>3</td>
<td>19.7</td>
<td>5.6</td>
<td>8.5</td>
<td>12.1</td>
</tr>
<tr>
<td>4</td>
<td>11.2</td>
<td>4.0</td>
<td>5.8</td>
<td>10.7</td>
</tr>
<tr>
<td>5</td>
<td>6.0</td>
<td>2.7</td>
<td>4.2</td>
<td>8.9</td>
</tr>
<tr>
<td>6</td>
<td>3.2</td>
<td>2.3</td>
<td>3.0</td>
<td>6.5</td>
</tr>
<tr>
<td>7</td>
<td>1.7</td>
<td>1.6</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>8</td>
<td>0.6</td>
<td>1.7</td>
<td>1.8</td>
<td>4.4</td>
</tr>
<tr>
<td>9</td>
<td>0.7</td>
<td>1.4</td>
<td>1.6</td>
<td>3.4</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>2.7</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>&gt;10</td>
<td>0.6</td>
<td>1.6</td>
<td>16.0</td>
<td>38.7</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 2.4: Transit domains: degree distribution.

2.2.4 Tier-1 domains

The measurement results for Tier-1 domains are presented in Table 2.5 where ASN denotes the Autonomous System Number. A Tier-1 AS does not have any provider but have peering agreements with other Tier-1 ASes in order to reach
all destination networks in the Internet. Tier-1 ASes also have many customers, including both stub ASes and lower level service providers. Compared with non-Tier-1 transit ASes, Tier-1 ASes should, generally, have a larger transit degree. The results of the performed measurements indicate that the average degree of Tier-1 domains is as high as 1564, and is significantly higher while comparing with a number of interconnection links measured for non-Tier-1 transit ASes.

Table 2.5: Tier-1 results

<table>
<thead>
<tr>
<th>ASN</th>
<th>Customers</th>
<th>Peers</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASes</td>
<td>%</td>
<td>ASes</td>
<td>%</td>
</tr>
<tr>
<td>3356</td>
<td>2515</td>
<td>91.1</td>
<td>217</td>
<td>7.9</td>
</tr>
<tr>
<td>701</td>
<td>2257</td>
<td>80.7</td>
<td>386</td>
<td>13.8</td>
</tr>
<tr>
<td>7018</td>
<td>2240</td>
<td>89.1</td>
<td>252</td>
<td>10.0</td>
</tr>
<tr>
<td>1239</td>
<td>1563</td>
<td>88.7</td>
<td>181</td>
<td>10.3</td>
</tr>
<tr>
<td>209</td>
<td>1376</td>
<td>80.6</td>
<td>246</td>
<td>14.4</td>
</tr>
<tr>
<td>3549</td>
<td>1299</td>
<td>85.5</td>
<td>208</td>
<td>13.7</td>
</tr>
<tr>
<td>2914</td>
<td>567</td>
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<tr>
<td>1299</td>
<td>530</td>
<td>83.3</td>
<td>101</td>
<td>15.9</td>
</tr>
<tr>
<td>6453</td>
<td>461</td>
<td>74.8</td>
<td>149</td>
<td>24.2</td>
</tr>
<tr>
<td>3561</td>
<td>456</td>
<td>84.4</td>
<td>80</td>
<td>14.8</td>
</tr>
</tbody>
</table>

2.3 Inter-domain routing

Technically, the Internet is a complex distributed system, composed of many independent networks. In the same environment, the end-users require the world-wide reachability and connectivity. They want to exchange traffic across the Internet, irrespective of whether the destination host is in the local network or in a different AS. Routing in the Internet is realized on two levels, intra-domain and inter-domain, implemented by two different sets of protocols which together ensure global reachability.

Inside an AS, an Interior Gateway Protocols (IGP) such as Intermediate System-to-Intermediate System (IS-IS) or Open Shortest Path First (OSPF) are used to propagate routing information. These protocols route packets within a single AS. Each router selects a shortest path to a destination prefix taking into account a metric which can be defined by the network administrator. Routers which provide inter-domain connectivity are called border routers. In OSPF the border routers are known as Autonomous System Border Routers (ASBR). The physical locations of these border routers are frequently referred to as Points of Interconnection (PoIs).
The routing between ASes is more complex than the routing inside an AS. It has to consider contractual agreements, signed by neighboring ASes. Many ASes buy Internet connectivity from one or more transit providers (upstream providers). In case of a peering relationship, the neighboring ASes share the costs, which arise from the maintenance of the connecting link. Therefore, such a peering link is exclusively used to exchange traffic with the neighbor AS and its customers. Transit traffic is not allowed to flow through peering links [35].

Today, Border Gateway Protocol (BGP) [83] is the de facto standard inter-domain routing protocol used in the Internet. Border routers from different ASes exchange routing information through external BGP (eBGP) sessions, and these advertisements are also propagated to all other BGP speakers within the AS through internal BGP (iBGP) sessions. External BGP sessions are established over inter-domain links, i.e., links between two different ASes (BGP peers), while internal BGP sessions are established between the routers inside an AS.

The BGP protocol is a policy-based routing protocol that enables operators to control inter-domain routes rather than always using the shortest AS paths. Administrators can discard unacceptable incoming BGP advertisements by specifying input filters per BGP peer. The accepted route advertisements are placed in the incoming Routing Information Base (RIB-In) together with the routes originated at this router. Before putting the received information to the RIB-In, some of the route attributes may be modified according to the local routing policies. In the next step, the BGP decision process is used to select the best route for each prefix among the available routes. The chosen route is then installed in the BGP routing table referred to as the RIB-Out. Finally, output filters can be determined for each peer. Then, these filters are used to decide which best routes are to be propagated to a BGP neighbor.

The BGP standard specifies a number of decision factors which enable determining a single best route for any given prefix (see Fig. 2.5). A BGP speaker can receive multiple route advertisements for the same destination prefix. Some attributes are associated with each route advertisement. If multiple BGP routes are received with the same value of the attribute in a higher priority, tie breaking is applied through comparing the attribute in the next priority.

The ‘local-preference’ attribute (in short, Local_pref) has the highest influence on routing decisions has. The Local_pref is a non-transitive attribute so that it can be used to locally rank routes. By using the Local_pref attribute it is possible to specify the preference among different routes towards a given destination (higher values are better). Therefore, the domain administrator has direct influence on how to route traffic. The results of the LCR software operation can be translated into the values of Local_pref attributes to determine the efficient distribution of the inter-domain traffic.

In the next step, the ‘AS_path’ attribute is analyzed by the BGP decision
process. An AS_path gives the information on the sequence of ASes that a route crossed to reach the current AS. In the selection process, routes with shorter AS_paths are preferred.

The ‘origin type’ that defines the origin of the path information is taken into account in the third step. The ‘origin type’ attribute can assume three values: IGP (the route advertisement is interior to the AS of origination), EGP (the path is learned via exterior gateway protocol) and INCOMPLETE (usually occurs when routes are redistributed from other routing protocols into BGP). The path with the lowest origin type is preferred: IGP is lower than EGP, and EGP is lower than INCOMPLETE.

The ‘multi-exit-discriminator’ (MED) is the next attribute in the selection process. This attribute is used to rank routes received from the same neighbor
AS and enables selecting a particular egress point in the local domain. This can be used for ‘cold-potato’ routing [91] which aims at carrying the traffic as long as possible in the own network, before handing it off to the neighbor. In general, MED values are only compared if the routes have been learned from the same neighbor AS. Then the decision process ranks routes according to the IGP cost of the intradomain path towards the exit point in the AS (called the BGP next-hop), preferring routes with a smaller IGP cost. This rule implements ‘hot-potato’ routing [92], where the transit traffic is passed to another AS as quickly as possible.

Finally, if there is still more than a single route left, the router breaks ties, for example by selecting the route to the neighbor which has the lowest router-ID (typically one of its IP addresses).

2.4 Inter-domain traffic engineering

Internet traffic engineering (TE) is the process of performing efficient optimization of both intra- and inter-domain resources. In [9] TE is defined as a large-scale network engineering for dealing with IP network performance evaluation and optimization. A more straightforward explanation of TE is also given in [66]: ‘to put the traffic where the network bandwidth is available’. Therefore, the nature of TE is to effectively perform routing optimization for enhancing network service capability without causing network congestion.

Inter-domain TE, an emerging topical research area, has evolved from its intra-domain counterpart. The main goal of techniques used in that environment is to control the flow of traffic between autonomous systems (ASes) in such a way that performance goals could be achieved under various resource constraints. There are many areas where it is beneficial and even necessary for the ISP to apply traffic engineering methods [31], [104]:

- Traffic fluctuation: An inefficient use of network resources can be caused by traffic fluctuations and network failures which degrade user performance. The reconfiguration of the routing protocols should be made by network operators in order to adapt to the changes in the traffic distribution.

- Congested edge link: As the links between domains are common points of congestion in the Internet an operator can change the inter-domain paths to direct some of the traffic to a less congested link.

- Upgraded link capacity: After installing new links between domains the routing changes may be required to direct traffic travelling via other interconnection links to the new link.
• Violation of peering agreement: An AS pair may have a business arrangement according to which the amount of traffic they exchange in both directions should be balanced. In case the traffic become unbalanced, an AS may need to direct some traffic to a different neighbor.

A network operator can configure BGP attributes to help achieving its TE objectives. By tuning the local routing policies that affect the selection of the best path for a destination prefix, the required paths can be computed. Generally, only a single path should be selected for a particular destination prefix. Some vendors have also implemented the BGP multipath functionality. In the Cisco’s BGP implementation, after enabling the BGP multiple paths option, up to six inter-domain routes can be installed simultaneously into the BGP routing table for the same destination prefix.

However, the aim of the BGP design was not traffic engineering. Thus, it does not include any direct support for common traffic engineering tasks, such as required load balancing across multiple links to a neighboring AS or directing traffic to a different neighbor. The type and the number of attributes available in BGP advertisements as well as the restrictions in the BGP decision process decrease the possibility of achieving the imposed traffic engineering goals. The next reason influencing the possibility of applying the traffic engineering methods directly in BGP is the number of possible changes to routing policies. There are too many cases to exhaustively test all possibilities. Moreover, introducing some changes in routing policy for the network which operates in the real world can have an unpredictable effect on the flow of traffic.

It is very difficult to find out the appropriate policy configuration as the result depends on many factors, such as the IGP parameters, the BGP advertisements received from neighboring ASes, the network topology, the current traffic patterns, etc. Since network operators cannot perform traffic engineering conveniently and directly based on BGP, some indirect BGP-based traffic engineering approaches should be applied. The LCR solution considered in this dissertation is one of these indirect traffic engineering methods which enables obtaining the optimal inter-domain traffic distribution in a relatively short time. Thus, it can also be applied to find out the solution in the real time. The results of the LCR computation can be directly translated into the BGP policy configuration.

2.4.1 Offline vs. online route computation

The purpose of our offline traffic engineering approach is to proactively optimize the global network configuration according to some predefined objectives. The computation of routing plans required for traffic engineering may be performed offline or online. The main difference between offline and online traffic engineering is the knowledge of a traffic matrix and a timescale of traffic optimization. The
2.4 Inter-domain traffic engineering

computation can be done offline for scenarios where routing plans need not be executed in the real-time. A basic diagram for the offline TE process is presented in Fig. 2.6.

Figure 2.6: Offline traffic engineering process [107].

Before routing optimization takes place, a traffic matrix should be forecasted. A network operator can use two general inputs to estimate the traffic matrix: a service level specification (SLS) and monitoring/measurement (e.g., [7], [74]). An SLS is a part of a service contract where the level of service is formally defined. The network operator can estimate the overall bandwidth demand between interconnected partners by summing up the traffic forecasted in each of the SLSes related to the individual customers. To estimate the future traffic matrix, monitoring/measurement mechanisms at the interconnection links can also be applied. After determining the traffic matrix, the methods for offline TE can be applied enabling a network operator to optimally distribute the predicted traffic onto the physical network. The average duration between two consecutive TE
cycles performed offline is denoted as the resource provisioning cycle (RPC) [99]. In practice, the offline TE computation is performed monthly as it is a common billing period between network operators. It is worthy to mention that the LCR solution proposed in the thesis enables computing the routing planes in a timescale of minutes. The main drawback of the offline TE is the lack of adaptive traffic manipulation according to traffic and network dynamics. The traffic changes caused by a traffic burst and network failures can decrease the efficiency of offline TE due to the differences between actual and forecasted traffic patterns.

An online computation is required when a network operator has to respond to network events, such as a traffic burst and network failures. To perform online computation, relatively simple and fast calculations are required to select routes, reallocate the resources and perform load balancing. Routing plans have to be adapted to changing network conditions on a timescale of hours or even minutes as they have to rapidly respond to dynamic traffic fluctuations. The general goal of the online resource optimization methods is to increase the efficient use of the existing network infrastructure. The new incoming traffic should be assigned in such a way that the possibility of accommodating further incoming traffic without congestion could be maximized. To overcome the problems with uncertainty of the traffic pattern, joint offline and online TE methods can be used together as they complement each other. In this two-step approach, offline TE provides guidelines to the algorithms developed for online traffic optimization which focus on events that are not forecasted by offline TE, adapting the routing plans to the new network conditions.

### 2.4.2 Control of the inter-domain traffic

Inter-domain TE techniques can also be divided on inbound and outbound TE techniques. The former technique is used to control inter-domain traffic entering a domain while the latter deals with the outgoing traffic. A domain may only require either inbound or outbound TE, or both, according to its business objectives. The outbound TE should be applied in case a domain contains popular content providers which generate a large amount of traffic that needs to be sent out of the network efficiently. On the other hand, in the case of domains with a large number of multimedia application receivers the inbound TE has to be performed to control traffic injected into the networks. Both inbound and outbound TE may be required by operators of transit domains as they exchange Internet traffic between each other. To perform outbound traffic engineering, three techniques are frequently applied. In the first technique BGP attribute ‘local preference’ is used. This attribute is the first criterion of the BGP decision process. By appropriate setting up of that parameter the required path toward destination through an upstream provider can be imposed. The value of that
attribute can reflect both the bandwidth of the link to the upstream provider as well as the cost of the path. A second technique, often used by large transit ISPs, tunes the intra-domain routing parameters to influence the way a packet crosses the transit ISP [34], [93]. Tuning the weights of the used intradomain routing protocol will indirectly influence the outgoing traffic of the domain. The selection of the route is limited by the diversity of routes received from upstream providers, which is determined by the connectivity and the policies of those ASes. The third technique applies explicit routing defined in Multi-Protocol Label Switching (MPLS). In the explicit routing, the route the Label Switched Path (LSP) takes is defined by the ingress node what enables a domain to enforce traffic to be delivered on the explicit paths to the desired egress points across downstream domains. Currently, some mechanisms supporting inter-domain MPLS have been proposed and implemented, such as those involving the Path Computation Element (PCE) [10], [24], [30].

2.5 Economic relations in inter-domain environment

ISPs have some costs which are rather fixed and others that depend on the usage. The cost of building a network requires some investment (a fixed cost) and, when there are no congestions, the incremental cost of adding traffic is zero. On the other hand, some ISP costs are dependent on usage, for example the traffic transit charges.

ISPs often wish to control next hop selection so as to reflect agreements or relationships they have with their neighbors. There are three major types of business relationship in the current Internet [14].

- Peering relationship: an interconnection between ISPs (typically without exchanging payment) that are in equal tiers of the hierarchy. The common reason for peering is the observation by each party that roughly equal amount of traffic is exchanged between their networks. In this type of business relationship, a pair of ASes provides transit services to the customers of each other. In case the traffic is exchanged through an exchange point, IXP operators often charge for use of the peering switch. Moreover, sometimes it is required to buy extra circuits and extra routers as well as rack space has to be rented. However, the overall cost of peering is fixed. Thus, the cost per unit traffic is inversely proportional to the amount of traffic.

- Transit relationship: an interconnection between ISPs that are in different tiers of the hierarchy. In the transit model, the purchaser has to pay to another ISP for the traffic exchange. The relationship of the transit
The arrangement is hierarchical: a provider-customer relationship. Unlike a peering relationship, a transit provider will route traffic from the transit customer to its peering partners. When purchasing the transit service, ISPs will consider other factors beside the low cost: performance of the transit provider’s backbone, location of access nodes, a number of directly connected customers, and a market position.

- Sibling relationship: an interconnection between ISPs where they set up a link between them that is to be used only in the event that the primary routes become unavailable due to a failure. The two ASes are merging ISPs or they adopt this scheme to obtain Internet connection backup.

In the peering arrangement, there is no Service Level Agreement (SLA) to guarantee rapid repair of problems. In the case of an outage, both peering partners may try to repair the problem, but it is not mandatory. This is one of the reasons why peering agreements with a company short of competent technical staff are broken. But in the transit arrangement there exists a contract and customers await that their transit provider meets the SLA.

The ISP hierarchy and types of business agreement between the ISPs are presented in Fig. 2.7. Two types of business relationships between operators were shown: transit and peering agreements.

![Figure 2.7: Types of business agreements between ISPs.](image)

In Fig. 2.8 the cost functions of transit and peering as well as the break-
even point of these two methods are presented [88]. By comparing the cost of the transit and the peering relations, an operator can choose the most suitable business agreement with the partner.

![Example cost functions of transit and peering relationships](image)

**Figure 2.8:** Example cost functions of transit and peering relationships [88].

Each AS (ISP) needs to carefully make decisions on which routes to export to its neighboring ISPs using BGP. The importance of export policies arise from the fact that no ISP wants to act as transit for packets that do not generate revenue. The business relationships influence the export policies of ASes in the Internet. According to [36] the ASes apply the following typical export policies:

- each AS exports to its providers its own routes and those it learned from its customers, but does not export to its providers the routes it learned from its peers or other providers;

- each AS exports to its customers its own routes and any routes it learned from others;

- each AS exports to its peers its own routes and those it learned from its customers, but does not export those it learned from its providers or other peers.

An operator needs to measure and charge the traffic going through its network correctly to maximize the income from the transmitted traffic, and similarly be able to correctly keep track of the payment requests and invoices, generated by other operators for the traffic they have carried.
Transit providers charge transit fees in order to recover their investments in infrastructure that make up their networks. The level of the price for transit traffic is usually calculated as a sum of the costs of running the network and the cost of transit the transit provider has bought, decreased sometimes by the cost of the traffic that is destined directly for peers and customers of the transit provider.

The transit fee can be based on a reservation made up-front for the number of Mbit/s. The traffic can either be limited to the amount reserved, or the price can be calculated afterwards.

Two main pricing schemes, namely capacity-based and usage-based models are prevalent for Internet services [67]. In the capacity-based model a price is based on the bandwidth of the customer’s connection link. The customer pays for a bandwidth configuration of the connection, but not the actual bits sent or received. The capacity-based pricing is used mainly for residential broadband Internet access services.

In the usage-based model a traffic generated by customers is the input for calculating the charges. According to [54], the following four main usage-based pricing models are currently used in the inter-domain billing for IP transit services:

- Percentile-based charging: In this model, providers monitor bandwidth usage over 5-minute intervals during each billing period, e.g., one month. At the end of the billing period the user is charged based on 95-th percentile value (the most commonly used percentile) among these measured values. Usually, a measurement of inbound and outbound bandwidth is performed and the larger value of the two probes is recorded in a log file for billing purposes. Sometimes, the difference between the average inbound and outbound traffic is also used to calculate the charge.

- Minimum commitment-based charging: In addition to the percentile-based model, in this model a customer has to commit to a minimum amount of usage which is usually billed at a flat rate per month (irrespective of the amount of bandwidth actually used). The traffic usage over that minimum commitment amount is charged as in the percentile-based model. Usually, the price for the committed bandwidth is considerably lower than the price charged for the bandwidth exceeding the minimum commitment. In practice, the greater the bandwidth commitment, the lower the unit price.

- Total-volume based charging: In this model the total volume of traffic a user generates during the entire charging period is the charging volume. The total cost of a transmission is simply calculated by multiplication of the unit price by the number of units used. The time-based charging model is a subset of the total-volume based model, where the duration of the
connection (total number of minutes in case of, e.g., voice calls) is the charging volume. This charging scheme is quite simple as the used volume is the only charging component.

- Tiered charging: In this model, a customer is charged a fixed rate per month regardless of the amount of bandwidth actually used (percentile-based model not used), but the amount of traffic volume the customer can send is limited to a certain level. The unit cost (given in e.g., $/gigabyte) changes when some thresholds are exceeded. The new cost is applied only to the amount of traffic which exceed the thresholds.

The report of TeleGeography’s IP Transit Pricing Service [95] gives the information on transit prices and their trends (see Fig. 2.9). According to the report, in Q2 2009, the median price of a fully committed Gigabit Ethernet port (1,000 Mbit/s) in major European and North American cities was approximately $10 per Mbit/s/month, after dropping approximately 20% per year for the past three years.

![Figure 2.9: Median IP transit price for Gigabit Ethernet port in selected cities.](image)

However, IP transit prices outside Europe and North America remain far higher, even in advanced markets. For example, the median price of a fully committed Gigabit Ethernet port in Q2 2009 was $31 per Mbit/s/month in Tokyo, and $40 per Mbit/s/month in Hong Kong.

Although prices are declining throughout the world, both prices and the rate of decline vary sharply. In Hong Kong, the median price for a 1,000 Mbit/s
port has declined at a compounded rate of 15% over the past five years, to $28 per Mbit/s/month. Prices have fallen more rapidly in other markets. For example, the median Gigabit Ethernet port price in New York City has fallen at a compounded annual rate of 22% between Q2 2005 and Q2 2010, to under $8 per Mbit/s/month. It means that the transit price in New York is less than one-third the price of a comparable port in Hong Kong.
This chapter presents an overview of papers related to the scope of the thesis. The survey of the literature related to general research on inter-domain traffic engineering is given in Section 3.1. The review of offline outbound TE mechanisms is given in Section 3.2. Selected papers on online outbound TE techniques are presented in Section 3.3. Papers on QoS-aware approach for inter-AS TE are discussed in Section 3.4, while papers on robust inter-AS route selection are presented in Section 3.5.
3. Related work

3.1 Inter-domain traffic engineering

With the rapid growth of Internet traffic, Internet Service Providers acknowledge that network management is important to operate their networks efficiently. In particular, ISPs attempt to control traffic routing in their networks in order to optimize the usage of their network resources. To respond to emerging problems associated with inter-domain traffic engineering some books and many papers have been published taking into account many aspects of the related problem. These aspects include a range of issues, starting from general guidelines for performing the inter-domain TE, through the mathematical modeling and optimization, to proposals of mechanisms and algorithms for solving the inter-domain TE challenges.

One of the books that cover a large spectrum of modeling and optimization methods is [76]. This is an authoritative reference on communications and computer network design through mathematical optimization-oriented modeling. The authors focus on traffic demands encountered in the real world of network design. Their generic approach, however, allows problem formulations and solutions to be applied across the board to virtually any type of backbone communications or computer network as well as to inter-domain TE problems.

In [8], a problem of optimal location of peer points for data exchange between Autonomous Systems in the Internet is described. Both the minimization of the cost of peering and improvement of the efficiency of inter-domain traffic flows were considered at the same time. To model the problem, a combinatorial optimization formulation was used.

The inter-domain routing issues from the mechanism design point of view are presented in [33]. A routing-mechanism design problem was formulated and solved by the authors. The proposed mechanism enables computing the lowest-cost routes for all source-destination pairs and payments for transit nodes on all of the routes.

The authors of [32] proposed fundamental objectives for inter-domain traffic engineering and specific guidelines for achieving these objectives within the context of BGP. Routing and traffic data from the AT&T backbone were used to demonstrate that certain BGP policy changes could move traffic in a predictable fashion, despite limited knowledge about the routing policies in neighboring ASes. The authors proposed also to relax some steps in the BGP decision process what should allow to obtain a greater flexibility for finding the optimal routes.

In [109], a model of a route selection for the inter-domain traffic engineering was investigated where routing to multiple destinations was assumed to be coordinated. In the first part, potential routing instability and inefficiency problems were identified. To overcome the emerging problems a set of practical guidelines to guarantee stability without global coordination was proposed.
A mathematical model for optimizing traffic routing in a multi-domain Internet-type network is presented in [96], [98]. In such an environment each domain is operated autonomously and has access to very limited information about the rest of the network. The proposed model attempts to reflect this situation through an appropriate problem decomposition with respect to individual domains. The usefulness of the Lagrangean and Dantzig-Wolfe decompositions is investigated and illustrated with numerical examples. The model is formulated in the context of multiple traffic classes.

A distributed scheme for optimization of inter-domain routing between collaborating domains was described in [97]. The authors presented an iterative distributed process where domains cooperatively determine a (sub)optimal, with respect to a common utility function, flow of inter-domain traffic. They also claimed that if the cooperating domains adhered to the results of the proposed process, they would reduce their operational costs, speed up operations, and increase profits.

The joint optimization of intra- and inter-autonomous system traffic engineering was proposed in [49]. The aim was to improve the overall network performance by simultaneously finding the best egress points for inter-AS traffic and the best routing scheme for intra-AS traffic. Some strategies were presented to solve the problem as well as performance evaluation of the proposed schemes were conducted.

### 3.2 Offline outbound TE techniques

A number of mechanisms are currently known for the outbound TE. The authors in [38] proposed offline optimization algorithms to distribute the traffic of a multi-homed stub domain among multiple downstream ISPs. Both monetary expenses and network performance (measured by the average latency) were optimized. A percentile-based charging model was considered to determine the cost-efficient inter-domain traffic distribution.

The authors in [100], [102] proposed a multi-objective evolutionary algorithm to solve a similar optimization problem. Similarly to [38], the charge incurred by the transit partners had to be minimized and the load balancing across the inter-domain links had to be optimized. In addition to these two objectives, the authors also considered the problem of minimizing the iBGP communication overhead to enforce the TE decisions.

An ISP subscription problem where a set of downstream ISPs had to be chosen so as to minimize the cost was introduced in [105]. To minimize the monetary expense, the optimal set of downstream ISPs from all the available candidates was determined. In the next step, the traffic was assumed to be assigned to the
chosen set of ISPs. The ISP selection problem was based on a percentile-based charging model and was solved through dynamic programming.

The authors in [48] addressed a similar ISP selection problem on top of a total-volume-based charging model. They focused on incentive-based offline inter-AS traffic engineering with end-to-end Quality of Service (QoS) guarantees. The chosen downstream ISP also had to provide end-to-end bandwidth guarantees toward the destination domains. To solve the problem a genetic algorithm was proposed.

A methodology to select the best set of upstream ISPs was also proposed in [26]. The authors proposed algorithm for selecting the best possible set of ISPs in terms of resiliency to inter-AS single-link failures. They focus also on the egress path selection problem proposing a stochastic search algorithm to allocate the network’s egress traffic between upstream ISPs. The algorithm aimed at cost minimization also ensuring that the selected paths to the major destinations of egress traffic are congestion-free.

Apart from the stub networks, a number of schemes that focus on transit domain TE issues were also proposed. The BGP TE approach proposed in [12] was the first work dealing specifically with outbound inter-domain TE for transit domains. The objective of the TE problem was to determine an optimal set of border routers for the advertisement of network prefixes. The chosen egress routers had to assure the traffic cost minimization (considered as a bandwidth consumption) while satisfying the bandwidth capacity constraints of the inter-domain links. After formulating the optimization problem in accordance with the operation of BGP, the problem was related to the Generalized Assignment Problem (GAP) [89]. To solve the problem, the authors proposed some heuristics.

The outbound inter-domain TE problem can be subdivided into two parts: single egress selection (SES) and multiple egress selection (MES) [12]. SES ensures that only one egress point is selected for each destination prefix, whereas MES allows for multiple egress points. The authors in [51] addressed a problem of selecting an egress router with the objective aiming at minimization of the total bandwidth consumption in the network satisfying the customer end-to-end bandwidth requirement at the same time.

In [16], two heuristic algorithms, combining the approximation algorithm proposed for the GAP problem with a simple greedy heuristic, were proposed to solve the SES and MES problems.

In [94] a new mechanism called TIE (Tunable Inter-domain Egress selection) was proposed. The selection of the egress point for each destination prefix is based on both the intra-domain topology and the goals of the network administrators. To demonstrate the effectiveness of the solution, two example optimization problems applying integer programming and multi-commodity flow techniques were analyzed.
In the literature, online outbound TE schemes have only focused on stub domains. They can be classified into the following two types [107]:

- Proactive: TE solutions are based on traffic predictors to forecast traffic for a short time interval (e.g., minutes) and then run a TE algorithm in a quasi-offline manner to produce solutions in a short timescale.

- Reactive: dynamic TE solutions adapt to incoming traffic demands without performing traffic prediction.

In [38], the authors proposed proactive online algorithms for multihomed domains to select appropriate ISPs for the outbound traffic. The proposed algorithms focused on minimization of the total expense and then optimization of the end-to-end latency. The exponentially weighted moving average (EWMA) method was applied to predict a short-term traffic. In the cited work, the traffic prediction was performed through detecting traffic changes based on a sequence of independent preceding observations. The proposed online TE algorithm is a greedy heuristic based on traffic sorting, which also was used for solving the bin-packing problem [37].

Another proactive online TE approach was addressed in [101]. The authors demonstrated that stub ASes can control their outbound traffic over relatively short timescales by designing a proper inter-domain traffic engineering technique. The obtained results also indicated that it is possible to apply a systematic BGP-based traffic engineering for stub ASes without a significant cost increase in terms of the number of iBGP messages.

For reactive TE mechanisms, the first work on quantifying the benefits of dynamic route selection with multihoming was proposed in [3]. The multihomed domain have subscribed to multiple downstream ISPs. To determine the end-to-end path performance through each downstream ISP toward the destination, the authors were using some measurements. Based on the performance obtained from the measurement, the domain dynamically switched the traffic to the ISP that had the best instant performance.

Based on the approach proposed in [3], the authors in [65] performed a round-trip time (RTT) measurement to select the best outbound route. They claim that the proposed approach is scalable and does not require RTT measurements via each ISP to a large number of destinations. The rationale behind this assumption is that two AS paths through two providers very often merge in the core of the Internet. Thus, the RTT difference between the two paths through the two providers can be determined taking into account a non-shared portion of the paths. Based on that finding, the authors proposed a scalable route (next-hop
provider) selection algorithm which used BGP information in a multihomed stub network.

The performance improvements resulting from a dynamic route control were presented in [2]. The authors performed measurements on the Akamai’s server network to show that multihoming to 2 or 3 ISPs can significantly improve Internet download performance. They also evaluated practical mechanisms and policies for realizing the performance benefits in practice. The results of evaluation have indicated that both active and passive measurement-based route control schemes have offered significant performance benefits when compared with using the single best-performing ISP.

3.4 QoS-aware algorithms for inter-AS TE

The authors in [50] extended outbound inter-domain TE to support end-to-end bandwidth guarantees across transit domains by establishing ISP-level service level agreements (SLAs) associated with the amount of available bandwidth [52]. To provide end-to-end bandwidth guarantees for the traffic, both an optimal egress point and the paths within the network satisfying SLAs and traffic demand requirements were determined.

The authors in [53] proposed an inter-domain TE system for provisioning end-to-end delay guarantees in the multi-provider commercial Internet taking also into account bandwidth requirements. The authors introduced an architecture describing the key functions required to support inter-domain QoS. To solve the optimization problem, a genetic algorithm for QoS-aware offline inter-domain traffic engineering was developed. Moreover, the QoS enhancements to BGP were proposed and the results of a testbed implementation were described.

In [47], the problem of provisioning end-to-end bandwidth guarantees across multiple ASes was analyzed. The authors reviewed a cascaded model for negotiating and establishing service level agreements for end-to-end bandwidth guarantees between ASes. Then, a network dimensioning system for the provisioning of end-to-end bandwidth guarantees was presented. The integer-programming problem was formulated and proved to be NP-hard. To solve the problem an efficient genetic algorithm and greedy-penalty heuristics were proposed.

A fairly large and diverse set of (network) QoS issues related to the problem of multi-period resource allocation at system edges was investigated in [42], [43]. The authors proposed a taxonomy for the classification of these problems and introduced a common mathematical framework under which these problems could be tackled. The work performed in [44] is the extension of the previously cited works of these authors. Here, they discussed and solved problems of finding the optimal set of peering and transit partners for one network operator at one point in time, given the routing information and the cost functions of the potential
peering/transit partners and the Internet exchange points. The work performed in the thesis extends the one presented in the cited paper as more optimization models and heuristics have been proposed and a non-splitting traffic approach has been applied.

3.5 Robust inter-AS route selection

Inter-domain outbound traffic engineering mechanisms presented in the previous sections aim to control traffic exiting a domain by assigning the traffic to the best egress points. However, these mechanisms have neglected the impact of inter-domain egress point failure on the achieved TE performance. The problem of resilient inter-domain traffic distribution was considered in a few papers. In [45], the authors proposed some reliability policies which enforce, e.g., the minimum number of transit partners or enough spare capacity to absorb a complete failure of one provider. The resilience related work presented in this thesis can be partly considered as the extension of the cited paper. The difference lies in the fact that the cited work considered the problem of optimizing the transit traffic with possibility of traffic flow splitting. In this thesis, on the contrary, non-splitting optimization models have been defined as well as new heuristic algorithms to find the problem solution have been proposed.

In [5] a bi-level (normal state (NS) and failure states (FS)) outbound TE problem was formulated aiming at protection of a selected outbound route to egress point failures. A tabu search heuristic to solve the problem was proposed and performance compared for the three alternative approaches. Simulation results demonstrated that the tabu search heuristic achieved the best performance in terms of our optimization objectives and also enabled to keep traffic disruption to a minimum.

A robust approach for outbound TE to manage traffic demand uncertainty through scenario-based robust optimization was considered in [46], [79]. The proposed models considered a set of inter-AS traffic matrices. The objective was to minimize the worst-case maximum inter-AS link utilization. At the same time, the performance deviation from the optimal solutions was minimized. Simulation results have shown that the robust outbound TE was capable of achieving reasonably good performance under all given traffic matrices.

The concept of multiple routing planes to enable controlled fast egress router switching for handling network failures was also proposed in [39], [106]. In case the failure occurs, backup egress routers determined in advance can be immediately activated without waiting for IGP routing re-convergence. The presented evaluation results indicated that the proposed egress router selection algorithm based on the multi-plane approach provided both high path diversity and balanced load distribution across inter-domain links with a small number of planes.
Paper [6] proposed a joint intra-domain and inter-domain robust TE approach. The model took advantage of the interaction of intra-domain and inter-domain TE techniques to achieve a good network performance under both normal state and any single intra- or inter-AS link failure. A two-phase heuristic to solve the problem was proposed and evaluated. The results have revealed that the joint TE approach enabled to achieve a higher robustness against intra- and inter-AS link failures than all other compared alternatives.

3.6 Economic issues in inter-domain area

Apart from technical aspects related to inter-domain service delivery, the economic considerations should also be taken into account when working in an inter-domain environment. The business aspects are very important (or even crucial) for establishing inter-carrier services.

The IPSphere Forum [55] proposed a framework at the service layer aiming at normalization of the processes and provision of business rules essential for the deployment of IP services in the inter-carrier context.

Paper [78] listed main economic concerns in the inter-domain context and proposed an economics-based architecture to automatically establish inter-domain services. The concept of alliance offering a common frame for collaboration between operators was explained as well as contract-based approach and customer relation issues were presented.

In [13], both technical and economic arguments for providing QoS in core and backbone networks were provided. The authors surveyed interconnection tariffs and described a commercial model that allowed incremental evolution towards the interconnected future.

The authors of [25] considered private agreements which became common for increased interconnection capacity between network operators. To examine the impact of these agreements on the Quality of Service and profits of the networks, an economy model with two networks serving the same region was proposed.

The methods for setting up transit and customer prices and QoS in a network consisting of multiple ISPs were described in [88]. The authors shown the existence of equilibrium strategies in such a situation and developed methods for achieving a positive profit using threat strategies with multiple Qualities of Service. The authors proved that if the number of ISPs competing for the same customers is large then it can lead to price wars. The economics of private exchange points and the relation between their viability and limits imposed both on the demand and cost were also considered.
Part II

LCR solution
Telecommunications industry is a very demanding market where the competition is still increasing. In such circumstances carriers and service providers wanting to operate in this market have to look for ways for increasing revenues and reducing operating costs. Due to the development of new advanced technologies, as well as the fast growth and strong expansion of the Internet, the importance of interconnection issues is still increasing. It is important especially as network carriers want to offer really global end-to-end services for their customers. To offer these services, operators build and diversify interconnect partner relationships for extending the geographical coverage \[21\]. As the number of alternatives increases, the need for developing algorithms supporting the choice of optimal routes becomes of primary importance.

The reminder of this chapter is organized as follows. Section \[4.1\] of this chapter presents a motivation for developing the LCR solution. In Section \[4.2\] the goals for providing a new tool for routing determination are listed. The network and functional models of the LCR solution are given in Sections \[4.3\] and \[4.4\] respectively.
4.1 Introduction

The multi-domain environment very often combines incumbent and virtual network operators. Due to the increase of network connectivity, operators have numerous routing alternatives. In such a scenario, service providers and operators that want to send a traffic to certain directions (destinations) outside their networks have many possibilities to choose routes offered by other connectivity providers. Since an important element of the operation budget is the interconnection cost, the critical problem is to route traffic through the cheapest routes in order to limit OpEx. Apart of the cost, a Quality of Service (QoS) and resilience parameters very often play a significant role in the total routing strategy. Moreover, frequent changes in tariff plans, which are complex and use highly granular models, are a characteristic feature of this market. Market characteristics mentioned above as well as the fast growth of voice and data traffic are the reasons that carriers pursuing efficiency can no longer rely on both slow and costly manual processes to arrange routing models, as the results of such operations are likely not to be efficient.

The telecommunications market is simply very dynamic. In order to keep up with changes, routing reconfigurations are required in shorter timeframes. On the other hand, operators would like to have the certainty that calls in their network are realized according to the lowest cost route in order to maximize their revenue. Therefore, flexibility in the provisioning and configuring systems is crucial to support both rapid service introduction and quick adjustment of routing models. Inefficiencies in implementing routing strategies can decrease carriers’ income, worsen network performance, and miss business opportunities.

4.2 Least Cost Routing (LCR) idea

The Least Cost Routing (LCR) solution, considered in this thesis, is a framework supporting an efficient distribution of inter-domain traffic. It helps to optimize connections between telecommunication operators by minimizing cost for served demands and maximizing the operator’s income, as well as an efficient use of the existing network infrastructure. Thus, to find efficient distribution of inter-domain traffic, some heuristic algorithms are proposed. The proposed heuristics can be put in three sets: algorithms with a greedy-based approach, algorithms which use the simulated annealing technique and evolutionary algorithms. By using algorithms implemented in the LCR framework the routing strategy can be efficiently executed as the traffic is sent through the most economical paths which meet imposed QoS and resilience requirements.

The goal of the cost minimization is very important, but often quality of service and resilience are also significant factors which have to be taken into
account while determining the total strategy on how to perform the routing. A higher quality and resilience will most often result in higher prices, thus there is a trade-off between the price and the quality of the potential paths through which the inter-domain traffic flows could be sent.

Apart from the cost and quality parameters, there are also some other factors that affect the solution for the LCR problem. Different operators have different charging agreements, they also offer connections to different directions. Moreover, the constraints of the physical network (e.g., the capacity constraints) are also some of the factors that have to be analyzed to find the required solution.

Using operators’ pricing lists, network configuration, and traffic history as the input, heuristic algorithms implemented in the LCR solution find automatically the efficient route configuration for the inter-domain traffic. The route configuration is executed by assigning the most suitable operator’s Points of Interconnection (egress routers) to particular traffic directions and termination points.

By using LCR functionalities, the operator receives a network configuration proposal that, when accepted by a system administrator, can be used by the management system for reconfiguring the network.

The LCR algorithm can also shorten the time needed for analysis of a large number of alternatives and helps a carrier in taking supporting decisions considering new agreements with other carriers.

We have to remember that we need credible statistical data describing the total traffic related to the period of time for which the planning is made. Nevertheless, in this thesis, we assume that such statistics are provided.

### 4.3 Network model

A general LCR connection model is presented in Fig. 4.1. A multi-domain communication network is represented by a set of Point of Interconnection (POI) nodes representing the gateways between domains and a set of abstract nodes $p = 1, 2, \ldots, P$ corresponding to a domain in the global graph, denoted here as the partners.

Each abstract node $p = 1, 2, \ldots, P$ represents a separate domain network and can be internally modelled as another directional sub-graph. An operator usually has many points in its network through which the traffic is exchanged with the interconnecting partners’ network domain.

Formally, POI can be defined as a geographical location where two networks interconnect and exchange traffic. These points (POIs) act as gateways between domains handling connections to other operators.

Some parameters are related to each POI. The capacity of POI is one of them. By the capacity in this context we mean the maximum traffic volume which can be sent through the POI during the considered time period, e.g., one month,
one day, one hour, etc. This limitation can result from technical constraints of particular locations, e.g., the interconnection link capacity. Other important factors related to the POIs and, more generally, to the interconnect partners are: charging schemes and price lists announced by partners. Different tariffs can be applied to the same POI, even for the same direction. It stems from the fact that an interconnection partner can offer some classes of service on the same directions with different prices.

The choice of routes can also be influenced by operator’s corporate priorities and preferences (not considered in the thesis). The priority means that, despite the fact that sending traffic through a particular path or to the particular destination is more expensive in comparison with other possible options, the traffic is transmitted just through that partner’s network. The described situation occurs
in the telecommunications interconnection market, as the operator enters into a privileged agreement with a particular partner. The preference means that in the case of routes with the same cost offered by different partners, the path offered by a preferred partner is chosen.

The connection model is presented from a standpoint of an operator that wants to send the traffic to selected destinations. It is assumed that the operator signed agreements with a certain number of partners $P$ that offer the possibility of terminating or transiting the traffic to some destinations. Not all interconnection partners offer the connections to all destinations. In the case of large operators, they often offer the global services, but smaller ones operate rather in narrower geographical zones. The problem to be solved by the algorithms applied for the LCR is to propose the optimal configuration of the routing paths for the whole traffic outgoing from an operator. The volume of the traffic to be carried to different directions is the main input to the developed algorithm.

### 4.4 Functional LCR model

The general functional LCR model is presented in Fig. 4.2. To determine the optimal routes, the implemented algorithms take into account multiple network-based parameters like operators’ price lists, network configuration, traffic history, etc. The most important parameter for choosing the routes is the interconnection cost (given in tariffs as the price per time/volume unit). The LCR model also enables taking into account quality of service of offered paths and their reliability parameters when calculating an optimal route.

Based on a series of reference data, the heuristic algorithms implemented in LCR find automatically the route configurations for all inter-domain traffic flows, assigning the most appropriate POIs for specific traffic directions and termination points. However, to find the solution, we need accurate statistical data describ-
ing the total traffic related to the period of time for which the planning is made. Therefore, the traffic forecasting techniques have to be used to predict the future traffic based on the traffic history. The considered model is the static one, i.e., we assume that the inter-domain traffic matrix for the considered time period is known in advance. The traffic is assumed to reach a maximum value during that period, considering possible peaks and a given network availability. The heuristic algorithms try to select the feasible paths that satisfy a set of required constraints, also achieving overall network resource efficiency. The efficient route determination is performed during an offline path computation process. The solution is presented as routing tables for all POIs in the network, along with statistical information, provided to aid the operator in the analysis of the solution. Thus, the operator obtains a network configuration table that can be manually or automatically implemented into the network control system. To establish connections along the proposed paths, the inter-domain traffic engineering techniques should be used.
The general mathematical formulation for the LCR optimization problem is based on Mixed-Integer Linear Programming (MILP). The goal of the mathematical models presented in this chapter is to find the distribution of the traffic which has to be sent to required destinations to assure the required level of path performance.

The reminder of this chapter is organized as follows. Section 5.1 presents a basic mathematical optimization model. In Section 5.2 a general description of tariffs as well as mathematical models of some types of tariffs are provided.
5. Mathematical models for LCR

5.1 Basic mathematical model

The formulation of the analyzed LCR problem is based on Mixed-Integer Linear Programming (MILP). In this model, we consider \( d \in D \) directions (each direction is related to one selected network prefix) and \( p \in P \) transit partners, each of them offering \( i \in I_p \) interfaces (here identified as egress routers). We also introduce \( e \in E \) possible timebands (i.e., time intervals with different cost unit). Each partner \( p \) offers \( t \in T_{pie} \) tariffs on its interface \( i \) within timeband \( e \). The parameter \( c_{dpiet} \) is the unit cost (transit cost per volume traffic unit of tariff \( t \) offered by partner \( p \) on interface \( i \) in timeband \( e \) to direction \( d \)). In case when direction \( d \) cannot be reached within tariff \( t \) offered by partner \( p \) on interface \( i \) in timeband \( e \), we assume that the unit cost \( c_{dpiet} \) is equal to infinity.

To determine the timebands, i.e., the periods of time with fixed price units at all considered tariffs, we have to find all time points when any partner’s tariffs change. We assume that a tariff changes if a unit cost related to that tariff changes. The change of a unit cost can result from pricing plans offered by operators where the peak-on and peak-off intervals are determined following the operators’ pricing policies. An example of a timeband determination is presented in Figure 5.1.

As the input constants, we have an aggregated traffic flow \( h_{de} \) that must be carried for direction \( d \) in timeband \( e \). Parameter \( K_{piet} \) denotes the maximum

![Figure 5.1: Example of timebands calculation](attachment:timebands.png)
amount of the traffic that can be carried on interface \( i \) within tariff \( t \) of partner \( p \) in timeband \( e \), while parameter \( Z_{pie} \) denotes the maximum amount of traffic that can be carried through interface \( i \) of partner \( p \) in timeband \( e \). The next parameter, \( L_{pe} \), indicates the limit of the overall traffic which can be sent through partner \( p \) in timeband \( e \). The presented tariff, interface or partner limits can be based on the economical reasons determined in Service Level Agreement between interconnected partners or technical features like capacities of interfaces, memory size, etc. The logical structure of the LCR connection model is presented in Figure 5.2 which shows also some variables and constraints introduced in the optimization model.

![Figure 5.2: LCR connection model: logical structure](image)

The variables and constraints of the general optimization model are given below:

**Binary variables**

\[ f_{dpie} \in \{0, 1\} \quad = 1 \text{ if a flow to direction } d \text{ going through interface } i \text{ of partner } p \text{ in timeband } e \text{ is present}; 0, \text{ otherwise}; \]
5. Mathematical models
for LCR

continuous variables
\[ x_{dpie} \geq 0 \quad \text{amount of traffic sent to direction } d \text{ by partner } p \text{ through interface } i \text{ within tariff } t \text{ in timeband } e \]
\[ g_{pie} \geq 0 \quad \text{total amount of traffic sent by partner } p \text{ through interface } i \text{ within tariff } t \text{ in timeband } e \]
\[ w_{pie} \geq 0 \quad \text{total amount of traffic sent by partner } p \text{ through interface } i \text{ in timeband } e \]
\[ v_{pe} \geq 0 \quad \text{total amount of traffic sent by partner } p \text{ in timeband } e \]

constraints
\[
\sum_p \sum_i \sum_t x_{dpie} = h_{de} \quad d \in D \quad e \in E \quad (5.1)
\]
\[
x_{dpie} \leq M f_{dpie} \quad d \in D \quad p \in P \quad i \in I_p \quad e \in E \quad t \in T_{pie} \quad (5.2)
\]
\[
\sum_p \sum_i f_{dpie} = 1 \quad d \in D \quad e \in E \quad (5.3)
\]
\[
\sum_d x_{dpie} = g_{pie} \quad p \in P \quad i \in I_p \quad e \in E \quad t \in T_{pie} \quad (5.4)
\]
\[
\sum_d \sum_t x_{dpie} = w_{pie} \quad p \in P \quad i \in I_p \quad e \in E \quad (5.5)
\]
\[
\sum_d \sum_i \sum_t x_{dpie} = v_{pe} \quad p \in P \quad e \in E \quad (5.6)
\]
\[
g_{pie} \leq K_{pie} \quad p \in P \quad i \in I_p \quad e \in E \quad t \in T_{pie} \quad (5.7)
\]
\[
w_{pie} \leq Z_{pie} \quad p \in P \quad i \in I_p \quad e \in E \quad (5.8)
\]
\[
v_{pe} \leq L_{pe} \quad p \in P \quad e \in E \quad (5.9)
\]

Each of direction demands is served by the traffic flows as required by Eq. (5.1). The inequalities given in Eq. (5.2) enforce variables \( f_{dpie} \) to be equal to 1 in case the traffic is sent through partner \( p \) and its interface \( i \) within any tariff \( t \) attached to this interface in timeband \( e \). The additional constant \( M \) is a sufficiently big number. Furthermore, the equalities given in Eq. (5.3) are necessary to assure that the whole traffic volume for the selected time period \( e \) is carried for direction \( d \) through not only one partner \( p \) but also through only one selected interface \( i \) of that partner. It means that we consider integral flow assignment, i.e., flows are non-bifurcated. It reflects the fact that due to, e.g., BGP routing requirements, only one path to each destination/prefix is considered. The amount of traffic sent within tariff \( t \), interface \( i \) and partner \( p \) are calculated according to equalities given in Eq. (5.4), Eq. (5.5) and Eq. (5.6), respectively. The introduced traffic limitations on tariffs \( t \) offered on interfaces \( i \) by partners \( p \) are met according to the inequalities described by Eqs. (5.7)-(5.9). The inequalities of such a form can also be related to the economical constraints resulting from agreement conditions. The inequalities given in Eq. (5.7) assures that the amount of the traffic that will be carried on interface \( i \) within tariff \( t \) of partner \( p \) in timeband \( e \) is lower than the maximum allowable traffic for this tariff. On the other hand,
the inequality given in Eq. (5.8) limits the maximum amount of the traffic that can be carried through interface $i$ of partner $p$ in timeband $e$, while Eq. (5.9) introduces the threshold for the maximum amount of traffic going through partner $p$ in timeband $e$. The problem of optimizing the total network cost can be formulated as follows:

$$\min F = \sum_d \sum_p \sum_i \sum_e \sum_t c_{dpiet} x_{dpiet}$$ (5.10)

### 5.2 Tariff models

A tariff defines the general structure of prices and charges, where charge is considered as the amount of money for the realized service [21]. A given tariff model is composed of two elements [90]:

- price: a monetary component associated with a unit of service;
- charging scheme: a calculation scheme, including a charging function which enables calculation of costs with reference to charging variables (e.g., time of usage, volume transferred, allocated bandwidth), and charging coefficients (e.g., price per suitable unit).

In literature, a considerable number of tariff models have been suggested for telecommunication services [71]. These models can be classified into the three groups [90]: linear tariff models, non-linear tariff models and discounts. In a linear tariff, the price per a defined unit of usage is equal for all units. The charge for a service is directly proportional to the number of used units. In the case of non-linear tariffs [40], there is no proportion between the total cost and the number of used units. Different prices can be assigned per used units. The most popular and the simplest non-linear tariff is a flat rate [68]. Under a flat pricing scheme, the user is charged a fixed amount per time, irrespective of usage.

Operators create also more sophisticated tariff models by mixing linear and non-linear tariffs. An example of such a combined model is the two-part tariff model which consists of two elements [90]: a fixed subscription fee for a certain period of time (monthly fee) and a per-unit charge. Two-part tariffs are present in interconnection domain in a number of ways. The Voice over IP (VoIP) tariffs are examples of two-part tariffs where charges are composed of a call initial charge and a per minute charge [87].

To decrease the charge for the customer, a special type of tariff model called a discount, or a global promotion, is used. In case of this model, total cost for realized service is decreased. Discounts are used together with applied tariff models and result in reduction of the total charge or decreasing the price per traffic unit when, e.g., the total traffic sent through a given operator exceeds the agreed traffic volume threshold.

Each tariff characteristic is presented in a form of two descriptions:
5. Mathematical models

(a) Unit (marginal) cost

(b) Volume cost

Figure 5.3: Cost structure in a linear tariff.

- in the first one, the unit cost is presented; if it changes on the basis of the traffic volume carried in the selected tariff, the unit cost can decrease or increase; our formulation is general and takes into consideration all possible changes;

- in the second one, the cost related to the total volume of traffic is given.

5.2.1 Linear tariff

In the linear (flat cost) tariff, the total cost is calculated as a linear function of a traffic volume. There is no initial cost. The structure of the cost related to such a simple tariff is shown in Fig. 5.3. The unit cost of the linear tariff is presented in Fig. 5.3(a) while the relation between the traffic volume and total cost is given in Fig. 5.3(b).

The number of linear tariffs offered by partner $p$ on interface $i$ within timeband $e$ depends on the operator and its pricing policy, e.g., if the unit costs for all destinations are different then the number of linear tariffs is equal to the number of destinations. Moreover, if an operator wanted to introduce some Classes of Service (CoSs) with assured QoS parameters then the unit cost probably would be higher and the number of linear tariffs would increase. On the other hand, the simplest case would be in situation when the unit costs for all destinations are the same. It means that only one linear tariff would be offered by partner $p$ on interface $i$ within timeband $e$.

**additional indices**

$t^l \in T_{pie}$ linear tariff ($l \in L$) of partner $p$ on interface $i$ within timeband $e$;

**additional constants**
5.2 Tariff models

\( c_{dpiet} \) marginal cost of traffic unit transfer in the linear tariff \( t^l \in T^{L}_{pie} \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \)

\( K^l_{piet} \) maximum amount of traffic which can be sent in the linear tariff \( t^l \in T^{L}_{pie} \) by partner \( p \) through interface \( i \) within timeband \( e \)

**additional continuous variables**

\( x^l_{dpiet} \) amount of traffic sent in the linear tariff \( t^l \in T^{L}_{pie} \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \)

\( g^l_{piet} \) amount of traffic sent in the linear tariff \( t^l \in T^{L}_{pie} \) by partner \( p \) through interface \( i \) within timeband \( e \)

\( \gamma^l_{piet} \geq 0 \) total cost input related to tariff \( t^l \in T^{L}_{pie} \) offered by partner \( p \) on interface \( i \) within timeband \( e \)

**additional constraints**

\[
\sum_d x^l_{dpiet} = g^l_{piet} \quad p \in P \quad i \in I_p \quad t^l \in T^{L}_{pie} \quad e \in E
\] (5.11)

\[
g^l_{piet} \leq K^l_{piet} \quad p \in P \quad i \in I_p \quad t^l \in T^{L}_{pie} \quad e \in E
\] (5.12)

\[
\sum_d c^l_{dpiet} x^l_{dpiet} = \gamma^l_{piet} \quad p \in P \quad i \in I_p \quad t^l \in T^{L}_{pie} \quad e \in E
\] (5.13)

The amount of traffic sent within tariff \( t^l \) through interface \( i \) by partner \( p \) in timeband \( e \) is calculated according to equalities given in Eq. (5.11). The inequalities given in Eq. (5.12) limit the maximum amount of the traffic that can be carried through tariff \( t^l \) through interface \( i \) of partner \( p \) in timeband \( e \). Equalities given in Eq. (5.13) sum up the cost of traffic sent to all directions \( d \) within tariff \( t^l \) through interface \( i \) by partner \( p \) in timeband \( e \).

5.2.2 Tariff with opening cost

A tariff with an opening cost (Fig. 5.4) is similar to the linear tariff described above, but involves an opening fee \( (v^b_{pit}) \) which has to be paid while using the tariff. The unit cost of the tariff with opening cost \( c^b_{dpiet} \) is presented in Fig. 5.4(a) while the relation between the traffic volume and total cost is given in Fig. 5.4(b). The opening cost of the considered tariff can be averaged over all timebands \( e \in E \). Taking into account this assumption, the adjusted opening cost could be written down as \( v^b_{pit}/|E| \) where \( |E| \) denotes the cardinality of the set \( E \), i.e., the number of timebands in the considered time interval.
5. Mathematical models for LCR

The marginal cost is analogously flat \( c^b_{driet} \) with no steps. Such a tariff can also represent a lump sum tariff if a marginal cost equals 0 \( (c^b_{driet} = 0) \). The mathematical model of the considered tariff is proposed below:

**additional indices**

\[ t^b \in T^B_{tie} \]  

tariff with opening cost \( (b \in B) \) of partner \( p \) on interface \( i \) within timeband \( e \)

**additional constants**

\[ v^b_{pit} > 0 \]  

opening cost of tariff \( t^b \) offered by partner \( p \) on interface \( i \)

\[ c^b_{driet} \geq 0 \]  
marginal cost of traffic unit transfer in the tariff with the opening cost \( t^b \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \)

\[ K^b_{tie} \]  

maximum amount of traffic which is permitted to be sent in the tariff with opening cost \( t^b \) by partner \( p \) through interface \( i \) within timeband \( e \)

**additional continuous variables**

\[ x^b_{driet} \]  

amount of traffic sent in the tariff with the opening cost \( t^b \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \)

\[ g^b_{tie} \]  

amount of traffic sent in the tariff with the opening cost \( t^b \) by partner \( p \) through interface \( i \) within timeband \( e \)

\[ \gamma^b_{tie} \geq 0 \]  

total cost input related to tariff \( t^b \) on interface \( i \) offered by partner \( p \) in timeband \( e \)

**additional binary variables**

\[ b^b_{pit} \in \{0, 1\} \]  

= 1 if traffic is sent through tariff \( t^b \) offered by partner \( p \) on interface \( i \); 0, otherwise

*Figure 5.4: Cost structure in a tariff with opening cost.*
5.2 Tariff models

additional constraints

\[
\sum_d x_{dpiet}^b = g_{piet}^b \\
\sum_e g_{piet}^b \leq \sum_e K_{piet}^b b_{pit}^b \\
g_{piet}^b \leq K_{piet}^b \\
\frac{v_{piet}^b b_{pit}^b}{|E|} + \sum_d c_{dpiet}^b x_{dpiet}^b = \gamma_{piet}^b
\]

(5.14) \quad (5.15) \quad (5.16) \quad (5.17)

The amount of traffic sent within tariff \( t_b \) through interface \( i \) by partner \( p \) in timeband \( e \) is calculated according to equalities given in Eq. (5.14). The constraint given in Eq. (5.15) is responsible for the fact that \( b_{pit}^b \) is set to 1 if any \( x_{dpiet}^b > 0 \). Otherwise, it is set to 0, as such a case is permitted by these constraints and the optimum solution strives for the minimal value and from such a standpoint \( b_{pit}^b = 0 \) is a better value. The inequality given in Eq. (5.16) limits the maximum amount of the traffic that can be carried through tariff \( t_b \) through interface \( i \) of partner \( p \) in timeband \( e \). The equation given in Eq. (5.17) sums up the cost of traffic sent to all directions \( d \) within tariff \( t_b \) through interface \( i \) by partner \( p \) in timeband \( e \).

5.2.3 Step tariff

When a step tariff (Fig. 5.5) is taken into account, the marginal cost changes when some traffic volume thresholds are exceeded. The new cost is related only to the amount of traffic which exceeds the threshold. The unit cost of the step tariff is presented in Fig. 5.5(a) while the relation between the traffic volume and total cost is given in Fig. 5.5(b).

additional indices

\( t^s \in T_{pie}^S \)  \quad \text{tariff with step marginal cost offered by partner} \ p \ \text{on interface} \ i \ \text{within timeband} \ e

\( n \in N_{piet}^s \)  \quad \text{number of different marginal costs in step tariff} \ t^s \ \text{offered by partner} \ p \ \text{on interface} \ i \ \text{in timeband} \ e \ (\text{there are} \ N_{piet}^s \ - \ 1 \ \text{thresholds in such a tariff})
additional constants

- \( s_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}}} > s_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}-1}} \)  
  \( n \in N_{p_{i_{e_{t}}}^{S}} - 1 \) traffic volume threshold in step tariff \( t^{s} \) of partner \( p \) on interface \( i \) in timeband \( e \)
- \( s_{p_{i_{e_{t}}}^{0}} = 0 \)  
  auxiliary constant
- \( c_{d_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}}}} \geq 0 \)  
  marginal cost of the traffic unit in the range \( (n-1; n] \) in step tariff \( t^{s} \) to direction \( d \) through partner \( p \) on interface \( i \) in timeband \( e \)
- \( v_{p_{i_{e_{t}}}^{0}} = 1 \)  
  auxiliary constant
- \( K_{p_{i_{e_{t}}}^{s}} \)  
  maximum amount of traffic which is allowable to send in the step tariff \( t^{s} \) by partner \( p \) through interface \( i \) within timeband \( e \)

additional continuous variables

- \( y_{d_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}}}^{n_{i_{e_{t}}}}} \geq 0 \)  
  auxiliary variable related to the amount of traffic sent within \( n \)th traffic volume threshold in the total volume tariff \( t^{s} \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \)
- \( x_{d_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}}}^{s}} \geq 0 \)  
  amount of traffic sent in the step tariff \( t^{s} \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \)
- \( g_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}}} \geq 0 \)  
  amount of traffic carried by partner \( p \) through interface \( i \) in tariff \( t^{s} \) within timeband \( e \) within \( n \)th traffic volume threshold
- \( g_{p_{i_{e_{t}}}^{s}} \geq 0 \)  
  total amount of traffic sent in the step tariff \( t^{s} \) by partner \( p \) through interface \( i \) within timeband \( e \)
- \( g_{p_{i_{e_{t}}}^{s}} \geq 0 \)  
  total cost input related to tariff \( t^{s} \) of partner \( p \) on interface \( i \) in timeband \( e \)

additional binary variables

- \( v_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}}} \in \{0, 1\} = 1 \) if \( g_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}}} > s_{p_{i_{e_{t}}}^{n_{i_{e_{t}}}}} \) \( (t^{s} \in T_{p_{i_{e_{t}}}^{S}}) \); 0, otherwise; \( n \in N_{p_{i_{e_{t}}}^{S}} - 1 \)
additional constraints

\[ \sum_n y_{dpiet}^{s_n} = x_{dpiet}^{s_n} \quad d \in D \quad p \in P \quad i \in I_p \quad t^s \in T_{pie}^S \]

\[ e \in E \quad n \in N_{priet}^s - 1 \] (5.18)

\[ \sum_d y_{dpiet}^{s_n} = g_{priet}^{s_n} \quad p \in P \quad i \in I_p \quad t^s \in T_{pie}^S \]

\[ e \in E \] (5.19)

\[ \sum_n g_{priet}^{s_n} = g_{priet}^{s_n} \quad p \in P \quad i \in I_p \quad t^s \in T_{pie}^S \]

\[ e \in E \] (5.20)

\[ g_{priet}^{s_n} - s_{priet}^{s_n} \leq K_{priet}^{s_n} u_{priet}^{s_n} \quad p \in P \quad i \in I_p \quad t^s \in T_{pie}^S \]

\[ e \in E \quad n \in N_{priet}^s - 1 \] (5.21)

\[ g_{priet}^{s_n} - g_{priet}^{s_n} \leq K_{priet}^{s_n} (1 - u_{priet}^{s_n}) \quad p \in P \quad i \in I_p \quad t^s \in T_{pie}^S \]

\[ e \in E \quad n \in N_{priet}^s - 1 \] (5.22)

\[ (s_{priet}^{n} - s_{priet}^{n-1}) u_{priet}^{n-1} \leq g_{priet}^{s_n} \quad p \in P \quad i \in I_p \quad t^s \in T_{pie}^S \]

\[ e \in E \quad n \in N_{priet}^s - 1 \] (5.23)

\[ g_{priet}^{s_n} \leq (s_{priet}^{n} - s_{priet}^{n-1}) u_{priet}^{n-1} \quad p \in P \quad i \in I_p \quad t^s \in T_{pie}^S \]

\[ e \in E \quad n \in N_{priet}^s - 1 \] (5.24)

\[ \sum_d \sum_n c_{dpiet}^{s_n} y_{dpiet}^{s_n} = \gamma_{priet}^{s_n} \quad p \in P \quad i \in I_p \quad t^s \in T_{pie}^S \]

\[ e \in E \] (5.25)

The equality given by Eq. (5.18) sums up the traffic sent in all traffic thresholds used in the step tariff \( t^s \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \). Due to the equation Eq. (5.19), all the traffic going to all directions \( d \) by partner \( p \) through interface \( i \) within timeband \( e \) within \( n \)th traffic volume threshold in the step tariff \( t^s \) is summed up. On the other hand, the summation of all the traffic going to all directions by partner \( p \) through interface \( i \) within timeband \( e \) within all \( n \) traffic volume thresholds in the step tariff \( t^s \) is assured according to Eq. (5.20). Both groups of constraints given by Eqs. (5.21)-(5.22) are responsible for the fact that \( u_{priet}^{s_n} \) is set to 1 if \( g_{priet}^{s_n} > s_{priet}^{s_n} \) and otherwise \( u_{priet}^{s_n} \) is set to 0. We are interested in such a partitioning in which if \( g_{priet}^{s_n} = s_{priet}^k + \varepsilon < s_{priet}^{k+1}, k < n \), then: \( g_{priet}^{s_i} = s_{priet}^i, i < k \) and \( g_{priet}^{s_k} = \varepsilon \); see Eqs. (5.23-5.24). The total cost calculation in the considered step tariff \( t^s \in T_{pie}^S \) is given in Eq. (5.25).

5.2.4 Total volume tariff

The total volume traffic tariff (Fig. 5.6) is similar to the step tariff in this sense that the marginal costs change when thresholds are exceeded. The difference lays
in the fact that for the whole amount of traffic carried in such a tariff only one unit cost is used at once, i.e., the cost related to the highest exceeded threshold. The unit cost of the total volume tariff is presented in Fig. 5.6(a) while the relation between the traffic volume and total cost is given in Fig. 5.6(b).

Figure 5.6: Cost structure in a total volume tariff.

**additional indices**

- $t^v \in T^V_{vpt}$ total volume tariff offered by partner $p$ on interface $i$ in timeband $e$
- $n \in N^v_{vpt}$ number of different marginal costs in volume tariff $t^v$ of partner $p$ (there are $N^v_{vpt} - 1$ thresholds in such a tariff)

**additional constants**

- $q^v_{vpt} > q^{n-1}_{vpt}$ $n$th ($n \in N^v_{vpt} - 1$) threshold in volume tariff $t^v$ of partner $p$ on interface $e$ in timeband $e$
- $c^v_{dpt} \geq 0$ marginal cost of the traffic to direction $d$ if the whole amount of traffic sent through partner $p$ on interface $i$ in timeband $e$ exceeds threshold $q^n_{vpt}$ in volume tariff $t^v$
- $u^n_{vpt} = 0$ auxiliary constant
- $K^v_{vpt}$ maximum amount of traffic which is allowable to send in the total tariff $t^v$ by partner $p$ through interface $i$ within timeband $e$

**additional continuous variables**

- $y^n_{dpt} \geq 0$ auxiliary variable related to the amount of traffic sent within $n$th traffic volume threshold in the total volume tariff $t^v$ to direction $d$ by partner $p$ through interface $i$ within timeband $e$
5.2 Tariff models

\[ x_{v_{dpiet}} \geq 0 \]
amount of traffic sent in the total volume tariff \( t^v \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \)

\[ g_{v_{priet}} \geq 0 \]
amount of traffic carried by partner \( p \) on interface \( i \) within tariff \( t^v \) within \( n \)th traffic volume threshold

\[ g_{v_{priet}} \geq 0 \]
total amount of traffic sent in the volume tariff \( t^v \) by partner \( p \) through interface \( i \) within timeband \( e \)

\[ \gamma_{v_{priet}} \geq 0 \]
total cost of the traffic sent within tariff \( t^v \) of partner \( p \) on interface \( i \) in timeband \( e \)

additional binary variables

\[ w_{v_{priet}}^n \in \{0, 1\} = 1 \text{ if } g_{v_{priet}}^n > q_{v_{priet}}^n (t^v \in T_v^{V_{pie}}); 0, \text{ otherwise}; n \in N_{v_{priet}} - 1 \]

additional constraints

\[ \sum_n y_{v_{dpiet}} = x_{v_{dpiet}} \]
\[ d \in D \quad p \in P \quad i \in I_p \quad t^v \in T_v^{V_{pie}} \]
\[ e \in E \quad n \in N_{v_{priet}} - 1 \] (5.26)

\[ \sum_d y_{v_{dpiet}} = g_{v_{priet}} \]
\[ p \in P \quad i \in I_p \quad t^v \in T_v^{V_{pie}} \]
\[ e \in E \] (5.27)

\[ \sum_n g_{v_{priet}} = g_{v_{priet}} \]
\[ p \in P \quad i \in I_p \quad t^v \in T_v^{V_{pie}} \]
\[ n \in N_{v_{priet}} - 1 \quad e \in E \] (5.28)

\[ g_{v_{priet}} - q_{v_{priet}}^n \leq K_{priet} w_{v_{priet}}^n \]
\[ p \in P \quad i \in I_p \quad t^v \in T_v^{V_{pie}} \]
\[ e \in E \quad n \in N_{v_{priet}} - 1 \] (5.29)

\[ q_{v_{priet}} - g_{v_{priet}} \leq K_{priet} (1 - w_{v_{priet}}^n) \]
\[ p \in P \quad i \in I_p \quad t^v \in T_v^{V_{pie}} \]
\[ e \in E \quad n \in N_{v_{priet}} - 1 \] (5.30)

\[ g_{v_{priet}} \leq K_{priet} (w_{v_{priet}}^n - w_{v_{priet}}^{n+1}) \]
\[ p \in P \quad i \in I_p \quad t^v \in T_v^{V_{pie}} \]
\[ e \in E \quad n \in N_{v_{priet}} - 1 \] (5.31)

\[ \sum_n \sum_d c_{d_{rouet}} x_{v_{priet}} \gamma_{v_{priet}} = \gamma_{v_{priet}} \]
\[ p \in P \quad i \in I_p \quad t^v \in T_v^{V_{pie}} \]
\[ e \in E \] (5.32)

The equality given by Eq. (5.26) sums up the traffic sent in all traffic thresholds used in the total volume tariff \( t^v \) to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \). Due to Eq. (5.27), the whole traffic going to all directions \( d \) by partner \( p \) through interface \( i \) within timeband \( e \) within \( n \)th traffic volume threshold in total volume tariff \( t^v \) is summed up. On the other hand, the summation of the whole traffic going to direction \( d \) by partner \( p \) through interface \( i \) within timeband \( e \) within all \( n \) traffic volume thresholds in total volume tariff \( t^v \) is assured. Both groups of constraints given by Eqs. (5.29)-(5.30) are responsible for the fact that \( w_{v_{priet}}^n \) is set to 1 if \( g_{v_{priet}}^n > q_{v_{priet}}^n \) and otherwise it is set to
0. Equality Eq. (5.31) assures that the total amount of traffic going by partner $p$ through interface $i$ within timeband $e$ within total volume tariff $t^v$ does not violate the tariff $t^v$ traffic limit. The overall cost calculation in the considered total volume tariff $t^v \in T^V_{pie}$ is given in Eq. (5.32).

5.2.5 Global promotion

The sense of a global promotion is related to an offer made by a partner which wants to encourage its clients to carry as much traffic as possible to different directions through its network. Thus, it proposes to reduce the cost if the total traffic sent by its premises exceeds a selected threshold value.

**additional constants**
- $m_p$ percentage by which the total cost related to the whole traffic carried by partner $p$ is reduced
- $W_p$ threshold value related to the amount of the traffic sent through all tariffs offered by partner $p$; when it is exceeded the cost decreases by $m_p\%$
- $M$ very large number

**additional continuous variables**
- $\gamma_{piet} \geq 0$ cost of the traffic transferred by partner $p$ through interface $i$ within tariff $t$ within timeband $e$
- $\phi_p \geq 0$ auxiliary variable related to the cost of the traffic transferred by partner $p$ used if threshold $W_p$ is not exceeded
- $\varphi_p \geq 0$ auxiliary variable related to the cost of the traffic transferred by partner $p$ used if threshold $W_p$ is exceeded

**additional binary variables**
- $r_p \in \{0, 1\}$ $= 1$ if the whole amount of the traffic carried by partner $p$ is larger than threshold $W_p$; 0, otherwise

**additional constraints**

\[
\begin{align*}
\sum_e v_{pe} - W_p & \leq \sum_e L_{pe} r_p & p \in P & \quad (5.33) \\
W_p - \sum_e v_{pe} & \leq \sum_e L_{pe} (1 - r_p) & p \in P & \quad (5.34) \\
\phi_p + \varphi_p & = \sum_i \sum_e \sum_t \gamma_{piet} & p \in P & \quad (5.35) \\
\phi_p & \leq M (1 - r_p) & p \in P & \quad (5.36) \\
\varphi_p & \leq Mr_p & p \in P & \quad (5.37) \\
\phi_p + \frac{100-m}{100} \varphi_p & = \delta_p & p \in P & \quad (5.38)
\end{align*}
\]
5.2 Tariff models

5.2.6 Tariff models: comment

Generally, we must remember that the following set of general equations related to indices is expressed as follows:

\[ \forall_{pie} T_{pie} = T_{pie}^L \cup T_{pie}^B \cup T_{pie}^S \cup T_{pie}^V \quad (5.39) \]

Obviously, different tariffs can be further combined (e.g., the step tariff with the tariff using the opening cost) or complicated (e.g., in a global tariff, only a subset of minutes is taken into account or the structure of the global tariff is step-based, etc.). We present quite simple and commonly used tariffs.

The general optimization model has been developed assuming that only one type of tariff is used on interface \(i\) of partner \(p\) in timeband \(e\). In case the mix of tariffs is used, some new variables and constraints have to be introduced:

**additional continuous variables**

\[ w_{pie}^L \geq 0 \quad \text{variable related to the amount of the traffic transferred by partner } p \text{ through interface } i \text{ within all linear tariffs } T_{pie}^L \text{ in timeband } e \]

\[ w_{pie}^B \geq 0 \quad \text{variable related to the amount of the traffic transferred by partner } p \text{ through interface } i \text{ within all tariffs with opening cost } T_{pie}^B \text{ in timeband } e \]

\[ w_{pie}^S \geq 0 \quad \text{variable related to the amount of the traffic transferred by partner } p \text{ through interface } i \text{ within all step tariffs } T_{pie}^S \text{ in timeband } e \]

\[ w_{pie}^V \geq 0 \quad \text{variable related to the amount of the traffic transferred by partner } p \text{ through interface } i \text{ within all total volume tariffs } T_{pie}^V \text{ in timeband } e \]

**additional constraints**

\[ \sum_{t} g_{piet}^L = w_{pie}^L \quad p \in P \quad i \in I_p \quad e \in E \quad (5.40) \]

\[ \sum_{t} g_{piet}^B = w_{pie}^B \quad p \in P \quad i \in I_p \quad e \in E \quad (5.41) \]

\[ \sum_{t} g_{piet}^S = w_{pie}^S \quad p \in P \quad i \in I_p \quad e \in E \quad (5.42) \]

\[ \sum_{t} g_{piet}^V = w_{pie}^V \quad p \in P \quad i \in I_p \quad e \in E \quad (5.43) \]

\[ w_{pie} = w_{pie}^L + w_{pie}^B + w_{pie}^S + w_{pie}^V \quad p \in P \quad i \in I_p \quad e \in E \quad (5.44) \]

The equalities given by Eqs. (5.40)-(5.43) sum up the traffic sent by partner \(p\) on interface \(i\) in timeband \(e\) within all linear tariffs, all tariffs with opening cost, all step tariffs and all total volume tariffs, respectively. The traffic sent in all tariffs used by partner \(p\) on interface \(i\) within timeband \(e\) is summed up according to the equality given by Eq. (5.44).
The formulation of the LCR problem is based on Mixed-Integer Linear Programming (MILP). The problem involves selecting a single egress link for traffic flows to every advertised prefix such that the total cost of carrying transit traffic is minimized. In the general case, the solution of such a problem could be very hard, especially if the number of involved discrete (binary) variables is large. The single egress selection problem has been proven to be NP-hard [12] by reducing it to the Generalized Assignment Problem (GAP) [89], which is itself NP-hard. Hence, to find the problem solution, some heuristic algorithms have been proposed.

The reminder of this chapter is organized as follows. Section 6.1 of this chapter presents an overview of greedy heuristic algorithms which try to minimize the overall cost of the transit traffic. In Section 6.2, heuristic algorithms based on the simulated annealing idea are described. Genetic algorithms for solving the LCR problem are given in Section 6.3. All sections consist of the scenario assumptions and performance evaluation of the proposed optimization heuristics as well as a short summary.
6. Mechanisms for inter-domain traffic distribution

6.1 Greedy heuristic methods

The section presents the greedy heuristic algorithms. After describing the operation of the developed heuristics the relevant assumptions and results of the performance evaluation are given.

6.1.1 Proposed algorithms

Greedy heuristic algorithms take into account the cost and available bandwidth on the inter-domain links. The traffic flows can be sorted according to the volume of the traffic flows and then assigned to feasible paths (partners and interfaces). While deciding on the traffic flow assignments the tariffs and unit costs related to these paths are considered.

Random assignment algorithm (RA)

In the random assignment algorithm RA, each of the aggregated traffic flows is randomly assigned to one of the feasible interfaces, i.e., interfaces that service the required destination and have enough spare capacity to support the flow. Neither the tariff cost nor the volume of traffic flows are taken into account here.

Greedy-cost descending algorithm (GCD)

The greedy-cost descending algorithm GCD takes into account the volume of the traffic flows while ordering traffic flows for allocating to the egress routers. In the greedy-cost algorithm GCD the following steps are performed:

- **Step 1**: The input data for the algorithm, such as the POIs configuration, connection scheme and the volume of the traffic flows and their destinations are determined.

- **Step 2**: All feasible interfaces and tariffs for the just considered traffic flow are identified by checking their ability to support the traffic flow.

- **Step 3**: The traffic flows are sorted in the descending order, based on the amount of the traffic for sending on required directions.

- **Step 4**: The assignment of the traffic flows starts from the traffic flow with the highest volume.

- **Step 5**: The interface with the minimum cost (unit price per volume) is selected from the set of feasible interfaces determined in Step 2 and the traffic flow is assigned to it.
• **Step 6**: After assigning the traffic flow to a feasible interface, the available bandwidth for the next flow is updated. The tariff, interface and partner limits are also decreased accordingly.

• **Step 7**: The next traffic flow is selected; **Steps 2-5** are repeated, until all traffic flows have been considered.

• **Step 8**: The cost of the inter-domain traffic flow distribution is calculated based on the performed assignment.

**Greedy-cost ascending algorithm (GCA)**

The greedy-cost ascending algorithm GCA is similar to the GCD algorithm. The difference is in the sorting operation. The traffic flows are sorted in the ascending order, based on the amount of the traffic for sending on required directions. The assignment of the traffic flows starts from the traffic flow with the lowest volume.

**Greedy-random algorithm (GCR)**

The greedy-cost random algorithm GCR is similar to the GCD algorithm. The difference is in the sorting operation. Instead of considering the volume of traffic flows in the assignment process like in the GCD heuristic the flows are chosen randomly by the GR algorithm for assignment process. The volumes of the traffic flows are not taken into account while deciding on the order of an assignment.

**Prioritized greedy-cost descending algorithm (PGCD)**

The prioritized greedy-cost descending algorithm algorithm PGCD is similar to the GCD heuristic. The PGCD algorithm extends the GCD heuristic by introducing the possibility of traffic flow reallocation in case the capacity limit for the just serviced traffic flow has been already exhausted. While comparing the algorithms the following additional step is performed in the PGCD heuristic after step **Step 5** of the GCD heuristic:

• **Step 6**: If the limit of the traffic for a partner or interface for the just serviced traffic flow is exceeded, the previous traffic allocation is cancelled except for the traffic allocations to priority destinations and the traffic flow is served as the first from the non-priority flows; the destination is assumed to be the priority one if the traffic flow previously allocated to the interface has been already reallocated.
Prioritized greedy-cost ascending algorithm (PGCA)

The prioritized greedy-cost ascending algorithm (PGCA) is similar to the GCA heuristic. The PGCA algorithm extends the GCA heuristic by introducing the possibility of traffic flow reallocation in case the capacity limit for the just serviced traffic flow has been already exhausted. While comparing the algorithms, the additional step is performed in the PGCA heuristic, the same as step Step 6 of the PGCD heuristic.

Lowest available bandwidth algorithm (LAB)

The lowest available bandwidth algorithm (LAB) takes into account the relation between the volume of the traffic flow and the available bandwidth of the feasible interfaces. The following steps are performed in the LAB heuristic:

- **Step 1**: The input data for the algorithm, such as the POIs configuration, connection scheme and the volume of the traffic flows and their destinations are determined.

- **Step 2**: Based on the data from Step 1, all feasible interfaces for the just considered traffic flow are identified by checking their ability to support the traffic flow.

- **Step 3**: The traffic flows are sorted based on the difference between the sum of capacities of all the feasible interfaces and the amount of traffic to be sent to the given destination.

- **Step 4**: The traffic flow allocation starts from the traffic flow for which the difference calculated in Step 3 is the lowest.

- **Step 5**: The interface with the lowest offered unit cost for the considered destination is selected from the set of feasible interfaces determined in Step 2 and traffic flow is assigned to it.

- **Step 6**: After assigning a traffic flow to a feasible interface, the available bandwidth for the next flow is updated. The tariff, interface and partner limits are also decreased accordingly.

- **Step 7**: The next traffic flow is selected; Steps 2–7 are repeated, until all traffic flows have been considered.

- **Step 8**: The cost of the inter-domain traffic flow distribution is calculated based on the performed assignment.
6.1 Greedy heuristic methods

Prioritized lowest available bandwidth algorithm (PLAB)

The prioritized lowest available bandwidth algorithm PLAB is similar to the LAB heuristic. The PLAB algorithm extends the LAB heuristic by introducing the possibility of traffic reallocation in case the capacity limit for the just serviced traffic flow has been already exhausted. The following steps are performed in the PLAB heuristic after step Step 5 of the LAB heuristic:

- **Step 6**: If the limit of the traffic for a partner or interface for the just serviced traffic flow is exceeded, the previous traffic allocation is cancelled except for the traffic allocations to priority destinations and the traffic flow is served as the first from the non-priority flows; the destination is assumed to be the priority one if the traffic flow previously allocated to the destination has been already reallocated.

Random mix (RMIX)

Random mix algorithm RMIX is based on both the GCD and the GCR algorithms. In this algorithm a fixed number of random traffic flow allocations (see the GCR algorithm) for \( d \) biggest traffic flows (see the GCD algorithm) is performed. At the end, the cheapest traffic flow distribution is chosen. The following steps are performed in the RMIX heuristic:

- **Step 1**: The input data for the algorithm, such as the POIs configuration, connection scheme and the volume of the traffic flows and their destinations are determined.

- **Step 2**: Based on the data from Step 1, all feasible interfaces for the just considered traffic flow are identified by checking their ability to support the traffic flow.

- **Step 3**: The traffic flows are sorted in the descending order, based on the amount of the traffic for sending on required directions.

- **Step 4**: The \( d \) biggest traffic flows are chosen from the ordered list determined in Step 3. The traffic flow allocation starts from the biggest traffic flow.

- **Step 5**: The interface with the lowest offered unit cost for the considered destination is selected from the set of feasible interfaces determined in Step 2 and traffic flow is assigned to it.

- **Step 6**: After assigning a traffic flow to a feasible interface, the available bandwidth for the next flow is updated. The tariff, interface and partner limits are also decreased accordingly.
6. Mechanisms for inter-domain traffic distribution

- **Step 7**: The next traffic flow is selected from the traffic flows; Steps 5–7 are repeated, until all traffic flows have been considered; at the end the cost of assigned traffic flows is calculated.

- **Step 8**: The random list of traffic flows for the assignment process is determined for \( d \) biggest traffic flows determined in Step 3; Steps 5–7 are repeated, until all traffic flows have been considered.

- **Step 9**: Step 8 is repeated \( n - 1 \) times; at the end the cheapest cost among the \( n \) runs is determined and the related assignment of the traffic flows is chosen.

- **Step 10**: The traffic flows not considered so far in the assignment process (see Step 4) are allocated to the feasible interfaces according to the GCD algorithm.

- **Step 11**: The total cost based on the assignment of all the traffic flows is calculated.

**Random mix full algorithm (RMIXF)**

The random mix full algorithm RMIXF is similar to the RMIX heuristic. The difference is in the number of the traffic flows chosen for creating the list for the allocation process. Instead of \( d \) biggest traffic flows, the RMIXF takes into account all traffic flows while preparing the random list for the allocation process.

**Weighted direction algorithm (WDIR)**

The weighted direction algorithm WDIR calculates the weights for the directions and related traffic flows. The following steps are performed in the WDIR heuristic:

- **Step 1**: The input data for the algorithm, such as the POIs configuration, connection scheme and the volume of the traffic flows and their destinations are determined.

- **Step 2**: Based on the data from Step 1, all feasible interfaces for the just considered traffic flow are identified by checking their ability to support the traffic flow.

- **Step 3**: The weight for each direction and related traffic flow is calculated. To compute that weight the volume of the traffic flow which has to be send to a given direction is multiplied by the sum of the unit costs of the cheapest and the second cheapest feasible interfaces. The unit costs of the considered interfaces are taken with different factors.
• **Step 4**: The traffic flows are sorted in the descending order based on the weights computed in **Step 3**; the traffic flow allocation starts from the traffic flow for which the weight is the biggest.

• **Step 5**: The interface with the lowest offered unit cost for the considered destination is selected from the set of feasible interfaces determined in **Step 2** and traffic flow is assigned to it.

• **Step 6**: After assigning a traffic flow to a feasible interface, the available bandwidth for the next flow is updated. The tariff, interface and partner limits are also decreased accordingly.

• **Step 7**: The next traffic flow is selected; **Steps 5–6** are repeated, until all traffic flows have been considered.

• **Step 8**: The cost of the inter-domain traffic flow distribution is calculated based on the performed assignment.

**Maximum traffic for interface algorithm (MAXINT)**

The maximum traffic for interface algorithm MAXINT calculates the weights for the interfaces. The following steps are performed in the MAXINT heuristic:

• **Step 1**: The input data for the algorithm, such as the POIs configuration, connection scheme and the volume of the traffic flows and their destinations are determined.

• **Step 2**: Based on the data from **Step 1**, all feasible interfaces for the just considered traffic flow are identified by checking their ability to support the traffic flow.

• **Step 3**: The weights for all interfaces are calculated. To compute the weight for an interface the maximal potential amount of the traffic volume which can be send through that interface is determined. In the next step the summed up amount of the traffic is decreased by the the capacity limit for the considered interface. The resulting traffic volume is multiplied by the unit cost of the interface (only one tariff is assumed per interface).

• **Step 4**: The interfaces are sorted in the descending order based on the weights computed in **Step 3**; the traffic flow allocation starts from the biggest traffic flow going through the interface for which the biggest weight was obtained.

• **Step 5**: The interface with the lowest offered unit cost for the considered destination is selected from the set of feasible interfaces determined in **Step 2** and traffic flow is assigned to it.
• *Step 6:* After assigning a traffic flow to the cheapest feasible interface, the available bandwidth for the next flow is updated. The tariff, interface and partner limits are also decreased accordingly.

• *Step 7:* The weights of the interfaces are recomputed according to the rule given in *Step 3.*

• *Step 8:* *Steps 4–7* are repeated, until all traffic flows have been considered.

• *Step 9:* The cost of the inter-domain traffic flow distribution is calculated based on the performed assignment.

**Greedy-cost algorithm with reallocation (GCREAL)**

The greedy-cost algorithm with reallocation algorithm GCREAL takes into account the impact of the current traffic flow assignment on the cost of the other assignments. The following steps are performed in the GCREAL heuristic:

• *Step 1:* The input data for the algorithm, such as the POIs configuration, connection scheme and the volume of the traffic flows and their destinations are determined.

• *Step 2:* Based on the data from *Step 1,* all feasible interfaces for the just considered traffic flow are identified by checking their ability to support the traffic flow.

• *Step 3:* The traffic flows are sorted in the descending order, based on the amount of the traffic for sending on required directions.

• *Step 4:* The traffic flow allocation starts from the biggest traffic flow.

• *Step 5:* The interface with the lowest offered unit cost for the considered destination is selected from the set of feasible interfaces determined in *Step 2* and traffic flow is temporarily assigned to it as well as the cost is calculated.

• *Step 6:* After temporarily assigning a traffic flow to the cheapest feasible interface, the available bandwidth for the next flow is updated. The tariff, interface and partner limits are also decreased accordingly.

• *Step 7:* The traffic flows blocked due to the temporal assignment of the traffic flow performed in *Step 5* are determined and the cost of their temporal assignments to the subsequent cheapest feasible interfaces is calculated.

• *Step 8:* The cost of the temporal traffic flow assignments performed in *Step 5* and in *Step 7* is summed up.
• **Step 9**: The reverse assignment of the traffic flows considered in **Step 4** and in **Step 7** is temporarily performed and the summed up cost of these assignments is calculated.

• **Step 10**: If the total cost of the temporal traffic flow assignments performed in **Step 5** and in **Step 7** is lower than the total cost obtained in **Step 8**, the temporal assignment of the traffic flows performed in **Step 5** and in **Step 7** is confirmed and fixed; otherwise the traffic flows are assigned reversely.

• **Step 11**: The sorted list prepared in **Step 3** is updated by excluding the traffic flows already allocated in **Step 10**.

• **Step 12**: **Steps 4–9** are repeated, until all traffic flows have been considered.

• **Step 13**: The cost of the inter-domain traffic flow distribution is calculated based on the performed assignment.

### 6.1.2 Algorithms evaluation

To evaluate each of the proposed algorithms the numerical experiments with the limited size of directions have been determined to show the performance of the heuristics. We create \( n = 30 \) instances per experiment, solve each instance and evaluate the average of the goal function as well as the 95% confidence intervals (the detailed results are presented in appendix). The experiment is specified by a given number of potential interconnection partners, possible routes, capacity constraints, and volume requirements of the traffic flows.

**Assumptions**

In our analysis, we consider \( P = 5 \) interconnection partners and \( D = 40 \) directions (prefixes, destinations). We assume that an operator is connected with each potential partner through a number of interfaces (egress routers). The number of interfaces through which the partner is connected with analyzed network was being changed for performed numerical experiments from \( I = 1 \) to \( I = 10 \) interfaces. There exists at least one interface which enables sending the traffic to a given direction. The total offered capacities of the interfaces offered by one partner is equal to about 2000 traffic units while the maximum capacities of the partners are the same and equal 1600 traffic units. The maximum amount of traffic which can be sent through all the partners is equal to 8 000 units. It results from the limits imposed on the traffic volumes which can be sent through the partners. The traffic load is determined in relation to the sum of the partners’ limit (100% traffic load corresponds to the sum of limits of all partners equal in the considered scenario to \( H = 8000 \) units). The volumes of the traffic flows are
randomly generated by using the uniform distribution with the values taken from 
50 ÷ 150% of the analyzed traffic load; e.g., for 10% traffic load the volumes of 
traffic flows are generated from the 10 ÷ 30 interval.

Interconnection partners offer linear tariffs for which the unit cost is randomly 
generated using the uniform distribution from the 1 ÷ 10 interval.

Performance evaluation

The described scenarios was used for testing each of the proposed algorithms 
presented in this section. The detailed results related to the heuristics are given in 
appendix. The results are presented for linear tariffs. The numerical experiments 
with the same assumptions related to the number of partners, interfaces and 
capacity limits were also conducted for step tariffs. The obtained results are 
comparable with the results for linear tariffs so they were not showed here.

In this section the results related to one of the analyzed scenarios is presented 
where the number of interfaces per partner is equal to \( I = 3 \). The obtained 
results are presented in Figs. 6.1-6.4.

In Figs. 6.1-6.2 the relative errors for considered assignment algorithms are 
presented. The results of the proposed heuristics are compared to the optimal 
cost of the traffic distribution computed by using the CPLEX software. The 
traffic distribution obtained by proposed algorithms is optimal up to the 10% 
traffic load for the considered experiment. The further increase of the traffic 
load reveals some differences among the considered algorithms. In case of the 
GCREAL algorithm it gives the optimal solution up to the 20% traffic load as it 
accepts reassigning the traffic flows. Further increase of the traffic load increases 
also the probability that during the traffic allocation process the traffic flows meet 
the constraints resulted from the limits of the interfaces. According to the results 
the LAB and LABREAL algorithms enable obtaining the best solutions for the 
40% traffic load as the relative errors for these heuristics are equal to 2.89% and 
2.45%, respectively. Further increase of the traffic load reveals the advantage of 
the random-based RMIX and RMIXF heuristics for which the best results are 
obtained up to 60% traffic load as the relative error does not exceed 2.86% for 
mentioned traffic load. The slightly worse results are obtained for the GCD and 
MAXINT heuristics for which the relative errors decrease while increasing the 
traffic load. The results for the heuristics are presented up to 70% traffic load as 
the further increase of the traffic load (i.e., increase of the volume of the traffic 
flows) results in the blocking the flows due to the exceeding of the limits related 
to the interfaces.

One of the parameters which has been used for evaluation of algorithms is 
efficiency of the routing. This parameter is defined as the ratio of the lower 
bound cost calculation for the traffic flows to the total cost which has to be paid 
for distributing the whole inter-domain traffic. The lower bound cost is obtained
6.1 Greedy heuristic methods

by multiplying the cheapest price available to the destination by the total amount of traffic to the destination summed up over all destinations. The efficiency is assumed to have the values from the range \((0, 1)\). Efficiency equal to 1 denotes the fact that the whole traffic is sent through the cheapest possible paths. It could happen when no restrictions imposed on the capacity exist or the total traffic is significantly lower than the capacity limits. The introduced parameter informs us about the cost loss due to traffic sent on routes more expensive than the cheapest
routes to the destination. It also indicates that some business arrangements could be made with related partners for redefinition of business agreements.

In Figs. 6.3-6.4 the efficiency of the inter-domain traffic distribution proposed by the considered algorithms is presented. Among the greedy-based algorithms the LAB algorithm is the most efficient one. The results indicate also that the performance of the LAB, GCD and MAXINT algorithms are quite similar and outperform the routing efficiency for the GCA algorithm.

Figure 6.3: Efficiency of the proposed assignment algorithms.

Figure 6.4: Efficiency of the proposed assignment algorithms.
The summarized blocking probability for proposed heuristics is given in Table 6.1. To explain the traffic rejection it is enough to remember the non-prioritized algorithms operation. The GCD algorithm, for example, starts a traffic flow assignment from the biggest flow exhausting the available capacity. On the other hand, PGCD and PLAB algorithms enable reassignment of the traffic flows in case some of them are supposed to be rejected during the algorithm operation. To calculate the blocking probability the number of instances with blocked traffic flows was summed up and related to all instances computed by the algorithms. The number of all instances is equal to 2520 and results from the number of numerical experiments. We analyzed 90 scenarios with different number of interfaces and performed 30 instances for each scenario. In some cases (180 instances) the traffic distribution could not be assigned as the volume of the traffic flows exceeded the interface limit. As we can see, the highest blocking probability can be noted for the GCA heuristic as the GCA algorithm starts the traffic allocation from the traffic flow with the smallest required bandwidth exhausting at the beginning the available bandwidth and blocking the traffic flows with higher required bandwidth. The best results were obtained for heuristics with the applied prioritization approach. The PGCD, PGCA and PLAB algorithms block less than 1% of the considered traffic flows.

Table 6.1: The blocking probability for heuristics

<table>
<thead>
<tr>
<th>Heuristic</th>
<th>No. of blocked traffic flows</th>
<th>Blocking prob. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCD</td>
<td>270</td>
<td>9.0</td>
</tr>
<tr>
<td>PGCD</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>GCA</td>
<td>468</td>
<td>15.6</td>
</tr>
<tr>
<td>PGCA</td>
<td>16</td>
<td>0.5</td>
</tr>
<tr>
<td>GCR</td>
<td>354</td>
<td>11.8</td>
</tr>
<tr>
<td>RMIX</td>
<td>384</td>
<td>12.8</td>
</tr>
<tr>
<td>RMIXF</td>
<td>388</td>
<td>12.9</td>
</tr>
<tr>
<td>LAB</td>
<td>268</td>
<td>8.9</td>
</tr>
<tr>
<td>PLAB</td>
<td>7</td>
<td>0.2</td>
</tr>
<tr>
<td>LABREAL</td>
<td>432</td>
<td>14.4</td>
</tr>
<tr>
<td>MAXINT</td>
<td>307</td>
<td>10.2</td>
</tr>
<tr>
<td>GCREAL</td>
<td>420</td>
<td>14.0</td>
</tr>
</tbody>
</table>

To check the performance of the proposed heuristics for more complex scenarios the additional numerical experiment with $P = 5$ interconnection partners and $I = 10$ interfaces (egress routers) per partner was analyzed. The number of directions $D$, and also the number of traffic flows, was being changed for performed numerical experiments from $D = 100$ to $D = 900$ directions. The capacity of the interface offered by one partner is equal to 4000 traffic units and is the same for all interfaces offered by all interconnection partners. The maximum capacities of the partners are the same for all partners and equal to 20,000 traffic units. The
6. Mechanisms for inter-domain traffic distribution

Table 6.2: Relative errors for heuristics in relation to the number of directions $D$ - part 1

<table>
<thead>
<tr>
<th>$D$</th>
<th>GCD</th>
<th>PGCD</th>
<th>GCA</th>
<th>PGCA</th>
<th>LAB</th>
<th>PLAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>3.26 ±0.24</td>
<td>3.26 ±0.23</td>
<td>3.68 ±0.28</td>
<td>3.68 ±0.28</td>
<td>3.26 ±0.23</td>
<td>3.26 ±0.23</td>
</tr>
<tr>
<td>600</td>
<td>4.10 ±0.22</td>
<td>4.10 ±0.23</td>
<td>4.77 ±0.33</td>
<td>4.77 ±0.33</td>
<td>4.10 ±0.22</td>
<td>4.10 ±0.22</td>
</tr>
<tr>
<td>700</td>
<td>6.02 ±0.27</td>
<td>6.02 ±0.26</td>
<td>6.72 ±0.35</td>
<td>6.72 ±0.35</td>
<td>6.02 ±0.26</td>
<td>6.02 ±0.26</td>
</tr>
<tr>
<td>800</td>
<td>14.15 ±1.92</td>
<td>14.15 ±1.92</td>
<td>15.18 ±1.93</td>
<td>15.18 ±1.91</td>
<td>14.15 ±1.91</td>
<td>14.15 ±1.91</td>
</tr>
<tr>
<td>900</td>
<td>10.90 ±1.43</td>
<td>10.47 ±0.58</td>
<td>7.46 ±2.62</td>
<td>11.17 ±0.49</td>
<td>10.23 ±</td>
<td>10.47 ±0.58</td>
</tr>
</tbody>
</table>

Table 6.3: Relative error for heuristics in relation to the number of directions $D$ - part 2

<table>
<thead>
<tr>
<th>$D$</th>
<th>GCR</th>
<th>RMIX</th>
<th>RMIXF</th>
<th>LABREAL</th>
<th>MAXINT</th>
<th>GCREAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>3.26 ±0.29</td>
<td>3.26 ±0.24</td>
<td>2.99 ±0.19</td>
<td>1.47 ±0.13</td>
<td>3.35 ±0.24</td>
<td>2.14 ±0.23</td>
</tr>
<tr>
<td>600</td>
<td>4.21 ±0.28</td>
<td>4.10 ±0.22</td>
<td>3.77 ±0.23</td>
<td>3.28 ±0.18</td>
<td>3.88 ±0.21</td>
<td>4.42 ±0.24</td>
</tr>
<tr>
<td>700</td>
<td>6.14 ±0.28</td>
<td>6.02 ±0.27</td>
<td>5.75 ±0.22</td>
<td>5.01 ±0.27</td>
<td>5.96 ±0.27</td>
<td>6.36 ±0.36</td>
</tr>
<tr>
<td>800</td>
<td>13.82 ±2.08</td>
<td>13.65 ±2.13</td>
<td>13.16 ±2.08</td>
<td>12.76 ±1.79</td>
<td>13.96 ±1.87</td>
<td>12.24 ±1.91</td>
</tr>
<tr>
<td>900</td>
<td>10.61 ±0.39</td>
<td>10.90 ±1.43</td>
<td>9.99 ±0.55</td>
<td>-</td>
<td>8.46 ±0.99</td>
<td>-</td>
</tr>
</tbody>
</table>

The maximum amount of traffic which can be sent through all the partners is equal to 100,000 units. The volumes of the traffic flows are randomly generated by using the uniform distribution with the values taken from $50 \div 150$.

The relative errors for proposed heuristics in relation to the number of directions $D$ are given in Tables 6.2, 6.3. The results are presented starting from $D = 500$ directions as for lower number of traffic flows the errors between the results obtained by the proposed heuristics and the optimal solution found by CPLEX is negligible. As we can see, for $D = 500$ directions the best results were obtaining by the LABREAL heuristic. Further increase the number of considered directions confirms the advantage of the LABREAL algorithm as for $D = 500$ directions the relative error equals to 5.01% while the subsequent best result (5.75%) is obtained by RMIXF algorithm. The worst results gives the GCA algorithm due to exhausting the cheapest interfaces and blocking the bigger traffic flows.

The general observation can be made regarding the obtained relative errors for the proposed heuristics. For low network load the optimal solutions are computed by the developed algorithms. The increase of the traffic load up to the certain value of the traffic load increases also the relative error. After exceeding that value the relative error decreases. The point where the tendency of the relative values is reversed depends on the capacity limits of the partners and interfaces as well as on the number of available interfaces. Due to the capacity limits the inter-
domain traffic distribution could not be realized for some instances as observed for $D = 900$ directions. The computation times of the optimal solutions for instances with $D = 900$ directions were relatively long and can be put in the interval $1.5\div3$ hours. On the other hand, the time for finding the solutions by the heuristics is of the order of maximum some minutes for GCREAL heuristic while the other heuristics find the solutions in some seconds.

### 6.2 Simulated annealing-based algorithms

Simulated annealing (SAN) is a stochastic technique which has its origin in statistical mechanics. The main idea is based on the physical process of annealing (cooling) in the chemical industry. This technique was also proposed in [64] as a general methodology within the area of stochastic search and optimization. Many combinatorial optimization problems applied simulated annealing with slight variations [108]. Simulated annealing uses a stochastic approach to direct the search. It allows the search to proceed to a neighboring state even if the move causes the value of the objective function to become worse.

#### 6.2.1 Simulated annealing algorithm (SAN)

The SAN algorithm implementation related to the LCR problem starts from an initial solution which is randomly generated from the set of all feasible solutions and the transit cost of that initial inter-domain traffic distribution is calculated. In the next step, the move in the random direction is performed, i.e., a new solution is generated. If a move to a neighbor $S'$ in neighborhood $N(S)$ decreases the objective function value, or leaves it unchanged then the move is always accepted. More precisely, the solution $S'$ is accepted as the new current solution if $\Delta \leq 0$ where $\Delta = C(S') - C(S)$. The $C(S')$ and $C(S)$ denote the cost of the new solution and the cost of the solution before the move, respectively. To allow the search to escape from a local optimum, moves that increase the objective function value are accepted with a probability $p_b \exp(-\Delta/T)$ if $\Delta > 0$, where $T$ is a parameter called the “temperature” and $p_b$ is a global constant taken from the $0 \div 1$ interval. This is called the Metropolis criterion [69]. As suggested in [64], the value of initial temperature $T$ is calculated according to the formula $T_0 = -C(S_0)/\ln(0.8)$ where $C(S_0)$ denotes the cost of initial solution. The temperature $T$ is decreased across successive iterations with the step $T_N = T_0/N$ where $N$ indicates the number of movements which determines the algorithm termination condition. The decrease of the temperature $T$ reduces the probability of accepting the movement which increases the cost of the solution.
6.2.2 Two-step heuristic (LABSAN)

The proposed LABSAN algorithm is a two-step algorithm. In the first step the initial solution of the SAN algorithm is generated by the LAB algorithm instead of being generated randomly. In the second step the SAN algorithm described above is applied. If exists the inter-domain traffic flow distribution cheaper than proposed by the LAB heuristic, then the stochastic search component of the algorithm performs a local modification of the initial mapping, reallocating only these egress flows which decrease the transit cost. Due to applying the two-phase approach the time required for finding solution can be significantly reduced assuring at the same time a good accuracy.

6.2.3 Performance evaluation

Scenario assumptions

We assume that there are $P=5$ interconnection partners and $D=40$ directions. In the considered experiment scenario there is one preferred partner with $I=4$ interfaces and four non-preferred partners with $I=3$ or $I=4$ interfaces. For the preferred partners the unit costs are uniformly distributed from the $1 \div 3$ interval while for the other partners are distributed from the $4 \div 10$ interval. At least one interface enables to send the traffic to a given direction. In the scenario, non-preferred partners are able to transit traffic to $70 \div 80\%$ randomly chosen directions while the preferred partner offers the transit to $90 \div 100\%$ directions. The maximum amount of traffic which can be sent through a partner is lower than the sum of the capacity of its interfaces. The amount of traffic to be sent to required directions is randomly generated from the $50 \div 150\%$ interval of the analyzed traffic load. The traffic load is determined in relation to the sum of the partners’ limit (100% traffic load corresponds to the sum of limits of all partners equal in the considered scenario to $H=8000$ units). The preferred partner is able to transit up to 50% of potentially maximum total traffic. The amount of traffic which can be sent through non-preferred partners is assumed to be equal to 1000 traffic units. We create $n=30$ instances per scenario, solve each instance and evaluate the average of the goal function as well as the 95% confidence intervals (not shown in the figures as these values are small and would make the figures illegible).

Results

The results obtained by the considered algorithms are summarized in Figs. 6.5-6.13. The performance of the simulated annealing algorithm SAN is presented in Fig. 6.5. The graphs are showed for 10%, 30%, 50% and 70% traffic loads. The global constant related to the probability of accepting the new solution was
assumed to be equal to $p_b=0.1$. In Fig. 6.5, the relation between the transit cost and the number of steps $N$ is presented.

![Figure 6.5: Cost for SAN algorithm.](image)

As we can observe, at the start of the SAN algorithm the cost is far from optimality as a random LCR problem solution is generated. While increasing the number of steps the cost decreases more than twice for some first steps, e.g., from 12632 to 5609 for 70% traffic load, while increasing the number of steps from $N=1$ to $N=300$, respectively. After exceeding a certain number of steps (dependent on the traffic load, e.g., $N=2000$ for 10% traffic load) further increase of the number of steps does not improve the solution. The cost decreases to a certain value, different for each of the considered traffic loads (e.g., 3949 for 30% traffic load).

Apart from the cost, a routing efficiency parameter is used to evaluate the performance of the proposed algorithms. The routing efficiency for the SAN algorithm is shown in Fig. 6.6.

The results indicate that the relation between the routing efficiency and the number of steps is similar to the same relation for the cost. The worst routing efficiency (0.19 for $N=1$ increasing to 0.47 for $N=15000$) has been obtained for 70% traffic load. It comes from the scenario assumptions where there is one preferred partner able to transit traffic up to 50% of total traffic. For the 70% traffic load, the traffic has to be distributed to other partners which offer more expensive tariffs.

The detailed results obtained while analyzing the interval for which the costs are changing are presented in Fig. 6.7.

According to the results, the higher traffic load the smaller impact of increas-
6. Mechanisms for inter-domain traffic distribution

Figure 6.6: Routing efficiency for SAN algorithm.

Figure 6.7: Relative cost for SAN algorithm.

ing the number of steps. To evaluate this impact the relative cost has been used. The relative cost is defined as the ratio of the difference between the cost value for the analyzed number of steps $N$ and the lowest value obtained by the algorithm to this lowest value. According to the results, the best improvement has been obtained for 10% traffic as the cost decreased by 363% while increasing the number of steps from $N=1$ to $N=2000$. The cost oscillations presented on the graphs
stem from the simulated annealing algorithm operation as a worse solution can also be accepted to escape from a local optimum. The impact of the probability of accepting the worse solution on the cost in relation to the number of steps $N$ is presented in Fig. 6.8.

![Figure 6.8: Cost vs. global constant.](image)

In the simulation scenario, 10% traffic load has been assumed. The graphs are given for four values of the constant global value $p_b$: 0.01, 0.05, 0.1 and 1. The results indicate that the worst results have been obtained for $p_b=1$ while for the other values of parameter $p_b$ the results are similar. It has to be noted that both too high and too low values of the $p_b$ parameter are not desirable as they can keep the SAN-based algorithms in a local minimum.

To evaluate the performance of the LABSAN algorithm a numerical experiment with 70% and 80% traffic load has been conducted. In Fig. 6.9, the transit cost for both SAN and LABSAN algorithms in relation to the number of steps is presented.

The routing efficiency is shown in Fig. 6.10 as well.

As can be seen, almost the same results as for the SAN algorithm are obtained for the LABSAN algorithm for a lower number of steps $N$. It comes from the LABSAN algorithm operation as it considers the solution found by the LAB algorithm as the initial solution for the SAN-based algorithm instead of a randomly generated solution like in the case of the SAN algorithm. However, the results depend on the traffic load. For 70% traffic load, LABSAN gives better results than the SAN algorithm. On the other hand, the SAN algorithm performs better in comparison with the LABSAN for 80% traffic load. This LABSAN algorithm
6. Mechanisms for inter-domain traffic distribution

Figure 6.9: Cost comparison for SAN and LABSAN algorithms.

Figure 6.10: Routing efficiency for SAN and LABSAN algorithms.

property is especially useful for more complicated scenarios with a higher number of partners and directions than those considered in the analyzed scenario as it enables to shorten the computation time required for finding the solution for the considered LCR problem.

To calculate the exact solution (denoted on the graph as OPT) we use the commercial MIP solver CPLEX [22]. The comparison of the transit cost obtained
by the LAB, SAN and LABSAN heuristics with the values computed by CPLEX is presented in Fig. 6.11. The routing efficiency for the considered algorithms is presented in Fig. 6.12. It can be stated that the heuristics perform well. The worst relative errors between the heuristic results and the optimal solution (obtained by CPLEX) have been calculated for the results obtained by the LAB
and LABSAN algorithms (Fig. 6.13). The results indicate that the relative errors are in the range from 0% up to 8.2% for 20% and 80% traffic load, respectively. The best results are achieved for the SAN heuristic as the highest relative error is lower than 6.46% for 80% traffic.

![Relative error graph](image)

**Figure 6.13: Relative error.**

### 6.2.4 Conclusions

In this section, the simulated annealing-based algorithms for optimized inter-domain traffic distribution have been presented and evaluated. The conclusion drawn here is that in order to increase the efficiency of operations within the interconnection environment, the development of a solution for finding the optimal routes becomes of a primary importance. The simulated annealing-based algorithms perform well. While applying the two-step heuristic the time required for finding a solution can be significantly reduced assuring at the same time a good accuracy.

### 6.3 Genetic-based algorithms

Genetic programming is a programming technique that through the use of ‘evolutionary’ operators tries to resemble the evolutionary process. The main idea is to mix genetic material between genes in operations like mutations and crossovers. The difference between mutations and crossovers is that a mutation uses only one gen and changes it at random while crossover uses two of them and switches the
genetic code between them. A chromosome consists of a fixed number of genes. A determined number of chromosomes makes up a population. There are different policies on how to pick the chromosomes that will be parents and different approaches on how to evaluate them and their children to see which chromosomes will stay in the population.

According to the evolutionary theory, the evolutionary concepts worked quite well, though during an immense amount of time. The hard part is to adjust the evaluating function that decides which chromosome is the better one.

### 6.3.1 Genetic algorithm

The evolutionary approach is very often used to solve optimization problems. It can also be used for solving the problem of efficient distribution of the inter-domain traffic considered in the thesis. In the papers [81], [80] the authors proposed a parallel evolutionary optimization algorithm, based on the defined evolutionary LCR model. The genetic-based algorithms proposed in the thesis are partially similar to algorithm proposed in cited papers extending them with the two-step heuristic and making the extensive performance evaluation.

The operation of the proposed genetic algorithm GEN can be described by the following steps:

- **Step 1**: Generate initial population.
  The genetic algorithm GEN starts by randomly generating a population with \( W \) chromosomes. Each of the chromosomes represents the potential solution for the LCR problem. The chromosome consists of \( G \) genes as one gene corresponds to one direction \( D \). The gene is composed of the following four parameters: partner \( p \in P \), interface \( i \in I_p \), tariff \( t \in T_{pie} \) and timeband \( e \in E \). The aggregated traffic volume which has to be sent to the specified direction influences the gen structure as only feasible mappings are considered.

- **Step 2**: Generate child chromosomes by crossover process.
  After generating the required number of chromosomes the crossover process is performed. Two parent chromosomes are selected and a new child chromosome is generated. As the results of crossover, we obtain \( 9W \) child chromosomes.

- **Step 3**: Perform mutation.
  Each generated child chromosome is subject to a mutation process with a probability \( p_m \).

- **Step 4**: Decode each chromosome to obtain its fitness value.
  A chromosome consisting of \( G \) genes represents the solution for the LCR
problem with a fitness value which can be calculated by using a fitness function. The fitness function takes into account the cost of sending traffic to the required directions as well as the so-called penalty part. The penalty impacts the fitness function if the chromosome contains an infeasible solution. The value of penalty informs about the unfitness of the traffic distribution proposed by the chromosome and equals to the amount of violated capacity over all used partners and interfaces. The fitness value is calculated by using the following formula (Eq. (6.1)):

$$f_v = \sum_d \sum_p \sum_i \sum_t c_{dpiet} x_{dpiet} + U_i \sum_p \sum_i [\max(0; w_{pie} - Z_{pie})] + U_p \sum_p [\max(0; v_{pe} - L_{pe})] \quad e \in E$$

(6.1)

The impact of the exceeded capacity of the partner and the interface resulted from the gene structure on fitness value of the chromosome is denoted by parameters $U_i$ and $U_p$, respectively.

- **Step 5**: Choose the best $W$ chromosomes.
  After calculating the fitness value for $10W$ (parent and $9W$ child) chromosomes the best $W$ chromosomes with the smallest fitness value (cheapest traffic flows assignment) are chosen.

- **Step 6**: Repeat Steps 2-5 until the termination criterion is met.
  To avoid long convergence of the algorithm, the genetic algorithm stops if the assumed number of generations $N$ has been reached.

### 6.3.2 LABGEN heuristic algorithm

The LABGEN algorithm is a combination of the LAB algorithm which takes into account the cost and the available bandwidth with the GEN algorithm described above. The initial solution generated by algorithm LAB is the input to the GEN algorithm. Due to applying the two-phase approach the time required for finding solution can be significantly reduced assuring at the same time a good accuracy.

### 6.3.3 Performance evaluation of the evolutionary methods

#### Scenario assumptions

We assume that there are $P = 5$ interconnection partners and $D = 40$ directions. In the considered numerical experiment scenario there is one preferred partner
with $I = 4$ interfaces and four non-preferred partners with $I = 3 \div 4$ interfaces. For the preferred partners the unit costs are uniformly distributed from the $1 \div 3$ interval while for the other partners from the $4 \div 10$ interval. At least one interface enables sending the traffic to a given direction. In the scenario, non-preferred partners are able to transit traffic to $70 \div 80\%$ randomly chosen directions while the preferred partner offers the transit to $90 \div 100\%$ directions. The maximum amount of traffic which can be sent through a partner is lower than the sum of the capacity of its interfaces. The amount of traffic to be sent to required directions is randomly generated from the $50 \div 150\%$ interval of the analyzed traffic load. The traffic load is determined in relation to the sum of the partners’ limit (100\% traffic load corresponds to the sum of limits of all partners equal in the considered scenario to $H = 8000$ units). The preferred partner is able to transit up to $50\%$ of potentially maximum total traffic. The amount of traffic which can be sent through non-preferred partners is assumed to be equal to 1000 traffic units. Considering the parameters of the genetic algorithm we assumed parameters $U_i$ and $U_p$ to be equal to 1000 while the number of chromosomes was assumed to be $W = 100$.

Results

The results of the solutions obtained by the considered algorithms are summarized in Figs. 6.14-6.19. In Fig. 6.14 and Fig. 6.15 the results obtained for genetic algorithm GEN are presented in relation to the number of generations $N$. The graphs are showed for 10\%, 30\%, 50\% and 70\% traffic load. The mutation probability is equal to $p_m=0.01$. In Fig. 6.14 the relation between the transit cost and the number of generations $N$ is presented. As we can observe, at the start of the GEN algorithm the cost is far from the optimal solution because a random population which forms a feasible LCR problem solution is generated. While increasing the number of generations at the beginning, the cost decreases significantly (e.g., from 10334 to 3946 for 70\% traffic load). After exceeding a certain value (dependent on the traffic load) further increase of the number of generations does not improve the solution. Apart from the cost, a routing efficiency parameter is used to evaluate the performance of the proposed algorithms. The routing efficiency for the GEN algorithm is shown in Fig. 6.15. The results indicate that the relation between the routing efficiency and the number of generations is similar to the same relation for the cost. The worst routing efficiency (0.35 for $N=1$, increasing to 0.5 for $N=100$) was obtained for 70\% traffic load. It comes from the scenario assumptions where there is one preferred partner able to transit traffic up to 50\% of the total traffic. For the 70\% traffic load, the traffic has to be distributed to other partners which offer more expensive tariffs.

The detailed results obtained while analyzing the interval for which the costs are changing are presented in Fig. 6.16 and Fig. 6.17. According to the results,
the higher traffic load the smaller impact of increasing the number of generations (Fig. 6.16). To evaluate this impact, the relative cost is presented in Fig. 6.17. The relative cost is defined as the ratio of the distance between the cost value for the analyzed number of generations $N$ and the lowest value obtained by the algorithm to this lowest value. According to the results, the best improvement
was obtained for 30% traffic as the cost decreased by 160% while increasing the number of generations from $N = 1$ to $N = 10$.

![Figure 6.16: Cost for GEN algorithm.](image)

![Figure 6.17: Relative cost for GEN algorithm.](image)

The impact of the probability mutation on cost and routing efficiency was presented in Fig. 6.18 and Fig. 6.19. In the simulation scenario, 10% traffic load has been assumed. The graphs are given for four values of the mutation
probability: $p_m=0.005$, $p_m=0.01$, $p_m=0.05$ and $p_m=0.1$. The relation between the number of generations $N$ and the cost is presented in Fig. 6.18 while Fig. 6.19 shows the relation for routing efficiency. The results indicate that the best results were obtained for $p_m=0.005$ while the worst ones for $p_m=0.1$. However, we checked that the results depend on the traffic load and the quality of initial chromosomes. Both too high and too low values of the mutation probability are not desirable as they can keep the GEN-based algorithms in a local minimum.

![Figure 6.18: Cost vs. mutation probability.](image)

To evaluate the performance of the LABGEN algorithm the simulation scenario with 30%, 40% and 50% traffic load has been analyzed. In Fig. 6.20 the transit cost for both GEN and LABGEN algorithms in relation to the number of generations is presented. The routing efficiency is shown in Fig. 6.21 as well.

As can be noticed, the same results as for the GEN algorithm are obtained for the LABGEN algorithm for a lower number of generations $N$. It comes from the LABGEN algorithm operation as it considers the solution found by the LAB algorithm as the initial solution for the GEN-based algorithm instead of randomly generated chromosomes like in the case of the GEN algorithm. This LABGEN algorithm property is especially useful for more complicated scenarios with a higher number of partners and directions than those considered in the analyzed scenario as it enables shortening the computation time required for finding the solution for the considered LCR problem. To calculate the exact solution (denoted on the graph as OPT) we use the commercial MIP solver CPLEX [22]. In Fig. 6.22 the comparison of the transit cost obtained by the LAB, GEN and LABGEN heuristics with the values computed by CPLEX is presented.
6.3 Genetic-based algorithms

Figure 6.19: Routing efficiency vs. mutation probability.

Figure 6.20: Cost comparison for GEN and CLAGEN algorithms.

It can be stated that the heuristics perform well. The worst relative errors between the heuristic results and optimal solution (obtained by CPLEX) have been calculated for the results obtained by the LAB algorithm and have been in the range from 0% up to 6.3% for 20% and 80% traffic load, respectively. The best results were achieved for the LABGEN heuristic as the highest relative error was lower than 1.36% for 80% traffic for that heuristic. In Fig. 6.23, the comparison
of the relative cost obtained for the LAB, GEN and LABGEN heuristics with the values computed by CPLEX is presented.

On the other hand, the comparison of the routing efficiency obtained by the considered heuristics with the values computed by CPLEX is presented in Fig. [6.24].

The computation time for the LAB heuristic in the analyzed scenario was
less than 1 second and did not depend on the traffic. For the GEN and LABGEN algorithms the number of iterations decided about stopping the algorithm operation. According to the results, the relation between the computation time and the number of generations is almost linear and depends on the traffic load. The computation time for \( N=100 \) generations was less than 1 second for 10% traffic load while to generate the same number of generations for 90% traffic load
required 10 seconds on average. We also checked that the time for finding the solution for more complicated scenario with $P=10$ transit partners offering the possibility of sending traffic to $D=200$ directions was very long and after 24 hours the algorithm was stopped.

**Conclusion**

In this section, the genetic algorithm for optimized inter-domain traffic distribution was presented and evaluated. The heuristic and combined heuristic with genetic algorithms have been proposed and evaluated. The conclusion drawn here is that in order to increase the efficiency of operations within the interconnection environment the development of a solution for finding the optimal routes becomes crucial. The genetic-based algorithms perform well. However, the main limitation of these algorithms is the computation time which would be unacceptable for more complicated scenarios.
Part III

Performance-based and cost-efficient inter-domain traffic distribution
In the highly connected Internet most of the domains have more than one inter-
connection link to different providers. In such a multi-homed scenario destina-
tions for inter-domain traffic may be reachable through multiple egress routers
with different offered costs and path performance. In this chapter, we address
the problem of ‘intelligent’ route selection in a multi-homed stub network in order
to minimize network latency to various destinations as measured by round-trip
time (RTT) together with transit cost minimization. As different providers show
different latencies for the same destinations, a dynamic provider selection based
on delay measurements can result in significant performance improvements.

The remainder of this chapter is organized as follows. Section 7.1 presents
network performance measures considered in the thesis. In Section 7.2 QoS
maximization models are developed. Optimization heuristics are given in Sec-
tion 7.3. The scenario assumptions and performance evaluation of the proposed
QoS maximization heuristics are presented in Section 7.4. Section 7.5 summarizes
the work presented in this chapter.
7. Optimized QoS schemes

7.1 Network performance measure

There are several ways to measure network performance. One of the parameters which network operator would like to optimize (in addition to cost minimization) is the quality of service (QoS) related to interconnections and routes offered by interconnected partners. In this chapter, we consider a length of AS-path (Autonomous System) and latency experienced on that path as the indicators of the QoS. The length of the routes in terms of AS hops is one of the factors influencing the QoS parameters. The AS-level paths to the destinations through the interconnected partners should be as short as possible. A higher number of hops usually correlates with higher delays and a higher loss probability for the packets, and thus a lower perceived performance for the end user. Longer paths are also more prone to inter-domain routing failures. However, there are also many cases when the same AS hop number does not necessarily correspond to the same or approximately the same latency experienced on the considered paths. This incompatibility can result, e.g., from a different intra-domain routing approach resulting in a different number of intradomain hops on the path to the destination offered by different providers. To analyze the relation between the cost and these two QoS indicators, the models considered in this chapter take also into account latency which would be experienced on the paths when choosing the assigned routes. The latency from provider’s network to the destination not only informs about the network response time but also serves as a measure of connection reliability. A large delay or rapidly increasing delay can indicate a potential availability problem.

We assume that the considered QoS parameters, i.e., the length of AS-path and latency experienced on the path going to direction $d$ through interface $i$ of partner $p$ in tariff $t$ realized in timeband $e$ are known in advance. The considered QoS parameters can be determined by an operator through measurements.

7.2 MILP formulations for QoS models

The basic optimization model presented in Chapter 6 can be easily extended in several ways to include QoS objectives related to the number of AS hops and the path latency. The performance metric which would take into account other QoS parameters as jitter and packet loss could also be defined, although it might be hindered by the fact that they are non-additive. In some of the proposed optimization models, QoS parameters are used in the goal function. We also propose models in which QoS parameters are considered as the constraints related to QoS requirements for aggregated traffic flows. On the other hand, in some models the required level of QoS performance is optimized while a constraint related to the total transit traffic is imposed. A solution of the problem should
be the allocation of traffic flows and egress routers, which brings the best value for one or more objective functions.

7.2 MILP formulations for QoS models

7.2.1 QoS optimization models

In the optimization models introduced here, QoS parameters are used in the goal functions. The models minimize the total length of the paths or the latencies experienced on the paths.

**AS-path length optimization model AO:** This model minimizes the total length of AS paths that traffic flows must traverse.

**Additional constants**

\(a_{dpi_e}\) length of the offered AS-path (expressed in hops) to destination \(d\) going through interface \(i\) of partner \(p\) in timeband \(e\)

**Additional variables**

\(y_{dpi_e}\) amount of traffic sent to direction \(d\) by partner \(p\) through interface \(i\) in timeband \(e\)

**Additional constraints**

\[ y_{dpi_e} = \sum_t x_{dpi_{et}} \quad d \in D \quad p \in P \quad i \in I_p \quad e \in E \]  

The equality given in Eq. (7.1) sums up all the traffic flows going to direction \(d\) by different tariffs through interface \(i\) of partner \(p\) in timeband \(e\).

The goal of this model is to choose the paths through which the traffic will be realized in such a way that the overall length of the chosen AS-paths is minimized:

\[
\text{minimize} \quad F = \sum_d \sum_p \sum_i \sum_e a_{dpi_e} y_{dpi_e} \tag{7.2}
\]

**Latency optimization model LO:** In this model, the overall latency experienced by traffic flows on the assigned paths is minimized. We assume that assigning the considered traffic flows to paths obtained in the optimization process does not impact the \(RTT\) time on that path.

**Additional constants**

\(b_{dpi_e}\) AS-path latency which can be experienced by the traffic flow sent to destination \(d\) through interface \(i\) of partner \(p\) in timeband \(e\)

The goal of this model is to choose the paths through which the traffic will be realized in such a way that the overall latency experienced by the traffic is minimized:

\[
\text{minimize} \quad F = \sum_d \sum_p \sum_i \sum_e b_{dpi_e} y_{dpi_e} \tag{7.3}
\]
7. Optimized QoS schemes

7.2.2 QoS-constrained models

The QoS-constrained optimization models take QoS parameters as the restrictions while the total cost of the transit traffic is minimized. The following different cases with respect to (wrt.) QoS constraints are defined as follows.

**AS-path length constraint wrt. interface (ACI):** In this model the restriction for average AS-path length experienced by the traffic flow going through interfaces is imposed.

**additional constants**

\[ \bar{A}_{pie} \]  
maximum average acceptable length of the used AS-paths going through interface \( i \) of partner \( p \) in timeband \( e \)

**additional variables**

\( w_{pie} \)  
total amount of traffic sent by partner \( p \) through interface \( i \) in timeband \( e \)

**additional constraints**

\[
\begin{align*}
w_{pie} &= \sum_d \sum_t x_{dpite} & p \in P & i \in I_p & e \in E \\
\sum_d a_{dpie} y_{dpie} &\leq \bar{A}_{pie} w_{pie} & p \in P & i \in I_p & e \in E
\end{align*}
\]  (7.4)  (7.5)

The equality given in Eq. (7.4) adds all the traffic flow volumes going through interface \( i \) of partner \( p \) in timeband \( e \). The inequalities given in Eq. (7.5) are necessary to assure that the average length value of the used AS-paths going through interface \( i \) of partner \( p \) in timeband \( e \) is lower than the maximum acceptable length.

**Latency constraint wrt. interface (LCI):** In this model the restriction for the average acceptable latency experienced by the traffic flow going through interface \( i \) is imposed.

**additional constants**

\[ \bar{B}_{pie} \]  
maximum average acceptable latency experienced on used AS-paths going through interface \( i \) of partner \( p \) and timeband \( e \)

**additional constraints**

\[
\sum_d b_{dpie} y_{dpie} \leq \bar{B}_{pie} w_{pie} & p \in P & i \in I_p & e \in E
\]  (7.6)

The inequalities given in Eq. (7.6) are necessary to assure that the average value of latency experienced by the traffic on the used AS-paths realized through interface \( i \) of partner \( p \) in timeband \( e \) is lower than the maximum average allowed latency.
AS-path length constraint wrt. partner (ACP): In this model, the restriction for the average AS-path length experienced by the traffic flow going through partners is imposed.

additional constants
\[ \bar{A}_{pe} \] maximum average acceptable length of the AS-paths going through partner \( p \) in timeband \( e \)

additional variables
\[ v_{pe} \] total amount of traffic sent by partner \( p \) in timeband \( e \)

additional constraints
\[
\begin{align*}
v_{pe} &= \sum_{d} \sum_{i} \sum_{t} x_{dpite} \quad p \in P \quad e \in E \quad (7.7) \\
\sum_{d} \sum_{i} a_{dpite} y_{dpite} &\leq \bar{A}_{pe} v_{pe} \quad p \in P \quad e \in E \quad (7.8)
\end{align*}
\]

The equalities given in Eq. (7.7) add all the traffic flow volumes going through partner \( p \) in timeband \( e \). The inequalities given in Eq. (7.8) are necessary to assure that the average length of the used AS-paths going through partner \( p \) in timeband \( e \) is lower than the maximum average acceptable length.

Latency constraint wrt. partner (LCP): In this model, the restriction for the average acceptable latency experienced by the traffic flow going through partner \( p \) is imposed.

additional constants
\[ \overline{B}_{pe} \] maximum average acceptable latency experienced on used AS-paths going through partner \( p \) and timeband \( e \)

additional constraints
\[
\sum_{d} \sum_{i} b_{dpite} y_{dpite} \leq \overline{B}_{pe} v_{pe} \quad p \in P \quad e \in E \quad (7.9)
\]

The inequalities given in Eq. (7.9) are necessary to assure that the average value of latency experienced by the traffic on the used AS-paths realized through partner \( p \) in timeband \( e \) is lower than the maximum average allowed latency.

AS-path length constraint wrt. timeband traffic (ACT): In this model the restriction for the average AS-path length experienced by the traffic flow realized in timeband \( e \) is imposed.

additional constants
\[ \overline{A}_{e} \] maximum average acceptable length of the used AS-paths in timeband \( e \)
additional constraints
\[ \sum_d \sum_p \sum_i a_{dpie} y_{dpie} \leq \bar{A}_e \sum_d h_{de} \quad e \in E \] (7.10)

The inequalities given in Eq. (7.10) are necessary to assure that the average length of used AS-paths in timeband \( e \) is lower than the maximum average acceptable length.

**Latency constraint wrt. timeband traffic (LCT):** In this model, the restriction for the average acceptable latency experienced by the traffic flow realized in timeband \( e \) is imposed.

**additional constants**
\( \bar{B}_e \) maximum average acceptable latency experienced on used AS-paths in timeband \( e \)

**additional constraints**
\[ \sum_d \sum_p \sum_i b_{dpie} y_{dpie} \leq \bar{B}_e \sum_d h_{de} \quad e \in E \] (7.11)

The inequality given in Eq. (7.11) is necessary to assure that the average value of latency experienced by the traffic on the used AS-paths realized in timeband \( e \) is lower than the maximum average allowed latency.

**AS-path length constraint wrt. overall traffic (ACO):** In this model, the restriction for the average AS-path length experienced by the overall traffic flow is imposed.

**additional constants**
\( \bar{A} \) maximum average acceptable length of the used AS-paths

**additional constraint**
\[ \sum_d \sum_p \sum_i \sum_e a_{dpie} y_{dpie} \leq \bar{A} \sum_d \sum_e h_{de} \] (7.12)

The inequality given in Eq. (7.12) is necessary to assure that the average length of used AS-paths for all traffic flows is lower than the maximum average acceptable length.

**Latency constraint wrt. overall traffic (LCO):** In this model, the restriction for the average acceptable latency experienced by the overall traffic flow is imposed.

**additional constants**
\( \bar{B} \) maximum average acceptable latency experienced on used AS-paths
additional constraint
\[ \sum_d \sum_p \sum_i \sum_e b_{dipe} y_{dipe} \leq B \sum_d \sum_e h_{de} \quad (7.13) \]

The inequality given in Eq. (7.13) is necessary to assure that the average value of latency experienced by the traffic on the used AS-paths is lower than the maximum average allowed latency.

For the presented models, the problem of optimizing the total network cost is the same as in the case of model with cost-only optimization and is stated as follows:

\[ \text{minimize} \quad F = \sum_d \sum_p \sum_i \sum_e \sum_t c_{dipe} x_{dipe} \quad (7.14) \]

**QoS optimization models with cost constraints**

In QoS optimization models with cost constraints cost parameters are considered as the constraints while the QoS-related values are optimized. As it has been defined, in the following optimization models we also assume that parameter \( b_{dipe} \) denotes the latency experienced on the path going to direction \( d \) through interface \( i \) of partner \( p \) realized in timeband \( e \). On the other hand, the parameter \( a_{dipe} \) represents the length of AS-path to direction \( d \) through interface \( i \) of partner \( p \) realized in timeband \( e \). To introduce the limits related to tariff \( t \), interface \( i \), partner \( p \), timeband \( e \) or overall transit traffic cost the following cost constraints used in QoS-based optimization models have been defined:

**Cost constraint wrt. tariff (CTQ):** In this model, the threshold for cost of the traffic sent through tariff \( t \) is imposed.

additional constants
\( C_{pict} \) maximum acceptable cost for transit traffic going through tariff \( t \) on interface \( i \) of partner \( p \) in timeband \( e \)

additional constraints
\[ \sum_d c_{dipe} x_{dipe} \leq C_{pict} \quad p \in P \quad i \in I_p \quad e \in E \quad t \in T_{pie} \quad (7.15) \]

The inequalities given in Eq. (7.15) are necessary to assure that the average cost of traffic carried through partner \( p \) and tariff \( t \) on interface \( t \) in timeband \( e \) is lower than the imposed threshold.

**Cost constraint wrt. interface (CIQ):** In this model, the threshold for the cost of the traffic sent through interface \( i \) is imposed.

additional constants
\( C_{piet} \) maximum acceptable cost for transit traffic going through interface \( i \) of partner \( p \) in timeband \( e \)
additional constraints

\[ \sum_d \sum_t c_{dpiet} x_{dpiet} \leq C_{pie} \quad p \in P \quad i \in I_p \quad e \in E \quad (7.16) \]

The inequalities given in Eq. (7.16) are necessary to assure that the average cost of traffic carried through such partners \( p \) and interfaces \( t \) in timeband \( e \) is lower than the imposed threshold.

**Cost constraint wrt. partner (CPQ):** In this model, the threshold for cost of the traffic sent through partner \( p \) is imposed.

additional constants

\( C_{pe} \)  maximum acceptable cost for transit traffic going through partner \( p \) in timeband \( e \)

additional constraints

\[ \sum_d \sum_i \sum_t c_{dpiet} x_{dpiet} \leq C_{pe} \quad p \in P \quad e \in E \quad (7.17) \]

The inequalities given in Eq. (7.17) assure that the cost of traffic carried through partner \( p \) in timeband \( e \) does not exceed the assumed threshold \( C_{pe} \).

**Cost constraint wrt. timeband (CEQ):** In this model, the threshold for the cost of the traffic realized in timeband \( e \) is imposed.

additional constants

\( C_e \)  maximum acceptable cost for transit traffic carried in timeband \( e \)

additional constraints

\[ \sum_d \sum_p \sum_i \sum_t c_{dpiet} x_{dpiet} \leq C_e \quad e \in E \quad (7.18) \]

The inequalities given in Eq. (7.18) are necessary to assure that the average cost of transit traffic in timeband \( e \) does not exceed the assumed threshold \( C_e \).

**Cost constraint wrt. overall traffic (COQ):** In this model, the threshold for the overall cost of the traffic is imposed.

additional constants

\( C \)  maximum acceptable cost for overall transit traffic

additional constraint

\[ \sum_d \sum_p \sum_t \sum_e c_{dpiet} x_{dpiet} \leq C \quad (7.19) \]
The inequality given in Eq. (7.19) is necessary to assure that the maximum cost of transit traffic is lower than the assumed threshold $C$.

The optimization function for cost-constrained models obviously depends on the aim. Thus, in case we want to minimize the overall length of chosen AS-paths, the formula is given as follows:

$$
\text{minimize } \quad F = \sum_d \sum_p \sum_i \sum_e a_{dpie} y_{dpie} \tag{7.20}
$$

## 7.3 Heuristic algorithms

In the general case, the solution of the integral assignment problem could be very hard, especially if the number of destinations is large.

To find the problem solution, some new heuristic algorithms are proposed. The greedy-cost heuristics proposed in this chapter extend the algorithms presented in [58]. Some novel heuristics which maximize the experienced QoS parameters while cost-constraints are imposed on the maximum cost of transit traffic are also considered. The descriptions of the proposed heuristics are presented below.

### 7.3.1 Greedy-based heuristic algorithms

In greedy-based heuristic algorithms proposed below the following steps are performed:

- **Step 1**: The traffic flows are sorted in the descending order based on the amount of the required bandwidth.

- **Step 2**: All feasible interfaces for the just considered traffic flow are identified by checking their ability to support the traffic flow. The selection is based on information such as the destination address prefix, available interface capacity, QoS parameters.

- **Step 3**: The metric of each feasible interface is computed. The interface with the lowest metric is selected from the set of feasible interfaces determined in Step 2 and traffic flow is assigned to it.

- **Step 4**: If the limit of the traffic for a partner or interface for the just serviced destination is exceeded, the previous traffic allocation is cancelled except for the traffic allocation to priority destinations, i.e., destinations for which the reassignment has been already performed.

- **Step 5**: After assigning a traffic flow to a feasible interface, the available bandwidth for the next flow is updated. The tariff, interface and partner limits are also decreased accordingly.
- **Step 6**: The next traffic flow is selected; **Step 2**, **Step 3** and **Step 4** are repeated, until all traffic flows have been considered.

The metric calculated in **Step 3** depends on the goal of the heuristic. In case of cost minimization, the metric denotes the cost for the transferred traffic while for performance maximization the quality of the route is considered. Considering the different methods for calculating the metric computed in **Step 3** a number of heuristics can be proposed as follows:

**Partner greedy-cost heuristic algorithm (PGC)**

The partner greedy-cost heuristic algorithm PGC aims at minimizing the transit cost. The metric computed in the PGC heuristic is related to the cost of sending the traffic through a partner. The cost of sending the considered traffic flow through all potential partners is calculated and summed up with the transit costs of the partners resulting from the already assigned traffic flows. The considered traffic flow will be assigned to the interface of such a partner for whom the absolute value of the summed transit cost is the lowest one.

**Destination greedy-quality heuristic algorithm (DGQ)**

The goal of the destination greedy-quality heuristic algorithm DGQ is to assign the traffic flows to the paths offering the best qualities. The overall quality of the paths through which the traffic flows will be realized should be maximized. To obtain it, the traffic flows are assigned to the interfaces through which the paths to destinations with the best available quality can be realized.

**Partner greedy-quality heuristic algorithm (PGQ)**

The partner greedy-quality heuristic algorithm PGQ aims at maximizing the quality of the paths realized through the partners. The metric computed in the PGQ heuristic is related to the quality of paths realized through a partner. The quality of paths proposed by all potential partners for sending the considered traffic flow is calculated and combined with qualities of the already realized paths through the partners. The considered traffic flow will be assigned to the interface of such a partner for whom the value of the quality is the highest one.

**7.3.2 Cost-constrained quality maximization heuristic (CCQ)**

In the cost-constrained quality maximization heuristic CCQ proposed below the following steps are performed:
• **Step 1**: The traffic flows are sorted in the descending order based on their bandwidth requirements.

• **Step 2**: All feasible interfaces for the just considered traffic flow are identified by checking their ability to support the traffic flow. The selection is based on information such as destination address prefix, available interface capacity, QoS parameters.

• **Step 3**: From the set of feasible paths, the paths that do not fulfill the imposed cost constraint requirements are removed.

• **Step 4**: The metric of each remaining interface is computed. The interface with the highest quality (lowest latency) is selected from the set of feasible interfaces determined in **Step 3** and traffic flow is assigned to it.

• **Step 5**: If the limit of the traffic for a partner or interface for the just serviced destination is exceeded, the previous traffic allocation is cancelled except for the traffic allocation to priority destinations, i.e., destinations for which the reassignment has been already performed.

• **Step 6**: After assigning a traffic flow to a feasible interface, the available bandwidth for the next flow is updated. The tariff, interface and partner limits are also decreased accordingly.

• **Step 7**: The next traffic flow is selected; **Step 2**, **Step 3** and **Step 4** are repeated, until all traffic flows have been considered.

### 7.3.3 Two-phase cost-constrained quality maximization heuristic (TCCQ)

The two-phase cost-constrained quality maximization heuristic performs in two phases. In the first phase, the algorithm maximizes the cost. The flows are sorted in the descending order based on the bandwidth requirements and the traffic assignment starts with the biggest flow. The considered aggregated traffic flow is assigned to an interface on which the tariff with the lowest cost is offered. After assigning all traffic flows to chosen interfaces, the transit cost is computed. As the algorithm in the first phase minimizes the cost, we obtain the distribution of traffic flows assuring the lowest cost. In the second phase, the algorithm checks if the requirement related to the maximum acceptable cost is fulfilled. In case the cost is higher than the imposed one, the heuristic finishes as the cost constraint cannot be met. Otherwise, the traffic flow assignment is analyzed and the flows are sorted in the descending order based on the quality of the paths through which they are realized. The traffic flow that experiences the worst path quality
7. Optimized QoS schemes for performance-based inter-domain traffic distribution

Table 7.1: Average measured QoS values offered by partners

<table>
<thead>
<tr>
<th>Measured value</th>
<th>Overall</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average AS-path [hops]</td>
<td>2.72</td>
<td>2.63</td>
<td>2.48</td>
<td>2.46</td>
<td>3.18</td>
<td>2.82</td>
</tr>
<tr>
<td>Average latency [ms]</td>
<td>149.6</td>
<td>148.6</td>
<td>130.6</td>
<td>149.0</td>
<td>154.5</td>
<td>165.5</td>
</tr>
</tbody>
</table>

is chosen first and then reassigned to such a feasible interface which provides the highest quality improvement with the minimum cost increase. The algorithm finishes when no more changes can improve the quality without exceeding the imposed cost constraints.

7.4 Performance evaluation

In order to evaluate the performance of the QoS-based models and proposed heuristics we set up a simulation scenario based on the performed measurements.

7.4.1 Scenario assumptions

To collect data related to the length of AS-paths and latencies we use the RIS Looking Glasses [85] querying the top 1000 websites [4]. We checked that each egress router can reach all of these websites as they are very popular destinations. We assume that 5 RIS collectors located in European Internet Exchange Points (IPX) correspond with potential interconnection partners of the operator that wants to maximize the performance of the traffic for end-users and minimize its transit cost. As the latency, we consider the round-trip time (RTT) experienced on the path realized through the given interconnected partner and the destination address obtained by ping requests.

The results of the performed measurements are presented in Table 7.1. They indicate that the average length of AS-paths offered to the analyzed destination addresses differs among RIS collectors being in the range of 2.46-3.18 while the average number of AS hops is equal to 2.72. The results indicate also that there is a big variability of latencies experienced on paths to the same direction through different partners what justifies our approach aiming at choosing the partners which offer the best paths.

The detailed results of latency measurements are presented in Figs. 7.1-7.3. The probability density function of latencies experienced on the paths offered by partners to queried addresses is shown in Figure 7.1. As the queried destination
addresses were spread all over the world, the measured latencies are spread in
the large range from as small as 0.5 ms up to as high as 800 ms for some websites
(not shown in Figure 7.1).

![Figure 7.1: PDF function vs. average measured latencies to destinations.](image)

The cumulative distribution function is presented in Figure 7.2. The results indicate that approximately 50% of paths experience latencies shorter than 120 ms. There are also 10% of destination addresses with latencies exceeding 300 ms.

The cumulative distribution function of standard deviations related to the latencies experienced on the paths offered by considered partners to queried destinations is presented in Figure 7.3. According to the results, in about 74% of destinations the standard deviation of latencies experienced on the paths offered by the considered partners is lower than 20 ms. However, there are 5% of cases where the standard deviation is higher than 100 ms with some cases where about 200 ms have been experienced.

To perform the cost analysis, we assume that the interconnection partners offer linear tariffs where the total transit cost is directly proportional to the total traffic volume. The unit cost for the used pricing model is generated from the $1 \div 10$ interval using the uniform distribution.

We also assume that each of the interconnected partners is connected with the operator using $I=4$ interfaces (egress routers for inter-domain links). In the analyzed scenario, each interface enables sending the traffic to 250 randomly selected directions from the set of the analyzed 1000 top websites.

The volume of each aggregated traffic flow is randomly derived from the $50 \div$
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7. Optimized QoS schemes

FOR PERFORMANCE-BASED INTER-DOMAIN TRAFFIC DISTRIBUTION

Figure 7.2: CDF function vs. average latencies experienced on the paths offered by partners.

Figure 7.3: CDF function vs. standard deviation of latencies experienced on the paths offered by partners.

150 interval using the uniform distribution. The total amount of traffic is equal to 100 000 traffic units. No capacity limits on tariffs, interfaces or partners have been imposed, i.e., each partner can transit all traffic flows. The overall available capacity is equal to 500 000 traffic units so the network load is equal to 20%.
Table 7.2: Transit cost: results for proposed heuristics

<table>
<thead>
<tr>
<th>Output</th>
<th>Metric–unit cost</th>
<th>Metric–partner cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GCD</td>
<td>RA</td>
</tr>
<tr>
<td>Cost [unit]</td>
<td>154.309</td>
<td>468.030</td>
</tr>
<tr>
<td>Latency [ms]</td>
<td>150.645</td>
<td>152.61</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.998</td>
<td>0.329</td>
</tr>
</tbody>
</table>

7.4.2 Evaluation of proposed schemes

To evaluate the proposed heuristics some numerical experiments were conducted. The results obtained for the proposed schemes are summarized in Tables 7.2-7.6 and Figures 7.4-7.8.

Table 7.2 presents the results of the considered heuristics aiming at minimization of transit cost for an operator. The total cost of the transit traffic has been minimized taking into account either the cost unit (GCD heuristic proposed in Chapter 6) or cost of the traffic going through the partners (PGC heuristic) as the metrics. The considered cost was used for determining the metric of the feasible path. The proposed heuristics (GCD and PGC), which take into account the cost and the traffic volume while assigning the traffic to the interfaces, significantly outperforms the random distribution of the traffic flows. The GCD heuristic provides the better both cost and performance parameters while comparing with the PGCD algorithm. One of the parameters which was used for performance evaluation of the proposed algorithms is efficiency of the routing. This parameter is defined as the ratio of the lower bound cost calculation for the traffic flows to the destination to the total cost for realizing these flows. The routing efficiency obtained by the GCD algorithm indicates that the traffic distribution in this case is very efficient as the value of the considered parameter is almost the highest possible one. By applying the GCD algorithm we obtained the value of the routing efficiency of 0.998 while the maximum value is equal to 1.

Table 7.3 presents the transit cost for the considered partners obtained by the greedy-cost heuristics. In case a partner cost is taken when determining the paths for traffic flows assignment (i.e., the PGCD heuristic is used) the cost is equally balanced among the available partners.

The results obtained for the overall latency minimization while using the DGQ, PGQ and RA heuristics are presented in Table 7.4. The transit costs obtained by the DGQ and PGQ heuristics are even higher than that for the random scheme RA. However, our goal here was to minimize the latency experienced by traffic on the used paths. Inter-domain traffic distribution realized according to the results from the DGQ heuristic will not experience the average latency
Table 7.3: Transit cost: results for partners

<table>
<thead>
<tr>
<th>Partner</th>
<th>GCD</th>
<th>PGC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost [unit]</td>
<td>Lat. [ms]</td>
</tr>
<tr>
<td>$P_1$</td>
<td>17335</td>
<td>129.86</td>
</tr>
<tr>
<td>$P_2$</td>
<td>29114</td>
<td>129.69</td>
</tr>
<tr>
<td>$P_3$</td>
<td>53936</td>
<td>140.70</td>
</tr>
<tr>
<td>$P_4$</td>
<td>34063</td>
<td>162.11</td>
</tr>
<tr>
<td>$P_5$</td>
<td>19861</td>
<td>196.66</td>
</tr>
</tbody>
</table>

Table 7.4: Latency minimization: results for proposed heuristics

<table>
<thead>
<tr>
<th>Output</th>
<th>Destin. latency [ms]</th>
<th>Partn. latency [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGQ</td>
<td>RA</td>
<td>PGQ</td>
</tr>
<tr>
<td>Cost [unit]</td>
<td>505 503</td>
<td>466 127</td>
</tr>
<tr>
<td>Latency [ms]</td>
<td>119.88</td>
<td>149.99</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.30</td>
<td>0.33</td>
</tr>
</tbody>
</table>

higher than 119.88 ms assuming that no congestion is introduced by the traffic flow directed according to the results obtained by using the proposed assignment scheme.

Table 7.5 presents the latency results for the considered partners in case the overall latency has been minimized. To obtain the results we apply the DGQ and PGQ heuristics.

Table 7.6 presents the results of latency minimization with the imposed cost constraint related to the overall cost of the transit traffic. To obtain the results

Table 7.5: Overall latency minimization: results for partners

<table>
<thead>
<tr>
<th>Partner</th>
<th>DGQ</th>
<th>PGQ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost [unit]</td>
<td>Lat. [ms]</td>
</tr>
<tr>
<td>$P_1$</td>
<td>70598</td>
<td>109.41</td>
</tr>
<tr>
<td>$P_2$</td>
<td>324468</td>
<td>128.35</td>
</tr>
<tr>
<td>$P_3$</td>
<td>78908</td>
<td>89.26</td>
</tr>
<tr>
<td>$P_4$</td>
<td>14505</td>
<td>203.80</td>
</tr>
<tr>
<td>$P_5$</td>
<td>17172</td>
<td>102.09</td>
</tr>
</tbody>
</table>
### Table 7.6: Overall latency minimization with the constrained overall cost

<table>
<thead>
<tr>
<th>Cost threshold</th>
<th>Transit cost</th>
<th>Latency [ms]</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>160 000</td>
<td>159 993</td>
<td>146.7</td>
<td>0.963</td>
</tr>
<tr>
<td>200 000</td>
<td>200 000</td>
<td>134.6</td>
<td>0.770</td>
</tr>
<tr>
<td>240 000</td>
<td>239 985</td>
<td>130.0</td>
<td>0.642</td>
</tr>
<tr>
<td>280 000</td>
<td>279 993</td>
<td>128.3</td>
<td>0.550</td>
</tr>
<tr>
<td>320 000</td>
<td>319 998</td>
<td>126.6</td>
<td>0.481</td>
</tr>
<tr>
<td>360 000</td>
<td>359 980</td>
<td>124.6</td>
<td>0.428</td>
</tr>
<tr>
<td>400 000</td>
<td>399 993</td>
<td>122.7</td>
<td>0.385</td>
</tr>
<tr>
<td>440 000</td>
<td>439 959</td>
<td>121.5</td>
<td>0.350</td>
</tr>
<tr>
<td>480 000</td>
<td>479 983</td>
<td>120.4</td>
<td>0.321</td>
</tr>
<tr>
<td>520 000</td>
<td>504 699</td>
<td>119.9</td>
<td>0.305</td>
</tr>
</tbody>
</table>

we applied the two-phase cost-constrained quality maximization heuristic TCCQ.

As we can observe, while the cost threshold is increased, the average latency of the transit traffic decreases. The relaxation of the requirements related to the transit cost enables choosing the paths with lower experienced latencies.

The impact of the introduced strict latency constraints on network performance is presented in Figures 7.4-7.6. The statement ‘strict latency’ means that in case the requirements related to the quality parameters of the paths cannot be met due to some reasons, the demand will not be serviced. Three types of latency constraints have been introduced: latency to the destination (unit latency), latency related to the partner and timeband latency. In case the unit latency is used the paths which violate the unit latency constraints are considered as the infeasible ones. On the other hand, when latency related to the partner is used, the average partner latency is calculated. If the assignment of the traffic flow to the just considered path causes that the imposed partner latency constraints are violated, the path will not be taken into account in the assignment process of the traffic flow. A similar process is applied in case the timeband latency is considered. The difference lies in the fact that instead of the average partner latency calculation the average timeband latency is computed. The details related to the amount of traffic not assigned due to constraint violation are presented in Fig. 7.4. The total amount of the traffic in the network equals to 100 000 units. The results indicate that more than half of the overall transit traffic would be rejected if the requirements related to the unit latency lower than 100 ms had to be fulfilled. The unit latency constraints gives the worst effect. As we can observe, even if we relax the latency constraint up to 200 ms, almost 20% of the traffic will not be serviced. In case the latency requirements related to partner are used, almost no traffic up to 130 ms will be transferred.
The latency of the serviced traffic is shown in Fig. 7.5. The traffic for which the latency requirements were not met has been rejected. Taking that fact into account it is clear that the latency of the remaining (serviced) traffic will be lower than the imposed constraints.

Figure 7.5: Latency of serviced traffic vs. imposed strict latency constraint.

The results for the routing efficiency are given in Fig. 7.6. As we can see, the
impact of the reduction of the latency requirements depends on the type of the metric. In case the timeband latency metric is used, the efficiency starts from about 86% for the latency constraint equal to 100 ms and increases nearly linearly up to almost 100% for the latency constraint decreased up to 200 ms. The effect of changing the latency constraints is quite different in case the partner latency is applied. As it can be seen, up to the latency constraint equal to 130.6 ms the efficiency is nearly constant and is equal to about 67%. While continuing the relaxation of the partner latency constraint, the sudden and considerable deterioration of the efficiency is observed. To explain this big change, Fig. 7.4 and Table 7.1 should be compared. As can be seen, almost no traffic is serviced for the partner latency constraint up to 130 ms. As can be checked in Tab 7.1 the lowest partner latency equals to 130.6 ms and is assured by partner $P_2$. After the partner constraint is slightly relaxed all the traffic can be realized. It means that all traffic flows can be realized and at least one feasible path exists to which the traffic flow going to a given destination can be assigned. However, these feasible paths not necessarily should be the cheapest ones. Indeed, the results indicate that they are not, as the efficiency decreased to as low as about 25%. The further increase of the partner latency constraint causes the increase of the efficiency as more partners are considered to be feasible. The steps observed for the partner latency plots in Fig. 7.5 and Fig. 7.6 are caused by the inclusion of the additional partners to the feasible set of partners. Then, the cheaper paths to the destinations can be found and traffic flows can be assigned to them, resulting in an improvement of the efficiency.

![Figure 7.6: Efficiency of serviced traffic vs. imposed strict latency constraint.](image-url)
The results of loose constraints imposed on the latencies are presented in Figs. 7.7-7.9. The loose constraint determines the work of the algorithm. In the first step, an attempt to send the traffic flows through the paths which fulfill the imposed constraints is made. If no paths with requested parameters exist the second step of the algorithm is applied as follows. After exceeding the imposed constraint the path through such a partner and interface is still considered to be feasible for traffic assignment but the requirements related to latency are decreased. It means that the operator still can send the traffic to a given direction through a path that violates the constraints but performance parameters, e.g., latency will be worse than requested. The results can be used by the operator, e.g., to check the level of performance and cost of the traffic which violates the imposed constraints. Based on the results, a new negotiation process can be started with the client to whom lower QoS parameters of the traffic can be proposed.

The cost of the traffic is presented in Fig. 7.7. In case the timeband latency constraint is considered the cost of the traffic distribution is the lowest possible for obtaining by using the proposed heuristics and equals to about 154000 cost units and almost does not depend on the imposed latency constraints. The loose constraint in this case means that all possible paths can be taken into account in the process of the traffic flows assignment.

![Figure 7.7: Cost of serviced traffic vs. imposed loose latency constraint.](image)

A similar analysis can be conducted for the unit latency constraints. However, here the cost of the traffic is slightly higher than for the case with the timeband constraints. It has to be noted that all partners offer the paths to all destinations...
and the unit costs are generated randomly. From the set of the feasible paths the cheapest one is chosen for traffic flow assignment. If the latency requirements could not be fulfilled the cheapest path from the set of remaining paths is chosen. The plot for the unit latency indicates that some paths fulfilling the requirements related to the unit latency exist. Otherwise, the cost would be the same as for the timeband latency plot. Quite different results were obtained for the partner latency plot. The cost of the traffic in this case is the same as for timeband latency up to the latency constraint of 130.6 ms. It comes from the fact that no partner is able to guarantee the average latency on the offered paths to all destinations below the mentioned value (see Table 7.1). Due to the application of the loose constraint rule, the cheapest paths from all possible paths are chosen assuring the lowest cost. After increasing the latency constraints above 130.6 ms partner $P_2$ has to be taken into account as the partner which guarantee to fulfill the latency requirements. Up to 148.6 ms, all traffic has to be realized through partner $P_2$ which offers the most expensive paths (see Table 7.5). Further latency constraint relaxation enables to include the additional partners to the set of the considered partners and decrease the cost. After including the last partner (for latency constraint higher than 165.5 ms) and relaxing the latency constraint above 180.06 ms (see Table 7.5) no better paths with respect to the latency can be used. Then, all possible paths are considered to be feasible and the cheapest ones are chosen assuring the same results as for the timeband latency plot.

The efficiency of the traffic is presented in Fig. 7.8. The plots related to the latency constraints in case of the efficiency are correlated with the same plots in Fig. 7.7.

![Figure 7.8: Efficiency of serviced traffic vs. imposed loose latency constraint.](image-url)
The best results were obtained for timeband constraints as the best paths for traffic assignment have been used. In case the partner latency constraint had been applied the best partner from the point of view of the guaranteed performance has been chosen while relaxing the requirements for the partner latency up to 130.6 ms. Unfortunately, it is the partner which offers the most expensive paths what results in efficiency as low as 27%. The latency constraint relaxation above 203.8 ms results in the same maximum efficiency equal to 100% for all three considered types of constraints.

The results related to the latency of the serviced traffic are presented in Fig. 7.9. In case the timeband latency constraint up to 150.6 ms, the latency of the serviced traffic is equal to the value of the latency constraint. This is because no paths which could improve the timeband latency exist, resulting in the traffic latency value obtained for the cost minimization heuristic. While relaxing the latency constraints up to 165 ms, some paths fulfilling the imposed constraint can be used, what can be observed as the latency decreases to 147 ms and next gradually goes up to the initial value equal to 150.6 ms. The decrease is caused by the assignment of the traffic flows to the paths fulfilling the imposed requirements.

![Figure 7.9: Latency of serviced traffic vs. imposed loose latency constraint.](image)

The plot for partner latency constraint reflects the same plots in Fig. 7.7 and Fig. 7.8. For the latency constraint up to 130.6 ms, the latency of the traffic is the same as the latency for the timeband constraint. The partner latency relaxation above that value causes that partner $P_2$ has to be used for traffic realization as the one fulfilling the imposed constraint. Further decreasing of the requirements
for traffic latency makes it possible to take into account more paths resulting in the traffic latency decrease. This is due to the algorithm operation where the cost is minimized for the feasible paths.

7.5 Conclusion

In the chapter, a comprehensive approach to the joint cost and performance optimization in the inter-carrier context was proposed. Several optimization models and heuristics for efficient distribution of inter-domain traffic between potential providers which take into account QoS issues were presented. Some of the analyzed schemes are cost effective, however the level of quality they provide could be not satisfying. Others provide the satisfied performance but are not cost-effective. The operator has to decide how the relation between the cost and performance in its network should look like. The results of the conducted research presented in this chapter can help the operators in choosing the most effective traffic distribution schemes while considering both the cost and performance parameters.
Internet Service Providers (ISPs) and operators that want to send traffic to certain directions (destinations/prefixes) outside their networks have many possibilities to choose routes offered by other connectivity providers in a multi-domain environment. This chapter covers the issues related to resilient inter-domain traffic distribution. The goal of the models and algorithms presented here is to optimize connections between telecommunication operators by minimizing costs for served demands and maximizing efficient use of the existing network infrastructure guaranteeing a required level of reliability at the same time.

The chapter is structured as follows. Section 8.1 introduces to the problem of the resilient optimized inter-domain traffic distribution. Section 8.2 provides a mathematical model of the considered LCR problem with some Mixed-Integer Linear Programming (MILP) formulations which take into account reliability requirements. Section 8.3 gives the description of the proposed heuristic optimization algorithms. The scenario assumptions and the obtained results are presented in Section 8.4.
8.1 Introduction

In this chapter, we consider resilience as a protection against a failure of one or more connections between interconnected domains. For example, according to one of the reliability policies, it has to be guaranteed that if one of the interconnection partners, to which a considerable amount of traffic is transmitted, fails, there should be enough capacity available from the other transit providers to compensate the failure by rerouting the traffic. To protect the traffic, one of resilience schemes for interconnection diversity has to be applied. Connection diversity can also be used for load balancing, or to split a large flow into smaller parallel connections if there are no connections with enough bandwidth to support the whole flow. Because of its importance for such applications, the connection diversity is a requirement for inter-domain traffic engineering [84].

A large number of resilience procedures and architectures affecting the level of the reliability has been developed in recent years. A unified Quality of Resilience (QoR) measure is one of the methods enabling comparison of different services/connections from the resilience point of view. Such a framework based on the evaluation of some quantitative recovery parameters, like, e.g., availability, was proposed in [17], [18]. The framework is especially useful from the optimization point of view as it allows to obtain a single number (QoR value) which can describe resilience of a connection just by combining listed parameters.

8.2 MILP formulations for reliability models

The goal of the reliability optimization algorithms implemented in the LCR solution is to find the distribution of the traffic which has to be sent on the required directions to assure the required level of resilience. A general optimization model presented in Chapter 5 can be easily extended in several ways to include resilience requirements.

8.2.1 QoR-based optimization models

QoR-based LCR optimization models take into account QoR parameters when searching the optimal routes. QoR parameters can be used in the goal function or can be considered as the constraints enforcing the required level of resilience for the traffic. We assume that the QoR values related to the path going to direction \(d\) through partner \(p\) on interface \(i\) within tariff \(t\) in timeband \(e\) are known. They can be delivered either by partners (e.g., QoR classes) or defined by an operator through measurement of QoR parameters and their normalization.
QoR optimization models

In QoR optimization models, the overall resilience experienced by traffic flows on assigned paths is maximized. We assume that assigning the considered traffic flows to paths obtained in the optimization process does not impact the QoR parameters on these paths.

QoR optimization model 1: In QoR optimization model 1 $QoR_{dpie}$ parameters are directly used in the goal function. Parameters $QoR_{dpie}$ are assumed to have the values from the range $(0, 1)$. The value $QoR_{dpie} = 0$ denotes that no resilience can be assured while the maximum resilience is assured for $QoR_{dpie} = 1$. It should be noted that some measurements would be necessary to obtain the real $QoR_{dpie}$ parameters. However, in this thesis we assumed that such values are given.

additional constant

$QoR_{dpie} \in (0, 1)$ resilience which can be experienced by the traffic flow sent to destination $d$ through interface $i$ of partner $p$ in timeband $e$

additional variables

$y_{dpie}$ amount of traffic sent to direction $d$ by partner $p$ through interface $i$ in timeband $e$

additional constraints

$$y_{dpie} = \sum_t x_{dpiet} \quad d \in D \quad p \in P \quad i \in I_p \quad e \in E \quad (8.1)$$

The goal of this optimization model is to choose the paths through which the traffic will be realized in such a way that the overall resilience experienced by the traffic flows on the assigned paths is maximized. The goal function can be formulated as follows:

$$\text{maximize} \quad F = \sum_d \sum_p \sum_i \sum_e QoR_{dpie} y_{dpie} \quad (8.2)$$

QoR optimization model 2: In QoR optimization model 2, new unit costs for the traffic going to direction $d$ by partner $p$ through interface $i$ within tariff $t$ in timeband $e$ are calculated taking into account the QoR parameters of the paths $QoR_{dpie}$. The new value of the unit cost considered in the goal function is assumed to be as follows:

$$C_{dpiet} = c_{dpiet}/QoR_{dpie} \quad d \in D \quad p \in P \quad i \in I_p \quad t \in T_{pie} \quad e \in E \quad (8.3)$$
The optimization problem considered in this model can be summarized as follows:

\[
\text{minimize} \quad F = \sum_d \sum_p \sum_i \sum_e \sum_t C_{dpiet} x_{dpiet} \quad (8.4)
\]

**QoR-constrained models**

The QoR-constrained optimization models can be prepared the same way as QoS-constrained optimization models presented in Chapter 7. The difference lies in the fact that in case of the former, the \(QoR_{dpi}\) parameters describing the resilience are considered, while the latter uses parameters reflecting the QoS of the paths (\(b_{dpi}\) is the AS-path latency; \(a_{dpi}\) is the length of the offered AS-path). Also, the goal function is similar: the models defined here take QoR parameters (replacing the QoS parameters) as the restrictions while the total cost of the transit traffic is minimized. As the goal function, we applied the function defined for QoR optimization model 1 (see Eq. (8.2)). The following different cases with respect to QoR constraints can be defined:

**QoR constraint wrt. interface (RCI):** In this model, the restriction for the average resilience experienced by the traffic flow going through interface \(i\) of partner \(p\) in timeband \(e\) is imposed.

**additional constants**

\(QoR_{pie}\) minimum required average resilience to be experienced by the traffic flows realized on paths going through interface \(i\) of partner \(p\) in timeband \(e\)

**additional variables**

\(w_{pie}\) total amount of traffic sent by partner \(p\) through interface \(i\) in timeband \(e\)

**additional constraints**

\[
\begin{align*}
    w_{pie} &= \sum_d \sum_t x_{dpiet} & p \in P & i \in I_p & e \in E \\
    \sum_d QoR_{dpiet} y_{dpiet} & \ge QoR_{pie} w_{pie} & p \in P & i \in I_p & e \in E & (8.5)
\end{align*}
\]

The equality given in Eq. (8.5) adds all the traffic flow volumes going through interface \(i\) of partner \(p\) in timeband \(e\). The inequalities given in Eq. (8.6) are necessary to assure that the average resilience experienced by the traffic flows realized on the paths going through interface \(i\) of partner \(p\) in timeband \(e\) will not be lower than the minimum acceptable value \(QoR_{pie}\).

**QoR constraint wrt. partner (RCP):** In this model, the restriction for the minimum average resilience experienced by the traffic flow going through any partner is imposed.
additional constants

\( QoR_{pe} \) minimum required average resilience to be experienced by the traffic flows realized on paths going through partner \( p \) in timeband \( e \)

additional variables

\( v_{pe} \) total amount of traffic sent by partner \( p \) in timeband \( e \)

additional constraints

\[
v_{pe} = \sum_{i} w_{pie} \quad p \in P \quad e \in E \tag{8.7}
\]

\[
\sum_{d} \sum_{i} QoR_{dpi} y_{dpi} \geq QoR_{pe} v_{pe} \quad p \in P \quad e \in E \tag{8.8}
\]

The equality given in Eq. (8.7) adds volumes of all the traffic flows going through partner \( p \) in timeband \( e \). The inequalities given in Eq. (8.8) are necessary to assure that the average resilience experienced by the traffic flows realized on the paths going through partner \( p \) in timeband \( e \) will not be lower than the minimum acceptable value \( QoR_{pe} \).

QoR constraint wrt. timeband traffic (RCT): In this model, the restriction for the minimum average resilience experienced by the traffic flow going in timeband \( e \) is imposed.

additional constants

\( QoR_{e} \) minimum acceptable average resilience to be experienced by the traffic flows realized on the paths in timeband \( e \)

additional variables

\( j_{e} \) auxiliary variable related to the total amount of traffic sent in timeband \( e \)

additional constraints

\[
j_{e} = \sum_{p} v_{pe} \quad e \in E \tag{8.9}
\]

\[
\sum_{d} \sum_{i} QoR_{dpi} y_{dpi} \geq QoR_{e} j_{e} \quad e \in E \tag{8.10}
\]

The equality given in Eq. (8.9) adds the volumes of all the traffic flows realized in timeband \( e \). The inequalities given in Eq. (8.10) are necessary to assure that the average resilience experienced by the traffic flows realized on the paths realized in timeband \( e \) will not be lower than the minimum acceptable value \( QoR_{e} \).

QoR constraint wrt. overall traffic (RCO): In this model, the restriction for the minimum average resilience experienced by all the traffic flows is imposed.

additional constants
Optimized protection schemes for resilient inter-domain traffic distribution

$QoR$  minimum required average resilience to be experienced by the traffic flows realized on all paths

additional constraints

$$\sum_d \sum_p \sum_i \sum_e QoR_{dpie} y_{dpie} \geq \overline{QoR} \sum_d \sum_e h_{de} \quad (8.11)$$

The inequality given in Eq. (8.11) is necessary to assure that average resilience experienced by the traffic flows realized on the assigned paths will not be lower than the minimum acceptable value $\overline{QoR}$.

For the presented models, the problem of optimizing the total network cost is the same as in the case of the model with cost-only optimization and is stated as follows:

minimize  \[ F = \sum_d \sum_p \sum_i \sum_e \sum_t c_{dpiet} x_{dpiet} \quad (8.12) \]

**QoR optimization models with cost constraints (RCC)**

In QoR optimization models with cost constraints, cost parameters are considered as the constraints while the QoR-related values are optimized. As it has been defined, also in the following optimization models we assume that parameter $QoR_{dpie}$ denotes the resilience experienced on the path going to direction $d$ through interface $i$ of partner $p$ realized in timeband $e$. To introduce the limits related to the acceptable unit $c_{dpiet}$, tariff $t$, interface $i$, partner $p$, timeband $e$ or overall transit traffic cost the same models like those defined in Chapter 7 can be used.

The optimization function for cost-constrained QoR optimization models differs from the cost-constrained QoS optimization models. In the models considered here we want to maximize the overall resilience experienced by the traffic flows on the paths. Thus, the formula is given as follows:

maximize  \[ F = \sum_d \sum_p \sum_i \sum_e QoR_{dpie} y_{dpie} \quad (8.13) \]

**8.2.2 Minimum number of partners (MNP) optimization model**

The MNP optimization model is based on the requirements for the interconnection with a minimum number of partners $P_{min}^e$ and minimum amount of traffic $T_{min}^e$ which has to be sent through these transit partners. Due to this multi-homing approach the impact of failures at the partners (transit providers) can be reduced.

additional constants

$P_{e min}^e \geq 0$  minimum number of partners $p$ in timeband $e$
\( T_{pe}^{\text{min}} \geq 0 \) minimum amount of traffic which has to be sent through transit partner \( p \) in timeband \( e \)

**additional binary variables**

\( a_{pe} \in \{0, 1\} = 1 \) if \( \sum_i w_{pie} > T_{pe}^{\text{min}} \); \( 0 \), otherwise;

**additional constraints**

\[
\begin{align*}
\sum_p a_{pe} & \geq P_e^{\text{min}} & e \in E & \quad (8.14) \\
T_{pe}^{\text{min}} - \sum_i w_{pie} & \leq M(1 - a_{pe}) & p \in P & e \in E & \quad (8.15) \\
\sum_i w_{pie} - T_{pe}^{\text{min}} & \leq Ma_{pe} & p \in P & e \in E & \quad (8.16)
\end{align*}
\]

The constraint given in Eq. (8.14) determines the minimum number of transit partners, while constraints given in Eqs. (8.15)-(8.16) force the minimum amount of traffic sent through the chosen transit partners. The parameter \( M \) is a large number.

### 8.2.3 Minimum free capacity (MFC) optimization models

The MFC optimization models assure that there is a minimum amount of spare (residual) transit capacity available at the partner or interface, e.g., as a percentage of the total traffic transmitted through that partner or interface or as a percentage of the total capacity of that partner or interface. The residual transit capacity is the difference between a given partner or interface capacity and the sum of the traffic already being transmitted through that partner or interface. Below, detailed mathematical models enforcing the minimum amount of spare capacity are presented.

**MFC at partner related to capacity (PMFCC)**

The required residual capacity is considered as a part of the total capacity of partner \( p \).

**additional constants**

\( \alpha_{pe} \) required residual capacity as a part of a limit of partner \( p \) in timeband \( e \)

**additional constraints**

\[
L_{pe} - \sum_i w_{pie} \geq \alpha_{pe} L_{pe} & \quad p \in P & e \in E & \quad (8.17)
\]
MFC at partner related to traffic (PMFCT)

The required residual capacity is considered as a part of the total traffic sent through partner $p$.

**additional constants**

$\beta_{pe}$ required residual capacity at a partner $p$ in timeband $e$ as a part of the total traffic

**additional constraints**

$$L_{pe} - \sum_i w_{pie} \geq \beta_{pe} \sum_d h_{de} \quad p \in P \quad e \in E \quad (8.18)$$

MFC at interface related to capacity (IMFCC)

The required residual capacity at interface $i$ is considered as a part of interface $i$ capacity at partner $p$ within timeband $e$.

**additional constants**

$\gamma_{pie}$ required residual capacity as a part of capacity of interface $i$ at partner $p$ in timeband $e$

**additional constraints**

$$z_{pie} - w_{pie} \geq \gamma_{pie} z_{pie} \quad p \in P \quad i \in I_p \quad e \in E \quad (8.19)$$

MFC at interface related to traffic (IMFCT)

The required residual capacity at the interface related to interface $i$ of partner $p$ in timeband $e$ as a part of the total traffic.

**additional constants**

$\delta_{pie}$ required residual capacity at the interface $i$ of partner $p$ in timeband $e$ as a part of the total traffic

**additional constraints**

$$z_{pie} - w_{pie} \geq \delta_{pie} \sum_d h_{de} \quad p \in P \quad i \in I_p \quad e \in E \quad (8.20)$$

The constraints given in Eqs. (8.17)-(8.20) force the minimum amount of residual capacity as a part of the capacity/traffic at the partner/interface.

### 8.2.4 Single partner protection (SPP) optimization model

The SPP optimization model makes sure that there will be enough spare/residual transit capacity if a single partner fails completely. It will be possible to send the traffic through the backup paths. The resilience assured by the model can be considered as the 1:1 protection scheme [20]. However, to apply the model the
amount of the traffic realized by any partner $p$ in a normal state cannot exceed the half of the overall available capacity.

**Additional variables**

- $b_{dpie} \geq 0$  
  amount of a traffic which would be sent to direction $d$ on backup path realized through interface $i$ of partner $p$ in timeband $e$; 0, otherwise;
- $s_{pe} \geq 0$  
  auxiliary variable related to the amount of traffic which would be sent on all backup paths realized through partner $p$ in timeband $e$

**Additional binary variables**

- $k_{dpie} \in \{0, 1\}$  
  = 1 if the traffic is sent to direction $d$ on backup path realized through interface $i$ of partner $p$ in timeband $e$; 0, otherwise;

**Additional constraints**

\[
\begin{align*}
\sum_p \sum_i f_{dpie} &= 1 & d \in D & e \in E & (8.21) \\
\sum_p \sum_i k_{dpie} &= 1 & d \in D & e \in E & (8.22) \\
\sum_i f_{dpie} + \sum_i k_{dpie} &\leq 1 & d \in D & p \in P & e \in E & (8.23) \\
s_{pe} &= \sum_d \sum_i k_{dpie} h_{de} & p \in P & e \in E & (8.24) \\
\sum_p v_{pe} + \sum_p s_{pe} &\leq \sum_p L_{pe} & e \in E & (8.25)
\end{align*}
\]

The constraints given in Eq. (8.21)-(8.22) assure that only one working path and one backup path exist for the traffic outgoing from the operator to any direction $d$. The requirement for the realization of the working and backup paths through different partners is fulfilled by applying the constraint of Eq. (8.23). The constraint of Eq. (8.24) sums up all the traffic which would be sent to all directions on backup paths going through partner $p$ in timeband $e$. Moreover, the sum of the traffic going through all working and backup paths cannot be higher than the sum of partners' limits (Eq. (8.25)).

### 8.2.5 Single interface protection (SIP) optimization model

The SIP optimization model makes sure that there will be enough spare transit capacity if any single interface fails completely. The additional variable and constraints are given below.

**Additional variable**

- $s_{pie} \geq 0$  
  auxiliary variable relate to the amount of a traffic which would be sent on all backup paths realized through interface $i$ of partner $p$ in timeband $e$
Numbered constraints

\[ f_{dpie} + k_{dpie} \leq 1 \quad d \in D \quad p \in P \quad i \in I_p \quad e \in E \quad (8.26) \]

\[ s_{pie} = \sum_d k_{dpie} h_{de} \quad p \in P \quad i \in I_p \quad e \in E \quad (8.27) \]

\[ w_{pie} + s_{pie} \leq Z_{pie} \quad p \in P \quad i \in I_p \quad e \in E \quad (8.28) \]

\[ \sum_i w_{pie} + \sum_i s_{pie} \leq L_{pe} \quad p \in P \quad e \in E \quad (8.29) \]

The constraint given in Eq. (8.26) determines that the backup path is realized through an interface disjoint path. The constraint of Eq. (8.27) sums up all the traffic which would be sent to all directions on backup paths going through interface \( i \) of partner \( p \) in timeband \( e \). The constraints given in Eqs. (8.28)-(8.29) assure that the traffic limits imposed on the interfaces and partners will not be exceeded.

8.3 Heuristic algorithms

The formulation of the analyzed LCR problem is based on Mixed-Integer Linear Programming (MILP). In the general case, the solution of such a problem could be very hard, especially if the number of involved discrete (binary) variables is large. To find the problem solution, some heuristic algorithms have been proposed. All proposed reliability heuristics are based on the prioritized greedy-cost descending algorithm PGCD described below.

8.3.1 Prioritized greedy-cost descending (PGCD) heuristic

The prioritized greedy-cost descending algorithm PGCD starts by sorting the aggregate traffic flows in the descending order. The sequence is based on the volume of the traffic flows which have to be sent to the required directions. The assignment of the traffic to interfaces is performed starting from the interface with the lowest offered unit cost for the considered direction. In case the capacity limit is exceeded for a partner or interface and the traffic could not be sent to a given direction, the previous traffic flows are reassigned in order to send the traffic flow to required destination. The traffic flow prioritization assures that all demands will be realized if it is feasible.

8.3.2 Minimum number of partners (MNP) heuristic

In the MNP heuristic the partner is preferred if it was already used for transiting the traffic and the amount of traffic sent through that partner is lower than the minimum traffic required to be sent through the partner.
8.3.3 Single partner protection (SPP) heuristic

The SPP heuristic starts by calculating the amount of traffic which has to be protected. This amount of traffic is taken as the minimum from the capacity of the biggest transit provider and the amount of traffic which potentially can be transiting through that partner. Then, the required amount of capacity is reserved at the other feasible interfaces at other transit partners.

8.3.4 MFC at partner related to capacity (PMFCC) heuristic

In the proposed PMFCC algorithm the temporary weight of the partner is introduced. The value of the weight is considered as a penalty and depends on the unit cost and the amount of the traffic already sent through that partner. The initial value of the weight is equal to 0. When traffic exceeds the imposed threshold related to the required minimum free capacity of the partner the value of the temporary weight is increased in order to block the traffic to be sent through that partner.

8.3.5 MFC at interface related to capacity (IMFCC) heuristic

The operation of the proposed IMFCC algorithm is almost the same as for the PMFCC heuristic. The temporary weight related to the interface is introduced. The initial value of the weight is equal to 0. When traffic exceeds the imposed threshold related to the required minimum free capacity of the interface the interface is blocked by setting up the high value of the temporary weight.

8.4 Evaluation of proposed algorithms

To evaluate the developed optimization models and heuristics, a connection scenario was defined. The scenario is specified by a given number of interconnection partners, possible routes, interface constraints, tariff definitions, and volume traffic requirements. The prepared connection scenario was used to evaluate the proposed mechanisms for resilient inter-domain traffic distribution.

8.4.1 Scenario assumptions

To perform the evaluation of the proposed algorithms the scenarios with $P_1=5$ interconnection partners and $D_1=40$ directions have been prepared. To make extensive studies we also investigated two types of scenarios:
8. Optimized protection schemes for resilient inter-domain traffic distribution

- **Type 1**: No preference for partners: the unit cost is uniformly distributed from the $\frac{1}{10}$ interval for all partners.

- **Type 2**: Partner preference: some partners are more preferable due to relatively lower offered transit costs. The unit costs are uniformly distributed from $\frac{1}{3}$ interval for the preferred partners while from the $\frac{4}{10}$ interval for the other partners.

We assume that there is one preferred partner with $I=4$ interfaces and at least two interfaces enable sending the traffic to a given direction. The maximum amount of traffic which can be sent through each of the partners in Type 1 scenarios is uniformly distributed from the range $90 \div 110\%$ of the fixed assumed value equal to 1600 units. In Type 2 scenarios, the preferred partners are able to transit up to $50\%$ of potentially maximum total traffic. The maximum amount of traffic which can be sent through a partner is lower than the sum of capacity of its interfaces. The amount of traffic to be sent to required directions is randomly generated from the $50 \div 150\%$ interval of the analyzed traffic load. The traffic is determined in relation to the sum of partners’ limit (100% traffic load corresponds to the sum of limits of all partners). In Type 1 scenarios each partner is able to transit traffic to $70 \div 80\%$ directions while in Type 1 scenarios the preferred partner can send to $90 \div 100\%$ directions.

8.4.2 Performance evaluation

The described scenarios were used for testing each of the optimization models and heuristic algorithms proposed in this chapter.

The results of the solutions obtained by our models are summarized in Figs. 8.1-8.9. To calculate the exact solution (denoted on the graphs as OPT) we use the commercial MIP solver CPLEX [22]. In Fig. 8.1 the comparison of the transit cost obtained by the PGCD heuristic and CPLEX is presented.

It can be stated that the heuristic performs well as the relative error of the heuristic is in the range from 0% up to 3.9% for 20% and 50% traffic load, respectively. The developed PGCD heuristic performs better for the case with preference partners as the relative error changes from 0% up to only 1.24% for 50% traffic load. The computation time for the developed heuristics is less than 2 seconds and does not depend on the traffic. In case of the CPLEX solver the computation time was in the range of less than 1 second for 10% traffic till 100 minutes for 90% traffic due to the binary model requirements.

The additional cost of the transit traffic for the MNP heuristic is shown in Fig. 8.2.

The reference cost denotes the cost of transit traffic without requirements of the minimum number of partners (obtained by the PGCD heuristic). The graphs
8.4 Evaluation of proposed algorithms

Figure 8.1: Cost results for PGCD heuristic and optimum solution OPT.

Figure 8.2: Cost results for MNP heuristic.

are presented for the scenario with the preferred partner for 10%, 30% and 50% traffic load. The results show that the additional cost for the transit traffic grows up even by 94% for 10% traffic load if it is required to send the traffic through \( P_{\text{min}}=5 \) transit partners. In case of the scenario without the partner preference the cost does not change with the increased \( P_{\text{min}} \) as 5 partners are already used in the optimal traffic distribution.

Apart from the cost, a routing efficiency parameter is used to evaluate the
performance of the proposed algorithms. The comparison of the routing efficiency for the $P_{min}=1 \div 5$ for the scenario with the preferred partner is shown in Fig. 8.3.

![Figure 8.3: Routing efficiency results for MNP heuristic.](image)

The results indicate that the worst routing efficiency (0.7 for 10% traffic load decreasing to 0.53 for 90% traffic load) has been obtained in case of $P_{min}=5$ as the traffic has to be distributed to all partners which offer more expensive tariffs. The results obtained for the MFC optimization models are summarized in Figs. 8.4-8.5. The impact of the traffic load on the transit cost for the PMFCC algorithm is presented in Fig. 8.4.

The graphs are presented for 10%, 20%, 30% and 40% of the required minimum free residual capacity $\alpha_{pe}$ at the partners. As we can see, a higher $\alpha_{pe}$ parameter results in a higher transit cost. According to the results, the transit cost increases from 9% to 66% while increasing the requirements for minimum free residual capacity $\alpha_{pe}$ at the partners from 10% to 40%. The cost increase can be explained by the fact that in the considered case the traffic has to be sent through more expensive interfaces to fulfill the residual capacity requirements needed for the protection of the traffic in case of failure.

The comparison of the PMFCC, PMFCT, IMFCC and IMFCT algorithms is shown in Fig. 8.5. The additional cost is presented in relation to the required minimum residual capacity at a partner related to the capacity ($\alpha_{pe}$) and the traffic ($\beta_{pe}$) as well as in relation to the required minimum residual capacity at an interface related to the capacity ($\gamma_{pie}$) and the traffic ($\delta_{pie}$).

The graphs are presented for the scenario with the preferred partner for 30% traffic load. The highest additional cost of the transit traffic for the compared
8.4 Evaluation of proposed algorithms

Figure 8.4: Cost results for PMFC heuristic.

Figure 8.5: Cost results for MFC heuristics.

algorithms was obtained for the PMFCT heuristic (21% for $\beta_{pie}=50\%$). The cost for the PMFCT scheme grows up almost linearly while increasing the requirements for the minimum free capacity of the partner related to traffic load. The cost for the IMFCT algorithm is lower than that for PMFCT as more traffic can be sent through a partner because the traffic limit of the partner is lower than the sum of the interfaces’ capacity. Due to this, the probability that traffic
will be sent through a cheaper tariff is higher than in the case of the PMFCC algorithm where the partner traffic limits are applied. There are no additional transit costs for the PMFCC and IMFCC algorithms till $\alpha_{pe} = \beta_{pie} = 30\%$. The transit cost increases from $\alpha_{pe} = \beta_{pie} = 40\%$ as just starting from this value the traffic distribution is influenced by the MFC algorithms.

The routing efficiency for the PMFCC, PMFCT, IMFCC and IMFCT algorithms in relation to the traffic load is shown in Fig. 8.6. The graphs are presented for the Type 2 with 40% of the required minimum residual capacity for all the compared algorithms. The PMFCT algorithm obtains the worst routing efficiency as the demands related to the minimum residual capacity and the partners’ limits force sending traffic through more expensive tariffs offered by the other partners.

![Figure 8.6: Routing efficiency results for MFC heuristics.](image)

The comparison of the transit cost for the SPP, MNP and MFC algorithms is shown in Fig. 8.7. In the case of the MNP heuristic $P_{min} = 2$ partners have to be used for traffic distribution. The results indicate that the SPP algorithm is the most cost effective one while comparing with the IMFCC and PMFCC heuristics with 50% requirements related to the residual capacity calculated as a part of traffic and capacity.

The comparison of the routing efficiency for the SPP and the PGCD algorithms while analyzing Type 1 and Type 2 scenarios is shown in Fig. 8.8.

The most efficient routing is applied in the SPP Type 1 case (the same results have been obtained for the PGCD Type 1 case) while the worst results are related to the SPP Type 2 case. It means that using the results of the SPP heuristic we
8.4 Evaluation of proposed algorithms

Figure 8.7: Cost results for proposed heuristics.

Figure 8.8: Routing efficiency results for SPP heuristic.

can cost-effectively protect the traffic against a failure while there are no preferred partners.

In Fig. 8.9 the routing efficiency for the QoR optimization model is presented. As we can see, introducing QoR parameters influence the results as during the path finding process both cost and reliability are considered.

However, the result depends on the relation between these two parameters.
In our computations, we assumed that the preferred partner offers low resilience ($QoR_{dpie} = 0.8 \div 0.86$) while for the other partners that value is in the range of $QoR_{dpie} = 0.9 \div 1.0$. It means that the partner which offers the cheapest routes to almost all directions provides more unreliable routes compared to the routes offered by other partners. As the result, during the route computation a better route from the resilience point of view is chosen. However, for the assumed parameters the chosen path is not cost effective what has been shown by presenting the routing efficiency results.

8.5 Conclusion

In this chapter, a comprehensive approach to both resilient and cost-efficient inter-domain traffic distribution in the inter-carrier context has been proposed. We have presented several optimization models for interconnections between providers which take into account reliability issues. A set of heuristic algorithms for inter-domain traffic distribution has been proposed and analyzed. Some of the analyzed protection schemes are cost effective, however, the level of resilience they provide could be not satisfying. Others provide the full protection but are not cost-effective. The operator has to decide how the relation between cost and reliability in its network should look like. The results of the conducted research presented in the chapter can help operators in choosing the most effective traffic distribution schemes while considering both the cost and resilience parameters.
Part IV

Summary
The main goal of the research presented in the dissertation was to propose mechanisms for efficient inter-domain traffic distribution. The mathematical models and heuristic algorithms have been presented and analyzed. An extensive performance evaluation has been provided throughout the careful study. The simulation analysis was made by using the self-written C++ simulator and CPLEX software.

A Least Cost Routing (LCR) solution has been proposed and evaluated in the thesis. The solution helps to optimize connections between telecommunication operators by minimizing cost for served demands and maximizing the operator’s income, as well as an efficient use of the existing network infrastructure. By using LCR algorithms the routing strategy can be more efficiently executed as the traffic is sent through the most efficient and economical paths. Many different factors that affect the solution of the LCR problem were considered. Apart of the cost of the transit traffic and the performance parameters, the constraints of the physical network have also been taken into account while performing the evaluation of the developed models and algorithms. The presented tariff, interface or partner limits can be based on the economical reasons determined in Service Level Agreements (SLAs) between interconnected partners or technical features like capacities of interfaces, memory size, etc.

A large number of optimization models and heuristic algorithms have been developed in the thesis. The performance evaluation of the proposed LCR solution has been conducted and presented in three parts. The parts differ in the goal of the optimization and imposed constraints. The models and algorithms considered in the first part take only cost into account. In the next two parts the cost, performance parameters and resilience are evaluated.

The general mathematical formulation for the LCR optimization problem
was presented in the first part. The formulation is based on Mixed-Integer Linear Programming (MILP). We consider integral flow assignment, i.e., flows are non-bifurcated. It reflects the fact that due to, e.g., BGP routing requirements, only one path to each destination/prefix is considered. One of the most important parameters for choosing the routes is the interconnection cost. In the thesis, mathematical models of four types of tariffs were developed. These models include linear tariffs, tariffs with opening cost, step tariffs and total volume tariffs. The case with the global promotion was also given.

In the general case, the solution of such an optimization problem could be very hard, especially if the number of involved discrete (binary) variables is large. Thus, to find the problem solution, some heuristic algorithms have been proposed. The proposed heuristics can be put into three sets: algorithms with a greedy-based approach, algorithms which use the simulated annealing technique and evolutionary algorithms. The algorithms which apply the greedy-based approach sort the traffic flows based on the amount of the traffic to be sent to destinations. These algorithms have been compared with the random assignment algorithm where each of aggregated traffic flows is randomly assigned to one of the feasible interfaces. The results indicate that the random-based algorithms are worse in comparison with algorithms which use the ordered list while allocating the traffic to interfaces.

The simulated annealing (SAN) implementation related to the LCR problem starts from an initial solution which is randomly generated from the set of all feasible solutions and the cost of that initial solution is calculated. In the next step, the move in the random direction is performed, i.e., a new solution is generated. The two-step heuristic (LABSAN) was also proposed. The LABSAN algorithm is a combination of the SAN algorithm with the LAB algorithm which takes into account the cost and the available bandwidth. According to the results, the two-step approach significantly reduced the time required for finding solution assuring at the same time a good accuracy. This property of the two-phase algorithm would be especially useful for more complicated scenarios with a higher number of partners and directions than those considered in the thesis as it enables shortening the computation time required for finding the solution for the considered LCR problem.

To solve the LCR problem, the algorithms using the evolutionary approach were also tested. The results indicate that these algorithms also assure a good accuracy. However, the problem is the computation time which for complex scenarios could be unacceptable. As it could be expected, the relation between the computation time and the number of generations is almost linear and depends on the traffic load. We also checked that the time computation for a more complicated scenario with \( P=10 \) transit partners offering the possibility of sending
traffic to $D=200$ directions was very long and after 24 hours the algorithm was stopped.

In the second part, some performance parameters were considered in the developed optimization models and algorithms. The length of the AS-path (Autonomous System path) and latency experienced on that path were used as the indicators of the QoS. In some of the proposed optimization models, QoS parameters were used in the goal function. We also proposed models in which QoS parameters were treated as the constraints related to QoS requirements for aggregated traffic flows. On the other hand, in some models the required level of QoS performance was optimized while the cost constraints were imposed. To find the problem solution some novel heuristics which optimize QoS parameters with imposed cost-constraints were also proposed. To collect data related to the length of the AS-paths and latencies we used the RIS Looking Glasses querying the top 1000 websites. The results of the performed measurements indicate that the average length of AS-paths offered to the analyzed destination addresses differs among RIS collectors being in the range of 2.46-3.18 while the average number of AS hops is equal to 2.72. As the queried destination addresses were spread all over the world, the measured latencies were spread in the large range from as small as 0.5 ms up to as high as 800 ms. The results indicated also that there is a big variability of latencies experienced on paths to the same direction through different partners what justifies our optimization approach. According to the results, in about 74% of destinations the difference between latencies experienced on the paths offered by the considered partners is lower than 20 ms. However, there are 5% of cases for which the standard deviation of latencies experienced on the paths offered by the considered partners are higher than 100 ms with some cases where the values higher than 200 ms have been measured.

The third part deals with the resilience issues. The goal of the reliability optimization algorithms implemented in the LCR solution is to find the distribution of the traffic which has to be sent on required directions to assure the required level of resilience. Some of the proposed optimization models take into account QoR parameters when searching for the optimal routes. In these models, the resilience was maximized or the resilience parameters were imposed as the constraints. Other models imposed the requirements related to the minimum number of transit partners through which the traffic had to be sent or to the minimum spare capacity on the interconnection links. The motivation behind these requirements is to assure sufficient available spare capacity in case of failure and necessity of reassigning traffic flows to the available paths.

In the thesis, a comprehensive approach to the joint cost and performance optimization in the inter-carrier context has been proposed. Several optimization models for interconnections between providers which take into account cost, QoS and resilience issues were presented. Some of the analyzed schemes are cost
effective, however, the level of quality they provide could not be satisfactory. Others provide good performance but they are not cost-effective. The operator has to decide how the relation between cost and performance in its network should look like. The results of the conducted research presented in the thesis can help operators to choose the most effective traffic distribution schemes while considering both the cost and performance parameters. The LCR algorithm can also shorten the time needed for analysis of a large number of alternatives and helps a carrier in taking supporting decisions considering new agreements with other carriers.

Achievements and contributions

The key achievements and contributions of the dissertation can be summarized as follows:

1. An in-depth analysis of Least Cost Routing has been provided. The advantages and drawbacks of the proposed LCR solution have been discussed. It was shown that the solutions described in this work allow for a significant decrease of the transit cost and an improvement of the transmission performance in the network.

2. A large number of optimization models have been developed. In the models, integral flow assignment has been assumed to reflect, e.g., BGP routing requirements where only one path to a given destination can be present in the routing table. The limits for the traffic going through tariffs, interfaces and partners have also been imposed.

3. Offline algorithms to optimize transit cost have been developed. The proposed heuristic algorithms took into account greedy-based methods, simulated annealing techniques as well as an evolutionary approach to find an efficient solution for the optimal distribution of the inter-domain traffic.

4. Heuristic algorithms to optimize network performance under cost constraints and to optimize cost under network performance constraints have been proposed.

5. To setup realistic parameters for the LCR software, an extensive analysis of the Internet topology has been conducted. The results of the measurements show that the multihomed ASes consist of 57% of the analyzed stub networks. Thus, it justified the effort for developing the solution which would help operators to choose the optimal paths.
6. To collect data related to the length of the AS-path and latencies, extensive measurements have been performed. Realistic performance data have been used in simulations to demonstrate that our algorithms yield good performance and low cost.

7. Mathematical models of the considered LCR problem with some Mixed-Integer Linear Programming (MILP) formulations which take into account reliability requirements have been provided. The QoR-based LCR optimization models take into account QoR parameters when searching the optimal routes. In case QoR-constrained optimization models are considered, the restriction for the average resilience experienced by the traffic flows is imposed. In QoR optimization models with cost constraints, cost parameters are considered as the constraints while the QoR-related values are optimized. Other models enforce the traffic flows to be sent through the minimum number of partners or assure the minimum spare capacity on the interconnection links. The protection against a failure of a single partner or a single interface is also considered.

8. Reliability optimization algorithms have been implemented in the LCR solution. The results of the evaluation indicate that the proposed heuristics enable finding the distribution of the traffic assuring a required level of resilience.

In the light of the presented achievements it can be stated that the thesis: *It is possible to efficiently distribute the inter-domain traffic using moderately complex routing algorithms*, has been proved.
Appendix
The detailed results related to the proposed heuristic algorithms are presented in this appendix. In our analysis, we consider $P = 5$ interconnection partners and $D = 40$ directions (prefixes, destinations). We assume that an operator is connected with each potential partner through a number of interfaces (egress routers). The number of interfaces through which the partner is connected with analyzed network was being changed for performed numerical experiments from $I = 1$ to $I = 10$ interfaces.

The results are presented in relation to the traffic load. We assumed that 100% traffic load corresponds to the sum of limits of all partners equal in the considered scenario to $H = 8000$ units.

The relative errors for heuristics are presented in Tables A.1-A.6. The obtained values are related to the optimum solution computed by the CPLEX software. The general observation can be made regarding the obtained relative errors for the proposed heuristics. For low network load the optimal solutions are computed by the developed algorithms. The increase of the traffic load increases also the relative error. However, while analyzing the results we can observe that the relative error increases up to the certain value of the traffic load. After exceeding that value the relative error decreases. The point where the tendency of the relative values is reversed depends on the capacity limits of the partners and interfaces as well as on the number of available interfaces.

The routing efficiency for the developed algorithms are presented in Tables A.7-A.9.

The results related to the rejected traffic flows are given in Tables A.10-A.17. The average volume of the blocked traffic flows is given together with the number of instances for which the blocked traffic flows exists. Taking into account the number of instances with rejected traffic flows the blocking probability for all developed heuristics are computed.
### Table A.1: Relative error for heuristics 1

<table>
<thead>
<tr>
<th>Traffic [%]</th>
<th>Case</th>
<th>Opt. cost [unit]</th>
<th>GCD ε [%] Cred.</th>
<th>GCA ε [%] Cred.</th>
<th>LAB ε [%] Cred.</th>
<th>GCR ε [%] Cred.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>I = 1, $L_{pi} = 2000$</td>
<td>777</td>
<td>0 -</td>
<td>0 -</td>
<td>0 -</td>
<td>0 -</td>
</tr>
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|              | I = 3, $L_{pi} = 540$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 4, $L_{pi} = 500$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 5, $L_{pi} = 400$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 6, $L_{pi} = 340$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 7, $L_{pi} = 290$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 8, $L_{pi} = 250$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 9, $L_{pi} = 230$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 10, $L_{pi} = 200$ | 777 | 0 - | 0 - | 0 - | 0 - |

| 30           | I = 1, $L_{pi} = 2000$ | 777 | 0 - | 0 - | 0 - | 0 - |
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|              | I = 3, $L_{pi} = 540$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 4, $L_{pi} = 500$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 5, $L_{pi} = 400$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 6, $L_{pi} = 340$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 7, $L_{pi} = 290$ | 777 | 0 - | 0 - | 0 - | 0 - |
|              | I = 8, $L_{pi} = 250$ | 777 | 0 - | 0 - | 0 - | 0 - |
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|              | I = 10, $L_{pi} = 200$ | 777 | 0 - | 0 - | 0 - | 0 - |
Table A.2: Relative error for heuristics 2

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Table A.3: Relative error for heuristics 3

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Table A.4: Relative error for heuristics 4

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<th>LABREAL ε [%] Cred.</th>
<th>MAXINT ε [%] Cred.</th>
<th>GCREAL ε [%] Cred.</th>
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<td>0 -</td>
<td>0 -</td>
</tr>
</tbody>
</table>

| 20          |      |                         |                        |                     |                   |                  |
| I = 1, Lₚᵢ = 2000 | 0.17 | 0.15                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 2, Lₚᵢ = 1000 | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 3, Lₚᵢ = 540  | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 4, Lₚᵢ = 500  | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 5, Lₚᵢ = 400  | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 6, Lₚᵢ = 340  | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 7, Lₚᵢ = 290  | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 8, Lₚᵢ = 250  | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 9, Lₚᵢ = 230  | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |
| I = 10, Lₚᵢ = 200  | 0.15 | 0.13                    | 0.15                   | 0.13                | 0.25              | 0.17             |

| 30          |      |                         |                        |                     |                   |                  |
| I = 1, Lₚᵢ = 2000 | 1.89 | 0.43                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 2, Lₚᵢ = 1000 | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 3, Lₚᵢ = 540  | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 4, Lₚᵢ = 500  | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 5, Lₚᵢ = 400  | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 6, Lₚᵢ = 340  | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 7, Lₚᵢ = 290  | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 8, Lₚᵢ = 250  | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 9, Lₚᵢ = 230  | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
| I = 10, Lₚᵢ = 200  | 1.87 | 0.44                    | 1.87                   | 0.44                | 1.48              | 0.34             |
### Table A.5: Relative error for heuristics 5

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<tr>
<th>Traffic [%]</th>
<th>Case</th>
<th>Random MIX</th>
<th>Random Full</th>
<th>LABREAL</th>
<th>MAXINT</th>
<th>GCREAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>I = 1, ( L_{pi} = 2000 )</td>
<td>( \varepsilon ) [%]</td>
<td>Cred.</td>
<td>( \varepsilon ) [%]</td>
<td>Cred.</td>
<td>( \varepsilon ) [%]</td>
<td>Cred.</td>
</tr>
<tr>
<td>40</td>
<td>( L_{pi} = 100 )</td>
<td>0.85</td>
<td>0.41</td>
<td>0.85</td>
<td>0.41</td>
<td>0.93</td>
</tr>
<tr>
<td>( L_{pi} = 500 )</td>
<td>2.39</td>
<td>0.41</td>
<td>2.45</td>
<td>0.42</td>
<td>2.16</td>
<td>0.37</td>
</tr>
<tr>
<td>( L_{pi} = 50 )</td>
<td>4.13</td>
<td>0.39</td>
<td>4.14</td>
<td>0.39</td>
<td>4.70</td>
<td>0.61</td>
</tr>
<tr>
<td>( L_{pi} = 300 )</td>
<td>16.31</td>
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<td>16.24</td>
<td>1.59</td>
<td>8.76</td>
<td>1.49</td>
</tr>
<tr>
<td>( L_{pi} = 400 )</td>
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<td>8.88</td>
<td>1.06</td>
<td>6.08</td>
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<td>1.05</td>
<td>5.34</td>
<td>1.03</td>
<td>4.87</td>
<td>0.97</td>
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<tr>
<td>( L_{pi} = 290 )</td>
<td>9.45</td>
<td>0.96</td>
<td>9.47</td>
<td>0.97</td>
<td>7.52</td>
<td>1.23</td>
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<tr>
<td>( L_{pi} = 250 )</td>
<td>5.80</td>
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<td>5.77</td>
<td>0.73</td>
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<td>6.51</td>
<td>0.94</td>
<td>6.56</td>
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<tr>
<td>( L_{pi} = 200 )</td>
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<td>0.46</td>
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<tr>
<td>( L_{pi} = 500 )</td>
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<td>2.94</td>
<td>0.62</td>
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<tr>
<td>( L_{pi} = 400 )</td>
<td>11.70</td>
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<td>11.78</td>
<td>1.54</td>
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<tr>
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<td>10.15</td>
<td>1.13</td>
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<tr>
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<td>7.98</td>
<td>0.80</td>
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<td>0.90</td>
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</tr>
<tr>
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<td>3.85</td>
<td>0.40</td>
<td>3.00</td>
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<td>15.95</td>
<td>1.74</td>
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<td>13.42</td>
<td>1.48</td>
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Table A.6: Relative error for heuristics 6

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<td>0.68</td>
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<td>1.62</td>
<td>5.17</td>
<td>1.56</td>
<td>4.21</td>
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<td>13.21</td>
<td>1.35</td>
<td>19.74</td>
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<td>0.73</td>
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<td>0.53</td>
<td>1.30</td>
<td>0.63</td>
<td>1.56</td>
</tr>
<tr>
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<td>I = 9, ( L_{pi} = 230 )</td>
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<td>4.26</td>
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</tr>
<tr>
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<td>I = 1, ( L_{pi} = 2000 )</td>
<td>2.05</td>
<td>0.52</td>
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<td>0.50</td>
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</tr>
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<td>1.75</td>
<td>2.72</td>
<td>1.75</td>
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</tr>
<tr>
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<td>I = 5, ( L_{pi} = 400 )</td>
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<td>1.62</td>
<td>13.64</td>
<td>1.62</td>
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<tr>
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<td>I = 6, ( L_{pi} = 340 )</td>
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<td>11.74</td>
<td>2.14</td>
<td>22.89</td>
</tr>
<tr>
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<td>I = 7, ( L_{pi} = 290 )</td>
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<td>1.71</td>
<td>8.82</td>
<td>1.71</td>
<td>9.20</td>
</tr>
<tr>
<td></td>
<td>I = 8, ( L_{pi} = 250 )</td>
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<td>8.22</td>
<td>4.26</td>
<td>10.41</td>
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<tr>
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<td>-</td>
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<tr>
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</tr>
<tr>
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<td>2.54</td>
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<tr>
<td></td>
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<td>2.56</td>
<td>2.35</td>
<td>2.56</td>
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<tr>
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<td>I = 5, ( L_{pi} = 400 )</td>
<td>10.81</td>
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<tr>
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<td>17.44</td>
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<td>16.66</td>
<td>1.90</td>
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</tr>
<tr>
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<td>-</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>I = 9, ( L_{pi} = 230 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>I = 10, ( L_{pi} = 200 )</td>
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### Table A.7: Routing efficiency for heuristics 1

<table>
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<th>Traffic [%]</th>
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<th>GCA</th>
<th>LAB</th>
<th>GCR</th>
<th>Rand. MIX</th>
<th>Rand. Full</th>
<th>LABREAL</th>
<th>MAXINT</th>
<th>GCREAL</th>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
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<td>I = 2, $L_{pi} = 1000$</td>
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<td>1.0</td>
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<td>1.0</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
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<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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</tr>
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<td>1.0</td>
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</tr>
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<td>1.0</td>
</tr>
<tr>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>I = 8, $L_{pi} = 250$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>I = 9, $L_{pi} = 230$</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>I = 10, $L_{pi} = 200$</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

| 20          | I = 1, $L_{pi} = 2000$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
|             | I = 2, $L_{pi} = 1000$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
|             | I = 3, $L_{pi} = 540$   | 0.996 | 0.994 | 0.997 | 0.997 | 0.999 | 0.997 | 0.997 | 0.996 | 1.0 |
|             | I = 4, $L_{pi} = 500$   | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
|             | I = 5, $L_{pi} = 400$   | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
|             | I = 6, $L_{pi} = 340$   | 0.993 | 0.987 | 0.980 | 0.988 | 0.995 | 0.995 | 0.996 | 0.993 | 0.997 |
|             | I = 7, $L_{pi} = 290$   | 0.999 | 1.0 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 1.0 | 0.999 |
|             | I = 8, $L_{pi} = 250$   | 0.999 | 1.0 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 1.0 | 0.999 |
|             | I = 9, $L_{pi} = 230$   | 0.994 | 0.990 | 0.994 | 0.993 | 0.997 | 0.997 | 0.997 | 0.992 | 0.998 |
|             | I = 10, $L_{pi} = 200$  | 0.995 | 0.993 | 0.995 | 0.990 | 0.995 | 0.995 | 0.998 | 0.993 | 0.999 |

| 30          | I = 1, $L_{pi} = 2000$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
|             | I = 2, $L_{pi} = 1000$ | 0.926 | 0.920 | 0.926 | 0.924 | 0.933 | 0.933 | 0.937 | 0.927 | 0.932 |
|             | I = 3, $L_{pi} = 540$   | 0.908 | 0.892 | 0.914 | 0.903 | 0.911 | 0.911 | 0.918 | 0.908 | 0.907 |
|             | I = 4, $L_{pi} = 500$   | 0.846 | 0.815 | 0.844 | 0.831 | 0.856 | 0.859 | 0.931 | 0.839 | 0.920 |
|             | I = 5, $L_{pi} = 400$   | 0.958 | 0.955 | 0.959 | 0.956 | 0.956 | 0.974 | 0.988 | 0.953 | 0.990 |
|             | I = 6, $L_{pi} = 340$   | 0.960 | 0.929 | 0.964 | 0.947 | 0.966 | 0.966 | 0.973 | 0.961 | 0.968 |
|             | I = 7, $L_{pi} = 290$   | 0.891 | 0.871 | 0.890 | 0.875 | 0.899 | 0.898 | 0.924 | 0.895 | 0.911 |
|             | I = 8, $L_{pi} = 250$   | 0.921 | 0.890 | 0.921 | 0.904 | 0.930 | 0.930 | 0.935 | 0.923 | 0.914 |
|             | I = 9, $L_{pi} = 230$   | 0.893 | 0.853 | 0.895 | 0.873 | 0.900 | 0.900 | 0.911 | 0.898 | 0.891 |
|             | I = 10, $L_{pi} = 200$  | 0.900 | 0.853 | 0.899 | 0.879 | 0.912 | 0.911 | 0.936 | 0.898 | 0.923 |
Table A.8: Routing efficiency for heuristics 2

<table>
<thead>
<tr>
<th>Traffic [%]</th>
<th>Case</th>
<th>GCD</th>
<th>GCA</th>
<th>LAB</th>
<th>GCR</th>
<th>Rand. MIX</th>
<th>Rand. Full</th>
<th>LABREAL</th>
<th>MAXINT</th>
<th>GCREAL</th>
</tr>
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<td>0.950</td>
<td>0.969</td>
<td>0.962</td>
<td>0.970</td>
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<tr>
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<td>$I = 2$, $L_{pi} = 1000$</td>
<td>0.861</td>
<td>0.814</td>
<td>0.842</td>
<td>0.829</td>
<td>0.864</td>
<td>0.865</td>
<td>0.868</td>
<td>0.865</td>
<td>0.860</td>
</tr>
<tr>
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<td>$I = 3$, $L_{pi} = 540$</td>
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<td>0.839</td>
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<td>0.709</td>
<td>0.709</td>
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<td>0.730</td>
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<td>0.707</td>
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<td>$I = 5$, $L_{pi} = 400$</td>
<td>0.894</td>
<td>0.852</td>
<td>0.897</td>
<td>0.864</td>
<td>0.900</td>
<td>0.900</td>
<td>0.924</td>
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<td>$I = 6$, $L_{pi} = 340$</td>
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<td>0.814</td>
<td>0.842</td>
<td>0.829</td>
<td>0.864</td>
<td>0.865</td>
<td>0.868</td>
<td>0.865</td>
<td>0.860</td>
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<tr>
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<td>$I = 7$, $L_{pi} = 290$</td>
<td>0.780</td>
<td>0.728</td>
<td>0.777</td>
<td>0.762</td>
<td>0.791</td>
<td>0.791</td>
<td>0.806</td>
<td>0.786</td>
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<td>0.794</td>
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<td>0.791</td>
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<td>0.770</td>
<td>0.773</td>
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<td>0.785</td>
<td>0.771</td>
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<td>0.710</td>
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<td>0.578</td>
<td>0.598</td>
<td>0.594</td>
<td>0.599</td>
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<td>0.598</td>
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</tr>
<tr>
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<td>$I = 2$, $L_{pi} = 1000$</td>
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<td>0.721</td>
<td>0.715</td>
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<td>0.725</td>
<td>0.731</td>
<td>0.721</td>
<td>0.724</td>
</tr>
<tr>
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<td>0.655</td>
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<tr>
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<td>$I = 4$, $L_{pi} = 500$</td>
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<td>0.515</td>
<td>0.537</td>
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<td>0.539</td>
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<td>0.543</td>
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<td>0.538</td>
</tr>
<tr>
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<td>0.656</td>
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<td>0.659</td>
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<td>0.618</td>
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<td>0.644</td>
<td>0.625</td>
<td>0.648</td>
<td>0.617</td>
</tr>
<tr>
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<td>0.618</td>
<td>0.618</td>
<td>0.615</td>
<td>0.618</td>
<td>0.598</td>
</tr>
<tr>
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<td>$I = 8$, $L_{pi} = 250$</td>
<td>0.596</td>
<td>0.530</td>
<td>0.596</td>
<td>0.575</td>
<td>0.597</td>
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<td>0.598</td>
<td>0.603</td>
<td>0.588</td>
</tr>
<tr>
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<td>$I = 9$, $L_{pi} = 230$</td>
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<td>0.550</td>
<td>0.600</td>
<td>0.589</td>
<td>0.608</td>
<td>0.608</td>
<td>0.610</td>
<td>0.604</td>
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<tr>
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<td>$I = 10$, $L_{pi} = 200$</td>
<td>0.550</td>
<td>0.490</td>
<td>0.550</td>
<td>0.518</td>
<td>0.551</td>
<td>0.551</td>
<td>0.570</td>
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</tr>
</tbody>
</table>
Table A.9: Routing efficiency for heuristics 3

<table>
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<tr>
<th>Traffic [%]</th>
<th>Case</th>
<th>GCD</th>
<th>GCA</th>
<th>LAB</th>
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Table A.10: Blocking for heuristics 1

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Table A.11: Blocking for heuristics 2

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Table A.12: Blocking for heuristics 3

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Table A.13: Blocking for heuristics 4

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Table A.14: Blocking for heuristics 5

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Table A.15: Blocking for heuristics 6

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