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COIMBRA

Catarina Isabel Dinis Francisco

A STUDY ON MULTIOBJECTIVE DYNAMIC ALTERNATIVE ROUTING

Tese no âmbito do Doutoramento em Engenharia Electrotécnica e de Computadores, Ramo de Especialização em Telecomunicações, orientada pela Professora Doutora Lúcia Maria dos Reis Albuquerque Martins e apresentada ao Departamento de Engenharia Electrotécnica e de Computadores da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

Fevereiro de 2021

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Resumo

A Internet tornou-se numa verdadeira plataforma de negócios cujo tráfego tem que ser gerido com eficiência. A chegada iminente das redes 5G aumenta o potencial do uso dos telemóveis e computadores portáteis para tarefas do quotidiano ou de trabalho colaborativo que exigem a satisfação de requisitos apertados de Qualidade de Serviço (QoS). Com o aumento do tráfego, em volume e dinamismo, e a estagnação da receita dos operadores, o sobredimensionamento deixou de ser uma opção viável e é imperativo que sejam utilizados mecanismos sofisticados para garantir simultaneamente uma gestão eficiente dos recursos e a satisfação dos Acordos de Nível de Serviço. Os operadores de Internet podem tirar partido de mecanismos de gestão de tráfego e de garantia de QoS através da adoção de *Multiprotocol Label Switching* (MPLS) nas suas redes.

De modo a maximizar a rentabilização dos recursos instalados sem deixar degradar o bloqueio para os diferentes fluxos de tráfego, esta dissertação começa por propor um método de encaminhamento alternativo dinâmico dependente do estado com formulação multiobjectivo para redes MPLS multi-serviço, o *Simplified MultiObjective Dynamic Routing* (SMODR). Este método de encaminhamento procura maximizar o tráfego transportado e minimizar o máximo bloqueio ponto-a-ponto para cada serviço e simultaneamente maximizar o tráfego transportado total mantendo o máximo dos bloqueios médios para cada serviço o menor possível. O problema é resolvido através de uma heurística que calcula periodicamente o conjunto de caminhos alternativos (um caminho por par origem-destino) que melhor se adaptam às condições de tráfego oferecido e que conduzem à obtenção de boas

soluções de compromisso para o modelo multiobjectivo subjacente. O SMODR é validado recorrendo a uma plataforma de simulação onde o seu desempenho é comparado com o de um método de referência de encaminhamento dinâmico.

Verificou-se ainda que, em situações de desequilíbrio de tráfego, caminhos alternativos únicos por par origem-destino (como no caso do SMODR) podem não ter os recursos necessários para transportar todo o tráfego de transbordo. Para resolver este problema é proposto um novo método de encaminhamento designado por *Dynamic Multicriteria Alternative Routing* (DMAR), que associa uma estratégia dependente do evento (baseada no bloqueio ou no sucesso no estabelecimento de uma ligação) à atualização periódica de múltiplos caminhos alternativos por par origem-destino e para um dado estado da rede. O desempenho do método é comparado com o de métodos de referência recorrendo a uma plataforma de simulação que permitiu simular tráfego dinâmico (ou não estacionário). Os resultados mostram que o DMAR faz uma utilização eficiente dos recursos disponíveis na rede tendo em conta os vários fluxos de tráfego numa rede mono-serviço, e também os diferentes serviços em ambientes multi-serviço, conduzindo a um melhor desempenho global da rede.

As redes MPLS devem ainda ser resilientes. No caso de uma falha num *link* de uma rede com encaminhamento alternativo dinâmico, futuros pedidos de ligação podem tentar caminhos alternativos, mas o tráfego em curso no *link* falhado no instante da falha é perdido. Para resolver este problema foi proposta uma estratégia que associa um método de encaminhamento alternativo dinâmico com um mecanismo de proteção local sem reserva de largura de banda, *Dynamic Alternative Routing with local Multiple paths Protection* (DARMP), realçando a importância de se projetar um mecanismo de proteção alinhado com o método de encaminhamento no sentido de se melhorar o desempenho da rede minimizando os recursos envolvidos também em caso de falha. O DARMP é validado por simulação através da comparação do seu desempenho com o de dois métodos de encaminhamento fixo com protecção local.

Os métodos de encaminhamento propostos neste trabalho são centralizados e dependentes do estado, sendo por isso adequados às emergentes redes definidas por *software*, ou *Software-Defined Networks* (SDN).

Abstract

The Internet has become a true business platform where the traffic has to be efficiently managed. The imminent arrival of 5G networks increases the potential of using mobile phones and laptops for everyday tasks or collaborative work with tight Quality of Service (QoS) requirements. With increasing traffic in volume and dynamism, and the stagnation of operators' revenues, overprovisioning is no longer a reasonable option and it is imperative that more sophisticated mechanisms are used to simultaneously guarantee an efficient management of resources and the fulfilment of the Service Level Agreements (SLAs). Internet operators can take advantage of traffic management and QoS guarantee mechanisms through the adoption of Multiprotocol Label Switching (MPLS) on their networks.

To maximize the profitability on installed resources without degrading the blocking for the different traffic flows, this dissertation begins by proposing a state-dependent dynamic alternative routing method for multiservice MPLS networks, *Simplified MultiObjective Dynamic Routing* (SMODR). This routing method seeks to maximize the carried traffic and to minimize the maximum point-to-point blocking probability for each service while maximizing the total carried traffic keeping the maximal service mean blocking probability as lower as possible. The problem is solved by a heuristic that periodically calculates the set of alternative paths (one path per source-destination pair) that best fits the offered traffic conditions and leads to good compromise solutions for the underlying multiobjective model. SMODR is validated using a simulation platform where its performance is compared to that of a reference dynamic routing method.

It has also been found that in situations of traffic imbalance single alternative paths per source-destination pair (as in the case of SMODR) may not have the resources to carry all the overflow traffic. To solve this problem a new routing method called *Dynamic Multicriteria Alternative Routing* (DMAR) is proposed, which associates an event-dependent strategy (based on the blocking or acceptance of a connection request) with the periodic update of multiple alternative paths per source-destination pair and for a given network state. The performance of the method is compared to that of reference methods using a simulation platform that allowed to simulate dynamic (or non-stationary) traffic. The results show that DMAR makes efficient use of the available network resources taking into account the various traffic flows in a single service network, as well as the different services in multiservice environments, leading to a better overall network performance.

MPLS networks must also be resilient. In the event of a link failure in a network with a dynamic alternative routing method, incoming connection requests may attempt alternative paths but the traffic in progress on the failed link at the time of the failure is lost. To address this problem, a strategy has been proposed that combines a dynamic alternative routing method with a local protection mechanism without bandwidth reservation, *Dynamic Alternative Routing with local Multiple paths Protection* (DARMP), highlighting the importance of designing a protection mechanism in line with the routing method to improve the network performance while minimizing the resources usage also in the event of a failure. DARMP is validated by simulation by comparing its performance against two fixed routing methods with local protection.

The routing methods proposed in this work are centralized and state-dependent, being adequate for the emerging Software-Defined Networks (SDN).

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Chapter 1

Introduction

1.1 Overview and Objectives of the Thesis

Telco operators are struggling with the ever-increasing traffic volume generated by services with distinct traffic patterns and Quality of Service (QoS) requirements. An efficient real-time traffic management is key to maximize the network performance, including in scenarios of load shifts or failures. It may involve monitoring the network performance, such as the collection of traffic measurements and performance metrics, or applying control mechanisms, such as acting on the routing tables.

Dynamic routing has been used to improve the network performance and resilience in recently proposed solutions applicable in network environments as diverse as Software-Defined Network (SDN) architectures and Data Center Networks (DCNs). Dynamic alternative routing is a special type of dynamic routing that allows a second chance to an incoming service connection for which the first-choice path does not have the available resources to meet its QoS requirements. It has been widely studied and implemented in circuit-switched voice telephone networks, one of the most well-known reservation-oriented networks, to improve the network performance due to its rerouting capability in congestion or failure situations. The use of dynamic alternative routing in MPLS networks, that also have the ability to provide service guarantees through the reservation of resources, brings similar benefits.

Classical dynamic alternative routing methods are typically single criterion aiming at the maximization of the carried traffic, maximizing the total revenue, even in abnormal operating situations, such as traffic overloads or network failures. However, the maximization of the carried traffic often leads to higher values of the maximal point-to-point blocking probability in single service networks. On the other hand, in multiservice multirate networks where the bandwidth is shared by all services, it does not guarantee fairness in terms of the quality of service provided to the individual services, which can be measured by the maximal service mean blocking probability. An attempt to solve this problem is proposed with the MultiObjective Dynamic alternative Routing (MODR) method, extensively documented in [52]. When applied in multiservice networks, its alternative routing optimization model is formulated with an explicit representation of several QoS objectives at network and service levels, including the incorporation of fairness objectives concerning service types (minimization of the maximal service mean blocking probability) and traffic flows of each service type (minimization of the maximal point-to-point blocking probability of all traffic flows of each service type). The purpose of MODR is then to periodically find the "best" set of single alternative paths that represent a compromise solution between the objective functions, according to the state of the network.

The main purpose of this thesis is to extend the multiobjective dynamic alternative routing concept introduced in [52], originally applying to circuit-switched loss networks, to the new technologies, as it is the case of MPLS. In this context, the requirements for the adoption of dynamic alternative routing in MPLS networks are detailed. Next step aims at reducing the computational complexity of the resolution strategy for the multiservice networks to make it more suitable for a realistic network environment. Instead of updating the complete routing plan, as proposed in the original heuristic, the new simplified heuristic explores the periodical update of the alternative paths for a subset of the available pairs of nodes. A selective alternative paths removal mechanism is also introduced to prevent the excess of alternative routing in congestion situations. This new method using the simplified heuristic for path calculation is designated as Simplified MODR (SMODR). In this work, the SMODR is validated in several load scenarios resorting to a simulation platform.

On the other hand, traffic in real networks is dynamic by nature leading to the occurrence of imbalanced traffic situations, unforeseen when dimensioning the network. In these scenarios, single alternative paths may not have the necessary resources to accommodate the overflow traffic from first-choice paths. A better network performance may be achieved if this overflow traffic is spread across multiple alternative paths (as opposed to using a single alternative path as in SMODR) taking advantage of the available bandwidth in the network. This thesis proposes a new routing scheme designated as Dynamic Multicriteria Alternative Routing (DMAR). DMAR is based on a path caching model where the set of alternative paths to be used by an event-dependent strategy like DAR [28], an event-dependent routing method that was implemented in the British Telecom (BT) circuit-switched voice network, is periodically updated according to an offered traffic estimate by a heuristic based on a biobjective shortest path algorithm using the blocking probabilities and the implied costs [40, 54], as in SMODR. While the minimization of blocking tends to find paths that lead to the minimization of the maximum point-to-point blocking for each service, minimizing the implied costs tends to find paths that maximize the revenue associated with the network traffic. In this work, the concept of implied cost is extended to allow multiple alternative paths. DMAR is then validated by a simulation study and its performance compared to that of reference methods in a diversified environment in terms of network model (single service and multiservice), network topology (fully meshed and sparser) and traffic matrices (with stationary and dynamic traffic).

Due to its rerouting capabilities dynamic alternative routing is already known to improve not only the network performance in the presence of traffic fluctuations but also the network survivability in case of a link failure. If such failure occurs in a network with alternative routing, an incoming connection request whose first-choice path traverses the failed link may attempt a link-disjoint alternative path. However, this approach does not address the traffic in progress on the failed link, which is lost. Traffic rescue can be accomplished by a recovery mechanism where a pair of link-disjoint paths (primary and backup) is provided between the failed link end nodes.

MPLS must meet the needs of real-time applications which impose a stringent recovery time in case of failure. The IETF MPLS working group has proposed a local protection mechanism designated as Fast ReRoute (FRR) providing recovery in tens of milliseconds. This work suggests a local protection mechanism without bandwidth reservation that can be used with any dynamic alternative routing method to improve the network performance also in case of a link failure. This new strategy allows rescuing not only incoming connections, which is typical of alternative source routing, but also connections in progress on the failed link, which is the new achievement in this approach. The proposed local protection mechanism makes use of the traffic splitting concept and it is suitable to save real-time traffic in the same network topologies where alternative routing is effective. The resulting method is designated as Dynamic Alternative Routing with local Multiple paths Protection (DARMP) and it is tested in this work against DAR [28], the same event-dependent dynamic alternative routing method that inspired DMAR. The typical routing paradigm in MPLS networks is the fixed routing. The new DARMP strategy is thus evaluated in this thesis through a simulation study where the network performance with DARMP is compared against the network performance considering the implementation of two other approaches of fixed routing with local protection. Performance results demonstrate the importance of designing a protection mechanism in alignment with the implemented routing method to improve the network performance while minimizing the resources usage, also in case of a link failure.

The main contributions of this thesis are the following:

- The description of the necessary assumptions to have dynamic alternative routing in MPLS networks, namely the connection admission control mechanism that is mandatory in case of alternative routing.

- The proposal and implementation of a simplified heuristic leading to a complexity reduction of the resolution strategy proposed in [52] for the multiobjective dynamic alternative routing problem in multiservice networks. The new SMODR method is validated in a simulation study.

- The proposal of a new routing method, DMAR, combining an event-dependent strategy with a periodic update of alternative paths according to an offered traffic estimate and based on a bicriteria shortest paths algorithm using the blocking probabilities and the implied costs.

- The description of the analytical model supporting DMAR for multiservice networks, namely the extension of the implied costs concept to allow the use of multiple alternative paths. This model also applies to single service networks, which are a particular case of the multiservice networks.

- The proposal and implementation of the heuristics in charge of the periodic path calculation in the scope of DMAR for single service and multiservice networks. A simulation study compares the performance of DMAR with that of reference methods in both single service and multiservice environments.

- The proposal and implementation of the DARMP strategy combining a local protection mechanism without bandwidth reservation with a dynamic alternative routing scheme in order to improve the network performance while minimizing the resources usage, also in case of a link failure. DARMP is evaluated in this work through a simulation study comparing its performance with that of two other routing schemes with local protection.

1.2 Organization of the Thesis

This thesis comprises a total of seven chapters, complemented by three appendices with supplementary material.

Chapter 2 presents a brief overview of recent work on dynamic routing strategies in communications networks. A special focus is on dynamic alternative routing given that it is the type of routing methodology addressed by this work.

Chapter 3 introduces fundamental concepts within the scope of the methods addressed in this work, namely the formalization of the network representation and the traffic models underlying the proposed dynamic alternative routing methods, including the extension of the formulation of the implied costs to include multiple alternative paths. A strategy to solving the multiobjective shortest path problem is further presented.

Chapter 4 starts with the description of the necessary assumptions to have dynamic alternative routing in MPLS networks, followed by a brief review on the original MODR method. Next, SMODR is proposed for a multiservice environment, with a new simplified heuristic and a new selective alternative paths removal mechanism. In the end, a simulation study evaluates the performance of SMODR in several load scenarios.

Chapter 5 begins by presenting DMAR and proposing the heuristics responsible for the path computation in both single service and multiservice networks, being followed by a simulation study evaluating the network performance of the routing method in a diversified environment in terms of network model, network topology and traffic matrices.

Chapter 6 proposes the DARMP strategy that combines a dynamic alternative routing scheme with a local protection mechanism with multiple protection paths and no bandwidth reservation. A simulation study includes the description of the routing and protection framework, as well as the analysis of the comparative performance of DARMP with two other approaches with fixed routing and local protection.

Finally, chapter 7 presents the main conclusions and outcomes of the work developed along this thesis.

Chapter 2

Dynamic Routing in Communications Networks

2.1 Introduction

Network routing can be broadly classified into circuit-switched, packet and transport routing [57]. In circuit-switched networks, a dedicated path with allocated bandwidth from source to destination is set up on-demand before the communication can take place, and it is maintained for the duration of the communication. On the other hand, in packet networks, the data traffic is transferred from source to destination in the form of packets, and each individual router along the path is responsible for choosing the outgoing link on a packet-by-packet basis as soon as the packet arrives. Finally, transport networks serve as the bearers of services at a physical level, and its links are typically maintained on a semi-permanent basis, with a high bandwidth value which is kept fixed for long periods of time.

Circuit-switched routing can be implemented through fixed and dynamic routing approaches. In fixed routing, the routing tables are fixed over time, whereas, in dynamic routing, as its name suggests, the routing tables may change over time to accommodate changes in the network traffic pattern or topology.

In the simplest case of fixed routing, there is a fixed single path connecting each pair of end nodes (this is called direct routing when the single path is the direct link). Hierarchical and non-hierarchical routing networks may be based on fixed routing, namely through the use of alternative routing, where traffic rerouting is allowed in case a first-choice path is denied access. In the fixed hierarchical routing networks widely used until the 90s, when the high-usage (direct) links were busy, calls would overflow to an alternative path in the immediate superior hierarchy, subjected to fixed hierarchical rules defined at the design stage. A common approach to non-hierarchical networks is also fixed alternative routing, where the set of admissible paths is pre-determined and the order in which they are used is maintained over time.

The evolution of the technology, not only at the network elements design, but also the emergence of new signaling mechanisms, the rise of data networks, and improved processing capabilities, allowed the appearance of a more flexible type of routing, capable of adapting to new network loads and conditions, the dynamic routing. Dynamic routing in circuit-switched networks has been an active research topic that regained importance with reservation-oriented networks, where a flow may be denied access to the network in case of unavailability of resources throughout the end-to-end path, as it is the case of MPLS and optical networks. Section 2.2 reviews some recent work on dynamic routing, and section 2.3 addresses alternative routing methods in its two variants in non-hierarchical networks: fixed alternative routing and dynamic alternative routing (a special type of dynamic routing, which uses alternative routing, and to which the methods proposed in this thesis belong to). Section 2.4 addresses recent approaches to dynamic routing for the purpose of improving network resilience.

To maximize network performance, including in scenarios of load shifts or failures, an efficient real-time traffic management is essential. It may include monitoring the performance of the network or implementing control mechanisms, such as updating routing tables. Dynamic routing can therefore be key, especially at a time of stagnant revenue for operators, who still have to deal with increased traffic volume, coupled with services with disparate and tight QoS requirements. As such, the use of a multiobjective formulation for dynamic routing problems may be advantageous as it allows to explicitly address various cost and QoS parameters, such as the bandwidth or the blocking probability, in the mathematical models by incorporating some parameters as objective functions and the remainder as constraints. Section 2.5 briefly reviews some work on multiobjective dynamic routing methods, exploring the advantages of multiple objectives in the context of dynamic routing.

In the emergent Software-Defined Networking (SDN) architecture [60], the control and data planes are decoupled enabling centralized management and control of devices and providing the SDN applications with an abstraction of the network. The network devices become simple forwarding devices and the network intelligence is centralized in a single logical point in software-based SDN controllers giving the operators vendor-independent control over the entire network via dynamic and automated SDN programs to quickly respond to business needs. The Path Computation Element (PCE) [73] is a core component of the SDN architecture and it is in charge of computing the paths for the entire network (it is indicated in particular for the calculation of CPU-intensive path computations such as multiobjective ones). Since in SDN the centralized controller maintains an overall view of the network through up-to-date network status information, the PCE can dynamically calculate optimized paths for the entire network in order to minimize the resources utilization while satisfying QoS requirements. In this sense, the evolution of the Internet towards SDN strengthens the proposal of centralized and state-dependent dynamic routing methods, as it is the case of the dynamic alternative routing methods with multiobjective formulation proposed in this work.

2.2 Dynamic Routing

Dynamic routing has been proposed to improve network performance, through the optimization of resource usage while fulfilling service or user requirements, in diversified environments, namely in SDN architectures and Data Center Networks (DCNs).

The work in [46] proposes a new heuristic to solve the routing problem in MPLS networks based on Segment Routing (SR) in an SDN environment. SR [27] is a source routing technology that can be applied to MPLS networks without any change in the MPLS data plane [9], according to which the path is defined at the source node as an ordered list of segments and encoded in the packet header as a stack of MPLS labels, improving SDN scalability as there is no path state maintenance required in each node along the path. The new algorithm not only reduces the extra network overhead caused by the segment labels in the packet headers when using SR by setting a limitation on the length of the paths, but it also contributes to the network load balance through the concepts of link criticality and link residual bandwidth. The link criticality parameter reflects the predicted traffic load on each link and it allows inferring about the likelihood of a link becoming a bottleneck. The algorithm works as follows: periodically, the traffic matrix for the following time interval is estimated based on traffic measurements from the previous time interval. Afterward, the k-shortest paths with a maximum length are computed for all pairs of end nodes allowing the calculation of the link criticality, for each link considered in the shortest paths. It follows the calculation of the congestion index for each link, defined as the ratio between the total carried traffic in the link and the remaining bandwidth in the same link. The weight of each link is calculated as a weighted sum of the link criticality and of the congestion index. At this point, the links whose residual bandwidth is lower than the requested bandwidth are deleted. Finally, every time that a new connection request arrives, the Bellman-Ford algorithm is ran using the link weight as cost and including a constraint for the maximum path length. The determination of the minimum weight path with a maximum hop count is accompanied by the update of the corresponding link residual bandwidth values. The performance results show that the new algorithm performs better than reference ones in terms of average network throughput and blocking probability. The authors also conclude that the algorithm time complexity makes it suitable for a dynamic online routing environment.

A Quality of Experience (QoE)-centric SDN-based multipath routing approach for multimedia services over 5G networks is proposed in [8]. It works by forwarding traffic through multiple dynamically chosen disjoint paths to optimize the network resource usage and the end-users' QoE. MultiPath TCP (MPTCP) is an IETF effort for a standard transport protocol allowing a TCP connection to spread traffic across several subflows, allowing to provide high throughput for large flows. The proposed strategy implements a QoE-centric Multipath Routing Algorithm (QoMRA) based on MPTCP on an SDN SR platform. The use of SR improves SDN scalability, and QoMRA dynamically controls the number of subflows based on the state of the network. The purpose is to split a large flow into subflows and to find multiple disjoint bandwidth-satisfying subflow paths that meet specific service QoE guarantees. When an MPTCP client requests new traffic from the MPTCP server, the SDN controller proceeds with the calculation of the shortest paths satisfying the QoE requirements. The admissible subflow paths are then mapped into SR paths and stored in a database along with their QoE requirements for future use of subflows belonging to the same MPTCP connection. The dynamic control of the number of generated subflows at the ingress source node is implemented by an admission control mechanism such that a flow is only admitted to the network if on each link the sum of the rates of the allocated subflows does not exceed the link capacity. Congestion is avoided by changing link weights using two parameters: link criticality and link congestion index, similarly to [46]. The SDN controller monitors the available capacity of all connected paths and, upon congestion or link failure, it triggers the calculation of new paths.

DCNs are communication networks interconnecting a pool of resources (such as data storage and computing power) in a data center. The work in [23] proposes a new adaptive routing approach to minimize the electricity costs and emissions in optical DCNs under multiple electricity market environments. It is assumed that all nodes in the network communicate with the power distribution companies, which periodically update the electricity price and emissions factor, resulting in the periodic update of the routing tables at the nodes. Depending on the electricity price and emissions, different geographical paths may be preferred. The authors propose analytical models for the calculation of electricity costs and emissions considering the blocking probability of network traffic on optical wavelength division multiplexing (WDM) networks with no wavelength conversion. The typical approach for the calculation of optical circuits between end nodes employs the shortest path routing approach, whether in terms of the number of hops (shortest-hop path, SHP) or the distance between the source and the destination nodes (shortest-distance path, SDP). This work proposes three adaptive routing approaches based on the least-dollar path (LDP), the least-emissions path (LEP), and the balanced-cost path (BCP) which creates a balance between the minimization of the electricity costs and the reduction of emissions. The performance of the new adaptive schemes (LDP, LEP and BCP) is compared against the performance of the traditional static schemes (SHP and SDP) in two realistic network topologies showing up to a 26% improvement in electricity cost and 5% in emissions.

It is also possible to find proposals for the application of dynamic routing in environments as different as Networks-on-Chip (NoCs). NoCs are interconnection infrastructures for communication between processing elements (PEs) in Systems-on-Chip (SoCs), which is a concept in which a single chip (a set of electronic circuits on one small flat piece of semiconductor material, normally silicon) holds many components of a computer, such as CPU, memory, storage, etc. A Minimal Adaptive routing Circuit Switching based switch (MACS) for a two-dimensional (2D) mesh topology NoC is suggested in [45]. PEs connect to a communication network via NoC switches, which are responsible for runtime establishment and management of inter-PE communication channels. The overall system performance is therefore directly affected by the NoC switch design, namely by its routing algorithm. Traditional NoC switches with a 2D topology establish a communication path using deterministic XY routing (according to which packets travel along X dimension and then along Y dimension, over a fixed path which is selected disregarding the network condition), which does not take advantage of the mesh topology and it leads to inefficient use of the resources, potentially not allowing the establishment of a path between PEs even if a valid path is available. Minimal routing simply selects the shortest path between two points in a 2D mesh. MACS enhances inter-PE communication by using minimal adaptive routing (where the chosen routing path is both a shortest path with available communication lines and a path that best maximizes bandwidth utilization to avoid bottlenecks and the resource starvation) and a distributed arbitration, reducing the communication channel setup latency.

2.3 Alternative Routing

2.3.1 Fixed Alternative Routing

Fixed alternative routing (FAR) is based on paths that do not change over time, enabling a simple control mechanism in the paths configuration, with the additional advantage of already ensuring some flexibility to the network as it allows several path possibilities to be tried in case of congestion or failure, offering a trade-off between performance and complexity between single path fixed routing and dynamic routing. If on the one hand single path fixed routing leads to higher mean network blocking probabilities and lacks failure resilience, on the other hand dynamic routing includes a higher computational complexity and it requires the integration with control and management protocols.

Routing methods based on FAR are often proposed for optical networks, as it is the case with the elastic optical networks (EONs) and the conventional fixed grid WDM networks. A brief description of recent proposals on FAR models in optical networks is depicted hereinafter.

The work in [12] proposes a new algorithm to solve the routing and wavelength assignment (RWA) problem in a wavelength routed optical network without wavelength converters in an attempt to reduce the network blocking probability. The RWA problem is split into routing and wavelength sub-problems, which are separately addressed. The routing problem is solved by a FAR approach that starts by calculating the k-shortest paths with minimum total length for each pair of nodes. These pre-determined k-shortest paths are then rearranged and sorted in ascending order of their cost. The cost for each link results from the number of times that it is used in the pre-determined set of k-shortest paths, and each path cost is the sum of the cost for each of the links that are part of the path. Upon the arrival of a connection request, the sorted paths are sequentially checked for wavelength availability according to the most-used approach, in which the wavelength is chosen in descending order of usage.

The EON is a proposed solution to avoid the spectrum waste in conventional WDM networks. Two important characteristics of EON contributing to the reduction of the spectral resource utilization are the rate-adaptive superchannels and the distance-adaptive modulation (DAM) which adjusts the modulation format depending on the physical distance between the end nodes (specifically, for the same data rate, a high-level modulation format with a low SNR tolerance and narrow-spectrum may be selected for a short path, whereas a low-level modulation with a high SNR tolerance and a wider spectrum may be used for a longer path). The work in [1] proposes a new routing method referred to as k-distance adaptive paths (KDAP) to improve the spectrum efficiency in EONs. The typical approaches to routing in EONs include fixed routing and FAR, where paths are mainly calculated based on physical distance (k-shortest paths algorithms), hop count or link-disjointness, which is not spectrally efficient. Using KDAP, the DAM is incorporated in the calculation of paths which are determined taking into consideration the physical distance between the end nodes, the path length in terms of links, the spectrum granularity and the bit rate required by the request.

Some recent works propose new approaches to estimate the mean blocking probability in networks with FAR. Common ways to estimate the mean network blocking probability include computer simulations or analytical approximations such as the well-known Erlang fixed point approximation (EFPA). The work in [47] applies to optical networks with FAR, and it proposes using a neural network for learning the mapping from optical network parameters (representing properties of the offered traffic load, the optical links and the alternative routing method) to the blocking probability. Results show that the new algorithm is thousands of times faster than a computer simulation and that for some light traffic situations is hundreds of times more accurate than EFPA.

The work in [74] considers a multiservice circuit-switched network with alternative routing and bandwidth reservation using two services with the same bandwidth requirement but different service times (and, consequently, different priorities). The highest priority service is the so-called long-lived and the lowest priority service is the so-called short-lived, being that the average service time of the long-lived service is much higher than the one of the short-lived service. In terms of routing model, for each pair of end nodes, a maximum number of overflow attempts to alternative paths is pre-configured. The set of alternative paths is ranked in ascending order of the hop count and, in case of equality, the order is determined at random. The routing method works as follows: upon the arrival of a long-lived (high priority) service request, if there is available bandwidth in all the links belonging to the first-choice path, the service request is accepted. However, if any of the links belonging to the first-choice path is busy, a randomly chosen short-lived (lower priority) service connection using that busy link is preempted and its resources released so that the long-lived service request is accepted. The preempted short-lived connection then overflows to its first alternative path. If the incoming high priority service request finds any of the links belonging to the first-choice path full of long-lived connections only, it will attempt an alternative path. This procedure is repeated until all the alternative paths are tried or the long-lived service request is accepted. If none of the alternative paths has available bandwidth, the request is blocked. On the other hand, upon the arrival of a short-lived service request, if there is available bandwidth in all the links belonging to the first-choice path, the request is accepted; otherwise, it will attempt the first alternative path. This procedure is repeated until all the alternative paths are tried, or the short-lived service request is accepted. If none of the alternative paths has available bandwidth, the request is blocked. A bandwidth reservation threshold value, per link and service, is implemented to protect the traffic on first-choice paths.

The authors in [74] develop two approximations for the estimation of the blocking probability: one based on the commonly used EFPA and the other one based on the overflow priority classification approximation (OPCA), a methodology already proposed by the same authors in previous work. The OPCA model works by using an artificially introduced hierarchical surrogate system where traffic is prioritized and layered according to the number of times that it has overflowed (seniority). The OPCA surrogate model applies to overflow loss networks operating as if under a preemptive priority regime where junior service requests (those with fewer overflows) are given priority over senior service requests (those with more overflows). The blocking probability calculation by OPCA is similar to that of EFPA, and the difference between the two lies in the preemptive priority of the surrogate model of OPCA. The authors compare and discuss the accuracy of the two approximations. More details can be seen in [74].

The same authors propose in [75] the use of the OPCA surrogate model to estimate the blocking probabilities in a multiservice circuit-switched (or MPLS) network with alternative routing and bandwidth reservation where, unlike in [74]: *i*) the services have different bandwidth requirements but the same priority, competing with fairness for the same resources, and *ii*) the bandwidth reservation value for first-choice traffic on each link is shared by all services. The routing tables are defined in the same way as in [74]. Three variations of the OPCA method are proposed based on a priority criterion associated with the number of times that a given service request overflowed. In the method originally referred to as OPCA, junior service requests have priority over senior service requests, regardless of the service type. In the service-based OPCA method, junior service requests have priority over more senior requests, if they belong to the same service. A third approximation referred to as max(EFPA,service-based OPCA) chooses the maximal value between the two mentioned approximations. The approximations are compared and their accuracy is discussed for the various services under different system parameter scenarios such as service rates, bandwidth requirements, links capacity, bandwidth reservation value, maximum number of alternative paths.

2.3.2 Dynamic Alternative Routing

Dynamic alternative routing is a special type of dynamic routing that has been of great importance given its widespread implementation in circuit-switched voice networks and in the Integrated Services Digital Network (ISDN) as a way to improve network performance while making a balanced use of the resources [3, 32]. Section 2.3.2.1 briefly reviews some of those implementations.

Dynamic alternative routing is especially suited in fully (or strongly) meshed network topologies, i.e., where there are at least two paths with two links length between each pair of nodes. In such networks, the first-choice path is usually fixed and constituted by the direct link, if exists, and the alternative paths are generally constituted by paths with two links. Upon the arrival of a connection request, the paths in the routing table are attempted until the connection is accepted (or blocked, and consequently lost, in case the access is denied in all the attempted paths). Dynamic alternative routing methods can be classified as time-dependent, state-dependent or event-dependent according to how the routing tables are updated. The routing tables may change *i*) at a given time or periodicity in time-dependent routing methods, *ii*) depending on the state of the network in state-dependent routing methods, or *iii*) depending on the occurrence of a particular event such as a blocked connection request in event-dependent routing methods. A bandwidth reservation mechanism is often used as a first-choice traffic protection mechanism to prevent network performance degradation by eliminating, in overload scenarios, the excessive use of alternative paths (usually longer than first-choice paths). Some methods also implement a crankback mechanism for returning the call control from an intermediate node to the source node allowing, in a network with alternative routing, that a source node can try an alternative path in case the previously attempted path is denied. There is a number of works proposing the implementation of dynamic alternative routing across a variety of technologies such as IP, MPLS, and optical, as well as in SDN environments. Section 2.3.2.2 reviews some of these works.

2.3.2.1 Implementations in the Circuit-Switched Telephone Networks and ISDN

Dynamic Non-Hierarchical Routing (DNHR) [2, 3] is an example of a time-dependent routing method where the routing tables are planned by taking advantage of the non-coincidence of busy hours among the traffic flows. DNHR was the first implemented dynamic routing method, deployed in AT&T long distance voice network in 1984 and replaced in 1991 by the RTNR (Real-Time Network Routing) method, described below in this section. DNHR provides a set of engineered paths (paths calculated off-line based on traffic forecasts for different times of the day, typically one week in advance) and, to cope with overloads and failures, when the blocking probability between a given pair of nodes surpasses an acceptable threshold value, it allows the addition of a set of real-time paths calculated based on five minutes traffic windows in a centralized processor which is aware of the network available capacity. DNHR implements a bandwidth reservation mechanism to protect the direct traffic and it is based on source routing, allowing crankback.

DNHR was upgraded to RTNR [2, 3] in 1991, allowing the support of multirate multiservice networks. RTNR is an example of a distributed call-by-call state-dependent routing method where, in the event of a blocked first-choice path, the service request is offered to the least loaded two links length alternative path, according to the information about the occupancy state of each link in the network which is obtained on a call-by-call basis on each source node. An admissible alternative path is considered to be lightly loaded if its available bandwidth is greater than a given threshold value, which varies with the service type and point-to-point blocking, in an attempt to fulfill each service quality requirement. RTNR also implements crankback.

Dynamically Controlled Routing (DCR) [32], also called High Performance Routing (HPR), is an example of a centralized periodic state-dependent routing method wherein the routing table for each pair of end nodes considers a single alternative path (without crankback signaling, meaning that if the first-choice path is blocked in its second link the call request is automatically lost). A centralized controller periodically (usually every 10 seconds) computes a new alternative path based on the network estimated links availability. This single alternative path is randomly chosen being that admissible paths with higher estimated residual capacity are more likely to be chosen. DCR implements a bandwidth reservation mechanism.

Dynamic Alternative Routing (DAR) [28] is an event-dependent routing method implemented by British Telecom in 1993. It works on the following manner: a connection is offered to the first-choice path and, if there are no available resources, the connection may overflow to an alternative path. If this alternative path is blocked, a new alternative path to be used in future incoming requests is randomly selected from within a set of admissible alternative paths, and DAR sticks with it as long as it is successful (sticky random principle). DAR also implements a bandwidth reservation mechanism to protect the direct traffic.

State and Time dependent Routing (STR) [39] was implemented by Nippon Telegraph and Telephone Corporation (NTT) in 1992. STR combines a centralized approach responsible for the periodic calculation of an ordered set of possible alternative paths for each pair of nodes taking into account the network capacity and the level of traffic in each period of time, with a distributed approach for the call level routing, where an alternative path is determined based on learning from previous calls. Crankback is not used and a bandwidth reservation mechanism is implemented. In the basic scheme, a single alternative path is used, and it is valid until blocked, at which point it is replaced by the following alternative path which is admissible in the corresponding period of time. More advanced schemes at the call level routing were also proposed, assuming the possibility of multiple overflows and signaling for notification of the source node of the available capacity in the second link of the assigned alternative path.

2.3.2.2 Dynamic Alternative Routing for Other Technologies

Traditional IP networks widely use shortest paths routing, in particular based on OSPF, where the selected path is the one with the lowest total cost as obtained by the link weights. However, when changing link weights (in the scope of a dynamic OSPF weight optimization or topology change), both ongoing and new flows of traffic are affected, possibly leading to major traffic shifts and network instabilities. To solve this problem, the work in [42] proposes a Scheme for Alternative Packet Overflow Routing (SAPOR) enabling flow-based routing. Assume that a microflow is an aggregate of packets between the same source and destination IP addresses. The SAPOR scheme is implemented in each router and it chooses the outgoing link for each incoming packet based on the following principles: *i*) packets belonging to the same microflow are routed on the same outgoing link, even in the overflow scenario, *ii*) microflows are carried over the outgoing link corresponding to the first-choice path while the capacity of the outgoing link is not reached, *iii*) if the capacity of the outgoing link is reached, new flows are routed on alternative outgoing links. The first principle is implemented by a hash based flow tracker, and the second and third principles are implemented by a token system.

A Dynamic Routing scheme called DR/ATM is presented in [20] for application in ATM networks, although according to the author the scheme is also applicable to MPLS networks with explicit routing. In DR/ATM the routing decisions are computed by a centralized entity called routing control point (RCP) based on link-state routing. From estimates of the traffic that is offered to each link, the RCP algorithm computes the minimum cost paths based on the additive costs resulting from the extension for multiservice of the link costs initially proposed in [61] and used in the Forward-Looking Routing method (FLR) [44], whose extension for multiservice networks is presented in [43]. For this reason, these costs are called ATM-FLR costs. DR/ATM was originally designed for fully or strongly meshed networks working as follows: for each incoming connection request, a fixed first-choice path (chosen according to the minimum hop count) is tried. If the access is denied by a Connection Admission Control (CAC) mechanism, a crankback signaling message is sent back to the source node triggering the corresponding RCP to compute a list of sorted alternative paths, which are afterward implemented on the source node routing table. If the connection request cannot be established through the first alternative path, the following alternative path is attempted, and so on. The number of connection attempts is limited by the number of alternative paths in the list and on the maximum number of allowed crankbacks. DR/ATM was also extended for weakly meshed networks where minimum-hop paths may be several hops long, making it difficult to specify a fixed first-choice path without compromising the network load balance. This is solved by using a random minimum-hop routing approach for the choice of the first-choice path, which adds very small random values to the link weights, making sure that the algorithm finds different minimum-hop paths, depending on the random numbers, distributing the traffic more evenly. In this scenario, if a connection request is blocked by a CAC mechanism for a link along the selected minimum-hop path, it is the node where the blocking link originates that triggers the RCP computation. The DR/ATM scheme was compared by simulation with others of reference, in particular with one of the DAR-type [28], having obtained better results in general.

Due to its efficiency and simplicity, based on the isolated learning in the source nodes, DAR [28], the routing method implemented in the British Telecom (BT) circuit-switched voice network, has also been proposed for other networks such as MPLS [4, 55, 69] and WDM [37]. These works are briefly summarized hereinafter.

The work in [55] introduces a QoS routing framework based on path caching that applies to MPLS networks. The framework has three phases: *i*) the Preliminary Path Caching (PPC) phase computes and caches the set of admissible paths for each pair of end nodes, *ii*) the Updated Path Ordering (UPO) phase selects the acceptable paths among the set of admissible paths computed in the PPC phase, namely by its ordering according to a certain criterion, using a specific routing scheme, *iii*) the Actual Route Selection (ARS) phase selects the path to be used by each incoming service request. The implemented routing schemes are based on an extension of DAR, or based on approaches using the maximum available capacity (with or without crankback, with a periodic update of the paths or an instantaneous calculation).

The same framework is reused in [69] to evaluate several mechanisms to give priority to a particular service in a flow-based multiservice network such as MPLS. The service priority is used as input to define the number of cached paths in the PPC phase. UPO phase enforces priority by using different routing schemes (a destination-based routing approach such as on the Internet, or one of several dynamic alternative routing methods, one being of the DAR-type) for different services. The ARS phase enforces priority by using different bandwidth reservation mechanisms to limit the access to the network. This work concludes that the performance perceived by a given service can be improved if the QoS routing schemes (namely PPC and UPO phases) are used in combination with network controls (ARS phase).

A DAR-like scheme is proposed in [4] to perform path selection in the scope of a distributed Generic Connection Admission Control (GCAC) algorithm for IP/MPLS networks. This GCAC algorithm considers a set of parameters that is advertised in the network containing topology constraints and traffic characteristics available from QoS signaling. Upon a connection request from a flow that must comply with a given QoS requirement, this information is used in the path selection procedure to only include links with high probability of accepting the connection.

An Adaptive Alternate Routing (AAR) scheme for wavelength-routed all-optical WDM networks, resembling circuit-switched voice networks at traffic level, is introduced in [37]. AAR is based on an extension to a generic topology network of the DAR method, which originally applies to fully meshed networks. In this context, the first-choice path is the shortest path and a blocked service attempt may try several alternative paths (not limited to a length of two links) due to the crankback capability. The main purpose of this work is to study the AAR scheme, namely in terms of its comparative performance with a fixed routing approach, and to understand the trade-offs of considering a number of alternative paths as opposed to a number of nodes in the network with wavelength converters. Results show that AAR performs better than fixed routing and, in lightly loaded network scenarios, allowing multiple alternative paths is more beneficial than equipping nodes with wavelength converters. However, as the load on the network increases, the association of AAR with wavelength converters in some nodes is more performant. The results also show that a small number of alternative paths in a network without wavelength converters achieves a better performance than a network with full wavelength conversion and fewer alternative paths. In summary, the study shows that the AAR method allows a good adaptation to the network traffic conditions.

Other works also propose dynamic alternative routing applied to optical networks [16, 48, 49]. These works are briefly summarized hereinafter.

The work in [49] proposes a new approach to routing for all-optical WDM networks to reduce the connection blocking probability. The purpose is to ensure the optimal traffic distribution for a given offered traffic matrix among the multiple paths between each pair of end nodes, calculated by a nonlinear multicommodity flow optimization problem. This approach is tested with two routing variants: traffic intensity based fixed alternate routing (TI-FAR) and traffic intensity based dynamic alternate routing (TI-DAR). In TI-FAR, the set of paths for each pair of nodes is sorted in descending order according to the optimal traffic intensities assigned to the routing paths instead of according to the hop counts and, in the event of a connection request, the paths are tried in sequence. In TI-DAR, in the event of a connection request, one path is randomly chosen among the set of those that have at least one common available wavelength according to a probability distribution based on the optimal traffic intensities assigned to the routing paths. These methods are evaluated in a simulation platform and their performance compared with that of reference methods. Results show that these routing approaches designed according to the optimal traffic distribution effectively contribute to the reduction of the connection blocking probability.

The same authors propose in [48] a different routing approach, now based on using link-disjoint paths for each pair of end nodes, also applicable to all-optical

WDM networks to reduce the connection blocking probability. The main purpose is to determine the set of link-disjoint paths for each pair of end nodes among the set of paths that is used by the optimal traffic distribution leading to the most carried traffic in the network. Two routing approaches are used: hop-count based fixed alternate routing algorithm (HC-FAR) and least-loaded dynamic alternative routing algorithm (LLR). HC-FAR sorts the set of link-disjoint paths for each pair of nodes that maximize the carried traffic in ascending order of hop count and, in the event of a connection request, the paths are tried in sequence. In LLR, in the event of a connection request, the set of link-disjoint paths for each pair of nodes that result in the optimal traffic pattern are sorted in descending order of the number of idle wavelengths and the paths are tried in sequence. These methods were evaluated by simulation and their performance compared to reference ones, showing lower connection blocking probability values.

Internet traffic continues to increase and it is unclear whether the current packet routing architecture based on electronic routers that have been used at the core of backbone networks will continue to scale as needed. On the other hand, optical fibers and switching elements have shown an incomparably higher capacity than electronic routers, which seems to justify an all-optical backbone network. In particular, the simplicity of circuit switching makes it suitable for optical implementations. Several optical network data transport architectures have been proposed to take advantage of the optical circuit switching capacity in a way that is compatible with packet switching at the network edge. The work in [16] proposes an optical backbone architecture called Coarse OPticaL circuit switching with Adaptive Rerouting (COPLAR) based on coarse optical circuit switching by default and adaptive rerouting of excess traffic over circuits with available capacity when needed. COPLAR is based on the provisioning of long-duration quasi-static optical circuits between end nodes at the boundary of the network, which are precomputed to carry most of the traffic based on the estimation of future traffic demands from historical traffic distributions. In the event of unexpected traffic changes or failures, the adaptive rerouting strategy explores path diversity by rerouting traffic in a load balanced manner among circuits with available capacity. In the scope of the COPLAR architecture, the provisioning of the quasi-static circuits is addressed by the authors in [17] while the adaptive rerouting mechanism is addressed in [18]. In COPLAR, a fully connected mesh of circuits is typically provisioned between the edge nodes. In the default network operating mode, an incoming packet is queued at the edge node and then carried over the direct link. If the queue is full, the incoming packet is rerouted to the low priority standby queue of another outgoing circuit in the routing table. This next hop is defined by an adaptive routing algorithm operating in real time and dynamically adjusting the traffic splitting ratios ensuring the load balancing across the circuits. The prioritization of the direct traffic is guaranteed by the lower priority of the standby queues for the rerouted traffic, which can only occupy residual capacity unused by direct traffic. The work in [18] evaluates the rerouting traffic mechanism of COPLAR on two real backbone networks (Abilene and GEANT) by comparing three routing strategies (COPLAR, COPLAR-NR (with no rerouting, in which case traffic is dropped once the direct link queue is full) and the standard OSPF). Results show that the adaptive rerouting strategy effectively carries excess traffic even under heavy load traffic scenarios.

Unlike the typical network topology associated with alternative routing, the work in [50] applies to sparse networks with paths of arbitrary length, so the set of shortest paths between a given pair of nodes may not include the direct link nor paths two links long. In such scenario, for each pair of end nodes, a list of feasible paths is pre-configured, sorted in ascending order of hop count, and a state-dependent routing method of the least loaded routing (LLR) type is implemented working as follows: the first-choice path attempted by an incoming service request is the path with the maximum available bandwidth, among the set of feasible paths for that pair of nodes, and not necessarily the shortest path in terms of hop count. In case of equality, the shortest path is chosen. If the first-choice path is blocked, an alternative path corresponding to the next path with the most available bandwidth is attempted. Note that alternative routing is being considered without the use of any bandwidth reservation mechanism for the sparser network topology. The authors develop two fast fixed-point approximation algorithms to estimate the blocking probability in multiservice multirate circuit-switched loss networks with arbitrary topologies assuming the implementation of the cited generalization of the LLR method. This generalization of LLR to arbitrary multihop topologies leads to overlapping among different paths used by the same pair of end nodes, which complicates the computation. The proposed approximation algorithms are tested by simulation and the accuracy of their models is discussed.

The possibility of using dynamic alternative routing is also considered as an advantage in the scope of a gradual upgrade of ISP legacy core networks to SDN. According to the work in [64], this upgrade is expected to take place over several years during which the SDN controllers manage the SDN-enabled devices and the legacy devices continue using OSPF-like routing protocols. The authors in [64] present a model to define the optimal scheduling for the router upgrades in the network taking into consideration two objectives: the maximization of the traffic traversing at least one SDN-enabled node (allowing the application of sophisticated policies such as access control) and the maximization of the number of dynamically selected routing paths enabled by SDN-enabled nodes (maximizing the traffic engineering (TE) flexibility). In the scope of the TE flexibility, it is highlighted the increased network performance under congestion or failures situations due to the rerouting possibility to alternative paths in SDN-enabled nodes.

2.4 Dynamic Routing for Failure Recovery

Dynamic routing typically aims to improve the performance of the network in the presence of traffic fluctuations, with the improvement of the resilience of the network being considered an advantageous side effect. However, recent work has also focused on using dynamic routing explicitly to resolve failure situations. Some of these works are briefly described below.

A Wireless Mesh Network (WMN) is a radio node infrastructure with a mesh topology in which link failures are common events, caused by factors such as node mobility, radio fading, link noise, etc. The use of SDN to manage a WMN network can enable a convenient centralized global network management. However, generally SDN-based networks cannot handle link failures quickly due to the non-negligible round-trip transmission delay between the SDN controller and the SDN-enabled devices. The work in [7] proposes a low-overhead node mobility prediction scheme to solve the SDN control delay in SDN-based WMNs. This approach implements a mobility prediction module that, upon the prediction of a link failure (i.e., a topology change due to node mobility), triggers the calculation of new paths which are sent to the routing tables of the SDN-enabled devices, before the link failure actually takes place. The link failure prediction module uses the signal-to-noise ratio (SNR) metric to measure the link quality and it works on two levels. First, at the data plane level, comparing past measured SNR values in each link with training values, and then at the control plane level, by checking the SNR values for the neighbors of the nodes which are identified by the data plane as being in mobility. After the link failure prediction, the SDN controller calculates the new paths satisfying *i*) the shortest path distance, *ii*) the lowest control overhead (by minimizing the change of traffic distribution and corresponding route control messages) and *iii*) the least impact on other traffic (given that rerouting through other links can cause traffic congestion elsewhere). The proposed approach is validated by simulation and it shows better performance upon link failure when compared with other reference approaches.

The work in [67] proposes an adaptive-alternative path restoration algorithm called NrPSR-R to apply in optical networks. When network survivability is enforced by a path restoration scheme, a new lightpath from the source to the destination node is determined by the algorithm taking into account the available network resources after the event of a failure. NrPSR-R starts by evaluating the network links using an algorithm based on power series routing (PSR), named PSR-R. In PSR-R the cost function for each link is given by a function expanded in a power series using the normalized physical link distance and the normalized number of available wavelengths in the link as input variables. NrPSR-R finds the Nr paths with the minimum cost, considering the new state of the network in terms of topology and the current state of the optical network (available wavelengths in each link and the physical link distance), and then it uses a preconfigured policy to choose one of the Nr paths to be deployed for the lightpath restoration attempt. Several policies were considered taking into account the number of hops, the number of available wavelengths or the optical SNR of the paths. The authors compared the performance of the NrPSR-R algorithm with that of other reference restoration algorithms on different scenarios in terms of rate of unsuccessful failure recovery and the results show a better performance for NrPSR-R.

Due to its rerouting capability, dynamic alternative routing has also been proposed to specifically deal with failures, namely in the scope of SDN [14, 65].

Resilience to failures in SDN networks traditionally requires the maintenance of the availability of the SDN controller, with non-negligible delays and signaling overheads. The work in [14] proposes a controller-independent protection scheme for SDN networks based on OpenState. OpenState is an extension of OpenFlow (a standard communication protocol that enables the SDN controller to directly interact with the forwarding plane of the SDN-enabled devices) that allows the definition of forwarding rules that automatically adapt on the basis of packet-level events (local information only). This scheme is based on pre-computed paths and inspired by the MPLS crankback mechanism, according to which a failure notification is backtracked along the flow path from the upstream node identifying the failure until the ingress LSR, or a specific "repair point", to find an alternative path to the destination node. The difference in the proposed solution is that it is not a notification but instead tagged data packets containing information on the failure event that are sent back on the original path until a reroute node is found. A reroute node receiving tagged packets will reroute the tagged packets to an alternative path and perform a state transition in the OpenState switch to enable the detour path for all subsequent packets.

A significant portion of Internet traffic is already based on the communication and data processing that takes place on DCNs, which makes the scalability and resilience of these networks critical. The work in [65] applies to DCNs based on a SDN architecture. In the context of SDN, source routing has been proposed to provide scalability with the disadvantage that, in the event of a network failure, it is necessary that the source node is informed, which can take at least on the order of one round-trip time to the SDN controller. This work proposes SlickFlow, a resilient source routing approach with a fast failure recovery through the combination of source routing with information of alternative paths carried in the packet header. In short, several paths are encoded as a sequence of segments in packet header: a primary path from source to destination node and then, for each hop (or subset of hops) in the primary path, an alternative path to be used if the next hop on the primary path is not available. As such, in the event of a failure in the primary path, packets can be rerouted to alternative paths by the nodes themselves, without the need to involve the SDN controller.

2.5 Multiobjective Dynamic Routing

Multiobjective optimization can be used to solve several types of problems in communication networks, especially considering the importance of multidimensional issues affecting QoS and cost factors. The formulation of a multiobjective problem involves several objective functions that need to be minimized (or maximized), having in mind all the parameters (or added constraints). In multiobjective optimization it typically does not exist a feasible solution that simultaneously optimizes all the objective functions. For this reason, the concept of optimal solution is replaced by the non-dominated (or Pareto optimal) solutions, which are feasible solutions for which it is not possible to improve any of the objectives without degrading one or more of the others. The Pareto front is the set of Pareto optimal solutions.

A state of the art review on multiobjective routing and network design models in telecommunications networks is presented in [19].

Dynamic routing is already known to improve network performance and cost. A multiobjective formulation of the dynamic routing problem can be especially advantageous so that paths may vary over time with the purpose of obtaining at any given time period the best overall network performance and cost, in a multiobjective perspective. Recent proposals for multiobjective dynamic routing are presented hereinafter for optical and wireless networks.

The work in [62] applies to WDM networks and it proposes a heuristic to solve the RWA problem in a dynamic online routing environment, based on multiobjective shortest path routing with an adaptive link weighting function. The purpose is to select the path between each pair of end nodes that results in the best compromise solution in terms of traffic, network and energy related objectives, being the traffic objectives related to the satisfaction of QoS requirements (bandwidth, delay and bit error rate (BER)), while the network objective is associated with the minimization of the mean network blocking probability, and the energy objective aims to minimize the energy consumption. The multiobjective shortest path routing problem is solved by a strategy based on a weighted sum objective function which aggregates the different traffic, network and energy related objectives by assigning a specific weight to each of the objective functions. The aim is to select the minimum cost path satisfying traffic QoS requirements, according to the additive link costs which are dynamically calculated at the time of invocation based on the status of the network and combining several link parameters that are weighted according to their relative importance with respect to both the individual (traffic, network or energy related) objectives and the aggregated one. Traffic parameters are expressed in terms of minimum requested bandwidth, maximum acceptable BER or maximum acceptable delay, and they also represent thresholds that must be satisfied for paths to be eligible. When several paths meet the QoS requirements, a selection criterion minimizes the use of expensive network resources, which results in a traffic cost function assigning a lower cost to links that best satisfy the QoS requirements and infinite cost to those not fulfilling the requirements. The cost function involving the network-related parameters assigns a cost to each link that is proportional to the link congestion and hit ratio (which is defined as the ratio between the number of accepted connections and the total number of requests on the link). The link power consumption function includes a fixed component related to the power consumption that is needed to keep the communication link "on" and a variable component depending on the traffic load that traverses the link.

The Internet of Things (IoT) is an emerging concept that refers to the connectivity among a wide variety of physical devices (generically designated by nodes from now on) in accordance with their energy resources, processing capabilities, mobility and communication technologies. With the evolution of smart nodes with wireless technology, the Mobile Ad hoc Network (MANET) technology is regarded as key in the IoT. A MANET is a decentralized wireless network with dynamic topology and auto-configuration. The network is ad hoc because mobile nodes have the ability to build a communication network with each other without depending on any pre-existing infrastructure, with each node also acting as a router, forwarding traffic on the network. The routing protocol has a prominent role in MANETs by enabling source nodes to select paths through which to send data to the destination nodes. Nodes mobility, traffic congestion and link quality of the intermediate nodes are crucial aspects to consider in the establishment of a reliable path between a pair of end nodes. The work in [72] presents a routing strategy called Mobility, Contention window and Link quality-aware Multipath Routing (MCLMR) to apply in MANETs, which takes into consideration the status of three performance metrics (mobility, contention window size and link quality) of the intermediate nodes in the selection of the “best” paths.

Every node in the network shares its location information with each of its neighbors allowing the calculation of the instantaneous relative velocity (IRV) between nodes. The mobility estimation of intermediate nodes is based on this IRV concept, and MCLMR gives higher priority to intermediate nodes with lower IRV values, which contributes to maintaining the stability of the network. The contention window size is the amount of time that a node needs to wait after collision (when two or more nodes transmit at the same time) before accessing the channels for subsequent data transmission. The MCLMR prioritizes the intermediate nodes with lower contention window values, minimizing data collisions and packet drops during data transmission. Changes in the network topology lead to a link failure and trigger a new route discovery process which is accompanied by control messages flooding the network, often resulting in the degradation of the network performance. To guarantee a successful data transmission, the MCLMR estimates the link quality of the intermediate nodes based on the Expected Number of Transmissions (ETX) metric, defined as the number of transmission attempts, including retransmissions, that is needed to successfully deliver a packet to the receiving end over a dedicated link.

The MCLMR is an on-demand routing protocol according to which the source node triggers the route discovery process when it has data to transmit, and the performance metrics are separately evaluated for each intermediate node. The selected “best” path uses the intermediate nodes with the best mobility, contention window size and link quality status, and it is determined based on the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), which is a multiobjective optimization method whose concept is based on the selection of the path with the shortest euclidean distance from the ideal solution (one with the best attribute values, i.e. maximum for a benefit criteria and minimum for a cost criteria) and the longest euclidean distance from the negative ideal solution (one with the worst attribute values, i.e. minimum for a benefit criteria and maximum for a cost criteria).

The same authors propose in [71] the energy, mobility, queue length and link quality-aware routing (EMBLR), a multiobjective routing approach for 5G IoT networks based on Device-to-Device (D2D) communications. In the D2D scenario, devices (or nodes) are directly connected to each other without the support of base stations, creating an ad hoc wireless network. The D2D communications reuse cellular resources and D2D is recognized as a key technology in 5G networks due to the enhanced cellular spectrum utilization. Several challenges have been identified to deploy reliable D2D communications in 5G networks, including resource management, selection of transmission band and routing path selection. The EMBLR scheme focuses on the routing path selection and addresses several factors affecting the overall network performance, namely energy constraints (due to the limited battery capacity on devices), network stability (as a consequence of the device mobility), link quality (as a result of a dynamic network topology) and traffic congestion (when several devices transmit their data packets to a single device, inducing a delay in the data transmission when data packets have to wait in the queue). In the scope of the route discovery process, EMBLR estimates several parameters (energy consumption, mobility, link quality and queue length size) of the intermediate devices between the source and destination. Then, all the parameter values are aggregated into a multicriteria node rank (MCNR) metric, providing a weight to each intermediate device based on the estimated value. The device with the highest MCNR metric value has a higher chance of being used in the selected path.

A Wireless Sensor Network (WSN) typically consists of a large number of low-cost and easy deployable sensors for monitoring purposes. Most WSN nodes are fixed, with low energy resources and low data rates. On the other hand, most nodes in MANETs are mobile, with higher energy reserves and processing capabilities. The work in [35] proposes a Multipath Energy and Quality of Service-Aware Optimized Link State Routing protocol version 2 (MEQSA-OLSRv2) to cope with the challenges of providing effective and efficient data routing in MANET-WSN convergence scenarios of IoT networks. MEQSA-OLSRv2 addresses these challenges by transmitting data over multiple paths to balance the load and increase reliability, by optimizing the flooding of topological information, and by using a MCNR metric comprising several node metrics related to energy consumption and QoS (lifetime, residual battery, queue length, idle time and node speed) to assess link quality and select the best paths to the destination. This MCNR metric is locally calculated in each node and periodically broadcast as a single metric. Nodes with higher MCNR metric values have higher chances to be selected.

2.5.1 Multiobjective Dynamic Alternative Routing

The routing methods covered in this work belong to the category of multiobjective dynamic alternative routing. Next, some methods of the same type are presented.

MODR, one of the methods that inspired this work and that will be reviewed in Chapter 4, is an example of a dynamic alternative routing method with a multiobjective formulation that applies to multiservice multirate circuit-switched networks and that is solved through a heuristic approach based on a bicriteria shortest path algorithm using blocking probabilities and implied costs [53].

The work in [30] applies to a multiobjective routing model for MPLS networks with alternative routing and two service classes, namely QoS and best-effort (BE) services. The model considers a hierarchy with two optimization levels: the highest priority objective functions (formulated at the network level for QoS traffic) include the maximization of the total expected network revenue associated with QoS traffic flows and the minimization of the maximal average blocking probability among all QoS service types, representing the fairness objective at the network level. At the second (lower priority) level of optimization, apart from the maximization of the total expected BE revenue, there are two service level objective functions including the minimization of the mean blocking probability for QoS services and the minimization of the maximal average blocking probability over all QoS flows, representing the fairness objective defined for every QoS service type. A heuristic procedure designated as Hierarchical MultiObjective Routing considering 2 service classes ($HMOR-S2$) is proposed and applied to a reference network. The theoretical foundations of a specialized heuristic strategy for solving the bi-level routing optimization problem, based on a bicriteria shortest path sub-model using implied costs and blocking probabilities, are presented in

[21].

The authors also present and test in [29] a meta-heuristic resolution approach, namely a simulated annealing procedure and a tabu search procedure, in an attempt to find potentially better solutions for the same multiobjective problem.

A new variant of the heuristic in [30] is proposed in [31] with the introduction of a Pareto archive strategy, with the designation Hierarchical MultiObjective Routing with 2 traffic classes and a Pareto Archive Strategy ($HMOR - S2_{PAS}$). It works by caching all the non-dominated solutions that are discovered during the heuristic execution time. At the end, the set of archived solutions is evaluated and the final solution is chosen using the Chebyshev distance to a reference point.

Chapter 3

Fundamental Concepts and Definitions

3.1 Introduction

This chapter introduces fundamental concepts within the scope of the methods employing multiobjective dynamic alternative routing addressed in this work. Section 3.2 includes the formalization of the network representation, section 3.3 describes the traffic models applying to the proposed dynamic alternative routing methods, and section 3.4 presents the formulation for the shortest path problem, including a strategy to solve the multiobjective case. It also describes the two biobjective shortest path algorithms used by the proposed multiobjective dynamic alternative routing methods.

3.2 Network Representation. Notation

The routing methods addressed in this work apply to multiservice multirate circuit-switched loss networks at traffic level, where each service has a different

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The content of this chapter is partly based on the following publication:

- C. Francisco, L. Martins, D. Medhi. Traffic model for Dynamic Multicriteria Alternative Routing for Single- and Multi-service Reservation-Oriented Networks. Tech. Rep. 1/2018, INESC-Coimbra, available online: https://www.uc.pt/en/org/inescc/res_reports_docs/research_reports bandwidth requirement and is routed independently. Each successfully established service connection occupies a given bandwidth value on each arc along the path and, in case the required resources are not available, the service connection is blocked and consequently lost, hence the classification of loss network.

The mathematical representation of such a multiservice network is presented hereinafter. Note that a single service network represents a particular case of the multiservice network.

The topology of a telecommunications network can be represented by a graph where the nodes represent the routers and the arcs represent the links. From this moment onwards, the terms 'arcs' and 'links' can be used interchangeably. The network graph $G = (N, L)$ comprises $N = \{1, 2, \ldots, |N|\}$ as the nodes set, and $L = \{\ l_1, l_2, \ldots, l_{|L|} : l_k = (i, j, C_k) \wedge i, j \in N \wedge C_k \in \mathbb{N} \wedge 1 \leq k \leq |L|\ \}$ as the arcs set, where C_k is the bandwidth of arc l_k. In the multiservice network, where $S = \left\{s_1, s_2, \ldots, s_{|S|}\right\}$ is the services set, $G_s = (N_s, L_s)$ is the subgraph consisting of the nodes and arcs that can be used by service s such that $N_s \subseteq N \wedge L_s \subseteq L$. In the developed routing models, the arcs are assumed as bidirectional at traffic level which means that each arc l_k can be used by connections from node i to node j, as well as from node j to node i, and the network resources are shared among the multiple services thus $N_s \equiv N$ and $L_s \equiv L$.

In fully meshed networks, it is customary to limit the length of the paths to two arcs. Likewise, setting a limit on the maximum length of the paths, dependent on the network mesh degree, may be advantageous to prevent the use of longer paths that result in the network performance degradation in case of overload.

Consider a path p^s_{ij} from the source node i to the destination node j for service s as a sequence of adjacent links such that the first link is $l_n = (i, m, C_n)$ and the last link is $l_p = (r, j, C_p)$, without repetition of nodes (except in adjacent links), with $i, m, r, j \in N$ and $s \in S$. Then, the routing domain from the source node i to the destination node j for service s, $\mathcal{P}^s_{ij}$, consists of the set of admissible paths with a maximum length of D arcs connecting the source node i to the destination node j for service s. $\mathcal{P}^s_{ij}$ is defined as follows:

$$\mathcal{P}^s_{ij} = \left\{p^{1s}_{ij}, p^{2s}_{ij}, \ldots, p^{M^s_{ij}}_{ij} : \left|p^{ms}_{ij}\right| \leq D \wedge 1 \leq m \leq M^s_{ij} \leq |N| - 1\right\} \tag{3.1}$$

where the value of M_{ij}^s may differ for different services and pairs of end nodes. The routing domain for service s and network G can then be defined as $\mathcal{P}^s = \cup_{i,j \in N} \mathcal{P}_{ij}^s$ and $\mathcal{P}_G = \cup_{s \in S} \mathcal{P}^s$, respectively.

3.3 Traffic Models

The multiobjective dynamic alternative routing methods addressed by this work rely on fixed-point iterators to compute the blocking probabilities and the implied costs associated with each link, according to given network topology, links capacity, offered traffic matrix and routing plan (and assuming Poissonian arrivals and statistical independence in the blocking probability in each link).

In the multiservice circuit-switched loss networks with alternative routing considered in this work, at a given point in time, a service connection can attempt two paths. Depending on the routing method in consideration, the alternative path to use at a given time instant t is selected within a set of one (as in SMODR) or multiple admissible paths (as in DMAR). The formulation of the traffic model for a multiservice network considering alternative routing in a given time instant within one alternative path possibility is presented in section 3.3.1 (as defined in [53]), and the case that considers a set of multiple alternative paths is presented next in section 3.3.2.

3.3.1 Alternative Routing with a Single Alternative Path

Consider that the ordered set of paths that can be used from the source node i to the destination node j for service s is defined by:

$$P_{ij}^s = \left\{p_{ij}^{1s}, p_{ij}^{2s}\right\}, \tag{3.2}$$

where p_{ij}^{1s} is the first-choice path and p_{ij}^{2s} the alternative path. Assume that all traffic flows are homogeneous Poissonian and independent, with negative exponential service durations and that there is statistical independence in the blocking of the links. Then, the blocking probability experienced by a connection being carried from node i to node j by path p_{ij}^{ms}, $B_{p_{ij}^{ms}}, m = 1, 2$ is given by:

$$B_{p_{ij}^{ms}} = 1 - \prod_{l_k \in p_{ij}^{ms}} (1 - B_k^s), \tag{3.3}$$

where $B_k^s = f(C_k, \overline{d_k}, \overline{a_k})$ is calculated using a simplified model based on the Kaufman (or Roberts) algorithm [38, 66] for small values of the link capacity, and on the uniform asymptotic approximation (UAA) for large values of the link capacity (typically for values higher than 80) [58, 59]. The calculation of B_k^s implies the knowledge of C_k, the capacity on link l_k, $\overline{d_k}$, the required bandwidth on link l_k by a connection of each service s (for which the following simplification $d_k^s = d^s, \forall l_k \in L$ applies), and the determination of $\overline{a_k}$, the average load that is offered to link l_k by each service.[1]

The average load that is offered to link l_k by service type s (the so called reduced load), a_k^s, is determined as follows:

$$\begin{aligned} a_k^s = & \sum_{i,j \in N : l_k \in p_{ij}^{1s}} a_{ij}^s \prod_{l_u \in p_{ij}^{1s} - \{l_k\}} (1 - B_u^s) \\ & + \sum_{i,j \in N : l_k \in p_{ij}^{2s}} a_{ij}^s B_{p_{ij}^{1s}} \prod_{l_n \in p_{ij}^{2s} - \{l_k\}} (1 - B_n^s), \end{aligned} \tag{3.4}$$

where a_{ij}^s is the offered load from node i to node j by service s.

The calculation of B_k^s is done through a fixed-point iterator that is summarized hereinafter. Assuming an initial fixed value for B_k^s ($B_k^{s(0)}$), B_k^s is determined as follows until a convergence criterion is met:

$$\begin{aligned} a_k^{s\,(x+1)} = & \sum_{i,j \in N : l_k \in p_{ij}^{1s}} a_{ij}^{s\,(x)} \prod_{l_u \in p_{ij}^{1s} - \{l_k\}} \left(1 - B_u^{s\,(x)}\right) \\ & + \sum_{i,j \in N : l_k \in p_{ij}^{2s}} a_{ij}^{s\,(x)} B_{p_{ij}^{1s}}^{(x)} \prod_{l_n \in p_{ij}^{2s} - \{l_k\}} \left(1 - B_n^{s\,(x)}\right) \end{aligned} \tag{3.5}$$

$$B_k^{s(x+1)} = f(C_k, \overline{d_k}, \overline{a_k}^{(x+1)}) \tag{3.6}$$

[1] For single service networks, the blocking probability on each link is calculated by applying the Erlang B formula.

$x = 0, 1, 2, \ldots$

In addition to the blocking probability another link metric, the implied cost, needs to be calculated to be used in the biobjective shortest path algorithm. The concept of implied cost associated with a link was first proposed in [40] for single service networks with fixed routing and alternative routing with a single alternative path. It was further extended for multiservice networks (without alternative routing) in [26, 59] and for multiservice networks with a single alternative path in [53].

The simplest case is the fixed routing. In this case, the traffic that is carried in the fixed path p_{ij}^{1s} is the following:

$$\lambda_{p_{ij}^{1s}} = a_{ij}^{s} \prod_{l_u \in p_{ij}^{1s}} (1 - B_u^s) \tag{3.7}$$

and the implied cost associated with link l_k as a result of establishing a service u connection is given by [26, 59]:

$$c_k^u = \sum_{s=1}^{S} \eta_k^{us} (1 - B_k^s)^{-1} \left[\sum_{i,j \in N : l_k \in p_{ij}^{1s}} \lambda_{p_{ij}^{1s}} \left(w^s - \sum_{l_n \in p_{ij}^{1s} - \{l_k\}} c_n^s \right) \right] \tag{3.8}$$

where w^s is the expected revenue for an accepted service s connection and η_k^{us} is the increase in the blocking probability experienced by a service s connection due to the acceptance of a service u connection on link l_k ($\eta_k^{us} = f(C_k - d^u, \overline{d_k}, \overline{a_k}) - f(C_k, \overline{d_k}, \overline{a_k})$). Similarly to the calculation of the blocking probabilities, the implied cost c_k^u is calculated through a fixed-point iterator.

In the case of alternative routing with a single alternative path, the expression 3.8 is updated considering the generalization of the original expression (eq. 7.7

in [40]) for a single service:

$$c_k^u = \sum_{s=1}^{S} \eta_k^{us} \left(1 - B_k^s\right)^{-1} \left[\sum_{i,j \in N: l_k \in p_{ij}^{1s}} \lambda_{p_{ij}^{1s}} \left(w^s - \sum_{l_n \in p_{ij}^{1s} - \{l_k\}} c_n^s \right) \right.$$
$$+ \sum_{i,j \in N: l_k \in p_{ij}^{2s}} \lambda_{p_{ij}^{2s}} \left(w^s - \sum_{l_n \in p_{ij}^{2s} - \{l_k\}} c_n^s \right) \tag{3.9}$$
$$\left. - \sum_{i,j \in N: l_k \in p_{ij}^{1s}} \lambda_{p_{ij}^{1s}} \left(1 - B_{p_{ij}^{2s}}\right) \left(w^s - \sum_{l_n \in p_{ij}^{2s}} c_n^s \right) \right]$$

which is equivalent to considering the following expressions [53]:

$$c_k^u = \sum_{s=1}^{S} \eta_k^{us} \left(1 - B_k^s\right)^{-1} \left[\sum_{i,j \in N: l_k \in p_{ij}^{1s}} \lambda_{p_{ij}^{1s}} \left(s_{p_{ij}^{1s}} + c_k^s \right) + \sum_{i,j \in N: l_k \in p_{ij}^{2s}} \lambda_{p_{ij}^{2s}} \left(s_{p_{ij}^{2s}} + c_k^s \right) \right] \tag{3.10}$$

$$s_{p_{ij}^{2s}} = w^s - \sum_{l_n \in p_{ij}^{2s}} c_n^s \tag{3.11}$$

$$s_{p_{ij}^{1s}} = w^s - \sum_{l_n \in p_{ij}^{1s}} c_n^s - \left(1 - B_{p_{ij}^{2s}}\right) s_{p_{ij}^{2s}} \tag{3.12}$$

where w^s is the expected revenue for an accepted service s connection and $s_{p_{ij}^{2s}}$ is the surplus value of a connection on path p_{ij}^{2s}.

3.3.2 Alternative Routing with Multiple Alternative Paths

Consider now that the set of paths that can be used from the source node i to the destination node j for service s is constituted by the first-choice path p_{ij}^{1s} and an alternative path p_{ij}^{ms} in $\mathcal{P}_{ij}^{s} \setminus \left\{ p_{ij}^{1s} \right\}$ with a stationary probability $r_{p_{ij}^{ms}}$, with

$\sum_{m=2}^{M_{ij}^s} r_{p_{ij}^{ms}} = 1$ [28].

In this context, the alternative paths from the source node i to the destination node j for service s are used independently of each other, and the average end-to-end blocking probability that is experienced by a connection being routed from node i to node j for service s is calculated as follows:

$$B_{ij}^s = B_{p_{ij}^{1s}} \sum_{m=2}^{M_{ij}^s} r_{p_{ij}^{ms}} B_{p_{ij}^{ms}}, \tag{3.13}$$

where, according to [28],

$$r_{p_{ij}^{2s}} : r_{p_{ij}^{3s}} : ... : r_{p_{ij}^{M_{ij}^s}} = \frac{1}{B_{p_{ij}^{2s}}} : \frac{1}{B_{p_{ij}^{3s}}} : ... : \frac{1}{B_{p_{ij}^{M_{ij}^s}}}, \tag{3.14}$$

ensuring fairness in the alternative routing as paths with lower blocking probability are used more often, and the blocking probability experienced by a service s connection being carried from node i to node j by path p_{ij}^{ms}, $B_{p_{ij}^{ms}}$, is given by eq. 3.3.

Considering $r_{p_{ij}^{ms}}$ as the ratio of overflow traffic that is offered to alternative path p_{ij}^{ms}, the value of a_k^s is now determined as follows:

$$\begin{aligned} a_k^s = & \sum_{i,j \in N : l_k \in p_{ij}^{1s}} a_{ij}^s \prod_{l_u \in p_{ij}^{1s} - \{l_k\}} (1 - B_u^s) \\ & + \sum_{i,j \in N \wedge m \geq 2 : l_k \in p_{ij}^{ms}} r_{p_{ij}^{ms}} a_{ij}^s B_{p_{ij}^{1s}} \prod_{l_n \in p_{ij}^{ms} - \{l_k\}} (1 - B_n^s). \end{aligned} \tag{3.15}$$

The fixed-point iterator responsible for the calculation of B_k^s is now updated. Assuming an initial fixed value for B_k^s and $r_{p_{ij}^{ms}}$ ($B_k^{s(0)}$, $r_{p_{ij}^{ms}}{}^{(0)} = 1/\left(M_{ij}^s - 1\right)$), B_k^s is determined as follows until a convergence criterion is met:

$$\begin{aligned} a_k^{s\,(x+1)} = & \sum_{i,j \in N : l_k \in p_{ij}^{1s}} a_{ij}^{s\,(x)} \prod_{l_u \in p_{ij}^{1s} - \{l_k\}} \left(1 - B_u^{s\,(x)}\right) \\ & + \sum_{i,j \in N \wedge m \geq 2 : l_k \in p_{ij}^{ms}} r_{p_{ij}^{ms}}^{(x)} a_{ij}^{s\,(x)} B_{p_{ij}^{1s}}^{(x)} \prod_{l_n \in p_{ij}^{ms} - \{l_k\}} \left(1 - B_n^{s\,(x)}\right) \end{aligned} \tag{3.16}$$

$$B_k^{s(x+1)} = f(C_k, \overline{d_k}, \overline{a_k}^{(x+1)}) \tag{3.17}$$

$$r_{p_{ij}^{ms}}{}^{(x+1)} = \begin{cases} 1, & if M_{ij}^{zs} = 2 \\ \frac{\left[B_{p_{ij}^{ms}}^{(x+1)}\right]^{-1}}{\sum_{n=2}^{M_{ij}^{zs}} \left[B_{p_{ij}^{ns}}^{(x+1)}\right]^{-1}}, & if M_{ij}^{zs} > 2 \end{cases} \tag{3.18}$$

$$x = 0, 1, 2, \ldots$$

To assure the convergence of the fixed-point iterators, given that multiple alternative paths are allowed, it was necessary to resort to heavy dampening techniques.

This work generalizes the use of implied costs to multiservice networks with multiple alternative paths. In such scenario, considering that the paths for each pair of end nodes are link-disjoint and that each path p_{ij}^{ms} can be used with probability $r_{p_{ij}^{ms}}$ to carry overflow traffic from node i to node j for service type s, the carried traffic in each alternative path is obtained by:

$$\lambda_{p_{ij}^{ms}} = r_{p_{ij}^{ms}} a_{ij}^s B_{p_{ij}^{1s}} \prod_{l_u \in p_{ij}^{ms}} (1 - B_u^s), \ m = 2, \ldots, M_{ij}^{zs}. \tag{3.19}$$

To calculate c_k^u, the expression 3.9 is updated as proposed:

$$\begin{aligned} c_k^u = \sum_{s=1}^{S} \eta_k^{us} (1 - B_k^s)^{-1} \Bigg[& \sum_{i,j \in N : l_k \in p_{ij}^{1s}} \lambda_{p_{ij}^{1s}} \Bigg(w^s - \sum_{l_n \in p_{ij}^{1s} - \{l_k\}} c_n^s \Bigg) \\ & + \sum_{i,j \in N \wedge m \geq 2 : l_k \in p_{ij}^{ms}} \lambda_{p_{ij}^{ms}} \Bigg(w^s - \sum_{l_n \in p_{ij}^{ms} - \{l_k\}} c_n^s \Bigg) \\ & - \sum_{i,j \in N : l_k \in p_{ij}^{1s}} \lambda_{p_{ij}^{1s}} \sum_{m=2}^{M_{ij}^{zs}} r_{p_{ij}^{ms}} \Big(1 - B_{p_{ij}^{ms}} \Big) \Bigg(w^s - \sum_{l_n \in p_{ij}^{ms}} c_n^s \Bigg) \Bigg] \end{aligned} \tag{3.20}$$

which is equivalent to considering the following expressions:

$$
\begin{aligned}
c_k^u = \sum_{s=1}^{S} \eta_k^{us} \left(1 - B_k^s\right)^{-1} \Bigg[& \sum_{i,j \in N : l_k \in p_{ij}^{1s}} \lambda_{p_{ij}^{1s}} \left(s_{p_{ij}^{1s}} + c_k^s \right) \\
+ & \sum_{i,j \in N \wedge m \geq 2 : l_k \in p_{ij}^{ms}} \lambda_{p_{ij}^{ms}} \left(s_{p_{ij}^{ms}} + c_k^s \right) \Bigg]
\end{aligned}
\tag{3.21}
$$

$$
s_{p_{ij}^{ms}} = w^s - \sum_{l_n \in p_{ij}^{ms}} c_n^s, \quad m = 2, \ldots, M_{ij}^{zs} \tag{3.22}
$$

$$
s_{p_{ij}^{1s}} = w^s - \sum_{l_n \in p_{ij}^{1s}} c_n^s - \sum_{m=2}^{M_{ij}^{zs}} r_{p_{ij}^{ms}} \left(1 - B_{p_{ij}^{ms}}\right) s_{p_{ij}^{ms}}. \tag{3.23}
$$

The $\sum_{m=2}^{M_{ij}^{zs}} r_{p_{ij}^{ms}} \left(1 - B_{p_{ij}^{ms}}\right) s_{p_{ij}^{ms}}$ portion in the $s_{p_{ij}^{1s}}$ expression represents what is lost, on average, in path p_{ij}^{1s} due to the fact that connections that are blocked in path p_{ij}^{1s} can be routed by an alternative path p_{ij}^{ms}, if the latter is not blocked.

3.4 Shortest Path Problem

The classical application of the shortest path problem consists in selecting a path, from a source node to a destination node, with a single objective based on a single metric. In this context, it is assumed that each link has an associated cost and that the objective is to choose the path with the lowest additive cost. This is the case in most large IP networks running routing protocols such as OSPF (Open Shortest Path First) or IS-IS (Intermediate System-Intermediate System).

However, many real-world problems involve more than one objective. This is especially true in multiservice networks, where there may be services with conflicting QoS requirements. This is the case of a video service that requires high bandwidth and low delay. This means, for example, that a path with the largest available bandwidth may not match the path with the lowest delay. In such cases, it may be advantageous to use a multiobjective approach to solve the routing problem as it allows to obtain compromise solutions in face of potentially conflicting objectives involved in the selection of paths.

Sections 3.4.1 and 3.4.2 describe the formulation for the single objective and multiobjective shortest path problem, respectively, including a strategy to be used in the multiobjective case. Two biobjective shortest path algorithms used in the scope of the dynamic routing methods proposed in this work (Modified Multiobjective Routing Algorithm (MMRA) and Bicriteria Shortest Path Algorithm (BSPA)) are also described.

3.4.1 Single Objective Shortest Path Problem

In the formulation of a single objective shortest path problem, a single metric is explicitly considered as the objective function. This metric can be of several types with respect to the aggregation function for the paths. Let m_k^s be the value of a service s metric associated with link l_k. This metric is classified as additive if the value of the metric calculated for any path $p^s \in \mathcal{P}_{ij}^s$ is such that $m_{p^s} = \sum_{l_k \in p^s} m_k^s$.

This work addresses additive metrics only (the implied costs), or metrics that can be converted into additive ones (the blocking probability, as explained hereinafter). The blocking probability in path p^s, B_{p^s}, is calculated as in eq. 3.3 where B_k^s is the blocking probability experienced on link l_k by a service s connection. It can be transformed into an additive metric by applying logarithms

$$\log\left(1 - B_{p^s}\right) = \log\left(\prod_{l_k \in p^s} \left(1 - B_k^s\right)\right) \tag{3.24}$$

$$\log\left(1 - B_{p^s}\right) = \sum_{l_k \in p^s} \log\left(1 - B_k^s\right). \tag{3.25}$$

When optimizing the non-blocking probability in path p^s, 1-B_{p^s}, the purpose of the shortest path problem is the following:

$$\max_{p^s \in \mathcal{P}_{ij}^s} \log\left(1 - B_{p^s}\right) = \max_{p^s \in \mathcal{P}_{ij}^s} \sum_{l_k \in p^s} \log\left(1 - B_k^s\right) \tag{3.26}$$

which is equivalent to

$$\min_{p^s \in \mathcal{P}_{ij}^s} -\log\left(1 - B_{p^s}\right) = \min_{p^s \in \mathcal{P}_{ij}^s} \sum_{l_k \in p^s} -\log\left(1 - B_k^s\right). \tag{3.27}$$

Considering each path $p^s \in \mathcal{P}_{ij}^s$, the purpose of the classical single objective shortest path routing problem is to find the optimal solution to the objective function m_{p^s}:

$$\min_{p^s \in \mathcal{P}_{ij}^s} m_{p^s} = \sum_{l_k \in p^s} m_k^s. \tag{3.28}$$

The optimal path in this scenario is thus the path presenting the lower value in terms of the metric m between the end nodes i and j and for service s.

3.4.2 Multiobjective Shortest Path Problem

In a multiobjective formulation of the shortest paths problem, there are several metrics that are explicitly considered as objective functions to optimize, so that each can be associated with a QoS goal. The multiobjective shortest path problem with $\mathcal{N}$ objectives between the end nodes i and j for service s is formulated as follows, considering each path $p^s \in \mathcal{P}_{ij}^s$:

(Problem $\mathrm{P}^{\mathcal{N}}$)

$$\min_{p^s \in \mathcal{P}_{ij}^s} m_{p^s}^u = \sum_{l_k \in p^s} m_k^{us}, \quad u = 1, \ldots, \mathcal{N} \tag{3.29}$$

where m_k^{us} is the value of metric m^u for service s associated with link l_k. In this context, $m_{p^s}^u$ is the value of the criterion associated with the objective function u for path p^s, and the value of path p^s is a vector of dimension $\mathcal{N}$. Accordingly, consider that the feasible region in the objective space is defined by:

$$\overline{\mathcal{M}}_{ij}^s = \left\{ \overline{m}_{p^s} \in \mathbb{R}^{\mathcal{N}} : \overline{m}_{p^s} = \left(m_{p^s}^1, m_{p^s}^2, \ldots, m_{p^s}^{\mathcal{N}}\right), \forall p^s \in \mathcal{P}_{ij}^s \right\}. \tag{3.30}$$

There is typically no single solution that minimizes all $\mathcal{N}$ objective functions so, in general, there is no optimal solution to this problem. When solving a multiobjective optimization problem, the optimal solution concept is replaced by the non-dominated solution (also referred to as efficient, Pareto efficient, Pareto optimal or non-inferior), if it is not possible to improve the value of any of the objective functions without worsening some of the other objective values. Without additional preference information, all non-dominated solutions are considered equally good.

In mathematical terms,

1. Let $p_1^s, p_2^s \in \mathcal{P}_{ij}^s$ be two feasible paths for service s. Then, p_1^s dominates p_2^s iff [70]

$$m_{p_1^s}^u \leq m_{p_2^s}^u, \forall u = 1, \ldots, \mathcal{N}$$
$$\exists u : m_{p_1^s}^u < m_{p_2^s}^u.$$

2. Let $p_1^s \in \mathcal{P}_{ij}^s$. Then, p_1^s is non-dominated iff there does not exist another feasible $p_2^s \in \mathcal{P}_{ij}^s$, $p_1^s \neq p_2^s$ that dominates it [70].

A strategy to solving problem $\mathrm{P}^{\mathcal{N}}$ consists in optimizing a weighted sum objective function (where the $\mathcal{N}$ weighted objectives are summed to form a composite objective function), and afterward using an efficient k-shortest paths algorithm.

Let A^s denote the set of all objective weighting vectors for service s where

$$A^s = \left\{ \alpha^s \in \mathbb{R}^{\mathcal{N}} : \sum_{u=1}^{\mathcal{N}} \alpha_u^s = 1, \alpha_u^s \geq 0 \right\}.$$

Using the weighted sum approach, the original problem $\mathrm{P}^{\mathcal{N}}$ has been converted into a scalar formulation with a single objective function:

(Problem P^1)

$$\min_{p^s \in \mathcal{P}_{ij}^s} m_{p^s}^* = \sum_{l_k \in p^s} \sum_{u=1}^{\mathcal{N}} \alpha_u^s m_k^{us}. \tag{3.31}$$

Theorem *If $p_*^s \in \mathcal{P}_{ij}^s$ is the optimal solution for problem P^1 then p_*^s is a non-dominated solution [70].*

The use of MPS, the k shortest paths algorithm proposed in [51], applied to an objective function which is a weighted sum of the original objective functions, allows to obtain non-dominated solutions. In the particular case of this work, admissible paths are limited in length (as defined in eq. 3.1), and the MPS variant proposed in [33] allowing to choose the k-shortest paths with a maximum length is used instead.

The routing problems addressed in subsequent chapters by SMODR and DMAR are solved by heuristic approaches based on biobjective shortest path algorithms formulated as in eq. 3.29 with $\mathcal{N} = 2$:

(Problem P^2)

$$\min_{p^s \in \mathcal{P}^s_{ij}} m^u_{p^s} = \sum_{l_k \in p^s} m^{us}_k, \quad u = 1, 2 \tag{3.32}$$

where $m^{1s}_k = c^s_k$ is the implied cost associated with link l_k as a result of establishing a service s connection, as defined in eq. 3.9 in the case of alternative routing with a single alternative path and in eq. 3.20 in the case of alternative routing with multiple alternative paths, and $m^{2s}_k = -\log(1 - B^s_k)$, where the log is used to transform the blocking probability experienced by a service s connection in link l_k, B^s_k, into an additive metric. SMODR uses the Modified Multiobjective Routing Algorithm (MMRA) and DMAR the Bicriteria Shortest Path Algorithm (BSPA), briefly described in sections 3.4.2.1 and 3.4.2.2, respectively, for the selection of the objective weights as well as for the selection of the final solutions from among the set of non-dominated solutions determined by the MPS variant [33].

3.4.2.1 Modified Multiobjective Routing Algorithm (MMRA)

MMRA is explained in detail in [52], and it is briefly described here.

The non-dominated solutions to problem P^2 are found by applying the MPS variant proposed in [33] to an objective function which is a weighted sum of the original objective functions (eq. 3.31 with $\mathcal{N} = 2$). The order by which the solutions are found depends on the search direction defined by the coefficients α^s_1 and α^s_2 of the sum function. The implied costs in links tend to present higher values than those of blocking, especially in situations of overload. Thus, in order not to give preference to any of the metrics in the link and as the metrics do not have the same variation range, for reasons of normalization, the values of α_1^s and α_2^s are determined as follows: $\alpha_1^s M_1^s = \alpha_2^s M_2^s \ \wedge \ \alpha_1^s + \alpha_2^s = 1$, where M_1^s and M_2^s are the average values for each metric for service s, respectively.

The paths corresponding to non-dominated solutions are selected based on the definition of priority regions in the objective functions space. The boundaries of the priority regions correspond to acceptable and required values for each objective function and they vary dynamically enabling an adaptation to the variable network load. Assuming a fully meshed network with alternative routing and a single alternative path, the intended solution is the first non-dominated solution to be found in the higher priority region, excluding the first-choice path. In particular situations, dominated solutions corresponding to an alternative path may be accepted, namely when such solution is dominated only by the one corresponding to the first-choice path but is not dominated by any other solution and it is situated in a higher priority region in relation to any other non-dominated solution different from the first-choice path.

3.4.2.2 Bicriteria Shortest Path Algorithm (BSPA)

BSPA is an improved version of MMRA and, instead of a single alternative path, it returns multiple alternative paths for a given pair $i \to j$ and service s.

The first step in BSPA and MMRA is the same, i.e., to solve problem P^2 by applying the MPS variant proposed in [33], with the same relative weight of the two metrics as in MMRA. Consider now that $\mathcal{P}_{ij}^{*s}$ is the subset of $\mathcal{P}_{ij}^{s}$ constituted by the two-arcs link disjoint alternative paths for pair $i \to j$ and service s. Then, the second step in BSPA is to sort the paths in $\mathcal{P}_{ij}^{*s}$ in ascending order of their euclidean distance to the global optimal (which, in this case, is (0,0)): $\sqrt{\sum_{u=1}^{2} (\alpha_u^s \times m_{p_{ij}^s}^u)^2}, \forall p_{ij}^s \in \mathcal{P}_{ij}^{*s})$. The intended solution is the ordered set of paths, $\mathcal{P}_{ij}^{*s}$.

Chapter 4

Simplified MultiObjective Dynamic Routing (SMODR)

4.1 Introduction

The default Internet architecture offers a best-effort service in which all applications are equally treated and there is no admission control leading, in case of network congestion, to the network performance degradation (or even to dropped packets) for both incoming and ongoing connections. Meanwhile, the Internet has turned into a business platform that needs to guarantee the fulfillment of QoS requirements for new types of applications, namely multimedia applications. This led to the introduction of new features on the network such as the support of service differentiation, namely with Integrated Services (IntServ) [13] and Differentiated Services (DiffServ) [11], and the appearance of technologies such as MPLS allowing the implementation of QoS mechanisms capable of guaranteeing the satisfaction of QoS requirements along a path and facilitating an efficient

The content of this chapter is partly based on the following publications:

- L. Martins, C. Francisco, J. Redol, J. Craveirinha, J. Clímaco, P. Monteiro. Evaluation of a Multiobjective Alternative Routing Method in Carrier IP/MPLS Networks. Networking 2009, Springer, pag. 195-206, 2009.

- L. Martins, C. Francisco, J. Redol, J. Craveirinha, J. Clímaco, P. Monteiro. A first evaluation of multiobjective alternative routing in strongly meshed MPLS networks. Technical report 14/2008, INESC Coimbra, available online: https://www.uc.pt/en/org/inescc/res_reports_docs/research_reports.

traffic distribution among the network resources.

The work in [52] already proposes, although without detailed formulation, extending the MODR method originally applying to multiservice multirate circuit-switched loss networks to MPLS networks with explicit source routing (i.e., where paths are defined by the source node) provided that the concept of effective bandwidth [41] be used. Modeling MPLS networks with explicit routing as multirate circuit-switched loss networks had already been suggested in [59], using the concept of effective bandwidth. The effective bandwidth further encapsulates traffic behavior and quality of service issues at the cell and packet levels [20, 59]. In MPLS, according to [5], the effective bandwidth is the minimum amount of bandwidth that can be assigned to a flow or traffic aggregate in order to deliver "acceptable service quality" to the flow or traffic aggregate.

This chapter extends to MPLS networks the multiobjective dynamic alternative routing concept introduced in [52, 53] and it is structured as follows. Section 4.2 describes the necessary assumptions to consider the use of alternative routing in MPLS networks. Section 4.3 briefly reviews the general features of the original MODR method. As the computational effort of MODR makes it difficult to use in a realistic MPLS environment, section 4.4 presents a new simplified heuristic that is computationally lighter while maintaining good results in terms of network performance in a multiservice environment. The resulting new method using the simplified heuristic is called Simplified MODR (SMODR) and it is validated by comparing its performance with that of the original MODR using a simulation platform. The simulation environment, as well as the simulation results, are presented and analyzed in section 4.5.

4.2 Alternative Routing in MPLS Networks

The implementation of alternative routing in the new networks requires an admission control mechanism to avoid the degradation of the network performance in situations of overload, and it can benefit from the combination of this type of strategy with service differentiation. Two QoS architectures have been defined for the Internet: IntServ and DiffServ. IntServ architecture specifies a fine-grained, flow-based QoS where each router along the path must support IntServ and application flows requiring QoS guarantees need to explicitly signal the QoS needs along the path prior to the transmission. If available in every device along the end-to-end path, the necessary resources are reserved via the Resource Reservation Protocol (RSVP) and the flow is admitted into the network; otherwise, the flow is rejected (admission control mechanism). However, IntServ presents scalability issues as each router traversed by a flow needs to keep a soft state of the connection.

DiffServ solves the scalability problem by specifying a coarse-grained, class-based mechanism for traffic management. In contrast with IntServ which is flow-based, DiffServ classifies each incoming packet into one of a limited set of service classes. This classification is done once, at the network boundaries, and the core routers simply apply per-hop behaviors (PHB) based on their markings. However, DiffServ does not solve the problem of the admission control which is key to guarantee QoS in case of overload.

The Pre-Congestion Notification (PCN) architecture [24] is suggested by the IETF to do connection admission control and flow termination for real-time applications generating inelastic traffic within a DiffServ domain. PCN enforces QoS by marking packets based on the utilization of links and gives early warnings if the overall rate of PCN traffic exceeds a certain rate threshold. The PCN egress nodes provide this feedback to decision points that use it as a basis for their decisions in terms of connection admission and termination. New flows are admitted on link l if the rate r(l) of PCN traffic is below the Acceptable Rate (AR(l)). New flows are blocked if the rate r(l) is above AR(l) and below Supportable Rate (SR(l)). Finally, if r(l) is above SR(l) new flows are blocked and some already admitted flows get terminated.

The traditional definition of RSVP supports per-flow reservations only, while extensions to RSVP enable RSVP reservations to be made for aggregated traffic, such as in DiffServ classification, in line with the IntServ over DiffServ framework [10]. This use of RSVP may be useful for the dynamic bandwidth allocation and admission control in a PCN domain, where end-to-end RSVP signaling can be used (with the PCN-domain considered as a single RSVP hop) [36]. In the context of admission control, when a new flow arrives at a PCN ingress node, it sends a control packet (e.g. a RSVP path message) to the PCN egress node. This control packet traverses the data path and gets marked if it crosses at least one link whose PCN traffic rate is above AR and below SR. If the control packet gets marked, the PCN ingress node will not accept the new flow.

MPLS is often proposed in combination with DiffServ. In MPLS networks packets are classified once, in the ingress label edge router at the edge of the network. The classification into a particular forwarding equivalence class (FEC) does not depend solely on the destination IP address of the received packet, as in pure IP. It can be based on any arbitrary scheme like the interface on which the packet arrived or the DiffServ Code Point value of IP packets. The label switching routers in the network core are not required to reclassify the packets. Packet processing simply relies on the lookup of the topmost label in the incoming packet and a swap operation is performed on the label stack. This makes packet processing fast and protocol-independent.

An MPLS traffic trunk is an aggregation of traffic flows belonging to the same FEC, receiving the same treatment (e.g., being routed over the same path and with the same label) and for that reason being placed inside the same label switched path (LSP). With MPLS, different service levels can be guaranteed by using separate LSPs and traffic engineering (TE) operations can be used to contribute to a more load-balanced network. The requirements for TE over MPLS were first defined in [6]. MPLS TE presents several advantages, namely the use of explicit LSPs which are not constrained by the destination IP address and that can be automatically computed by the underlying routing protocols or defined through manual administrative configuration. Administratively specified explicit paths can be completely specified or partially specified, and they should be associated with a "path preference rule" attribute indicating if the path is "mandatory" or "non-mandatory". A "mandatory" value indicates that only the configured path can be used, even if unfeasible; a "non-mandatory" value allows an alternative path to be attempted. From a TE perspective, a set of traffic parameters can also be associated with traffic trunks to reflect their resource requirements. The use of the effective bandwidth concept as a possibility for the allocation of bandwidth in MPLS traffic trunks is suggested in [6].

Within the scope of this chapter, a DiffServ-aware-MPLS meshed network with PCN is assumed. In the context of MODR, flow termination is not considered and therefore the PCN threshold rates for a given link l (AR(l) and SR(l)) have the same value which corresponds to the link bandwidth. In case of blocking, a second chance may be given to incoming flow requests if alternative routing is allowed. Note that a key advantage of MPLS TE is the use of explicit routing, where alternative routing is allowed in an explicit path if the "path preference rule" attribute is specified with a "non-mandatory" value.

Regarding MPLS, each explicit LSP is treated as a point-to-point path with a constant bandwidth value over a given period of time. In this case, traffic with different bandwidth requirements is classified into the same FEC and carried in the same LSP between adjacent nodes and, for the time duration of each flow, it requires a constant bandwidth value on each LSP which is equivalent to the effective bandwidth that is characteristic of that type of flow. The effective bandwidth is a simplified stochastic measure of bandwidth allocation that encapsulates the effects of the statistical multiplexing of different flows with their respective QoS requirements. Additionally, bursts and bandwidth variations can be forgotten because the PCN Acceptable Rate allows PCN boundary nodes to convert measurements of PCN markings into decisions about connection admission. At this point, blocked connection requests in explicit LSPs with a "non-mandatory" value may attempt an alternative path.

In summary, in the scope of the multiservice MODR method, each LSP is treated as a multiservice point-to-point path with a constant bandwidth value which is shared by all the services. Each incoming connection into the LSP is admitted to the network if the effective bandwidth that is required for that connection is available in the LSP; otherwise, it is blocked (and offered to an alternative path, if the LSP is instantiated with a "non-mandatory" value). This behavior together with the proper adjustment of the PCN Acceptable Rate allows the consideration of a quasi circuit-switching capability superimposed on the current Internet routing model.

4.3 Review of MODR

MODR is a multiple objective dynamic routing method for strongly meshed multiservice multirate circuit-switched loss networks with alternative routing, extensively documented in [52].

MODR is a centralized periodic state-dependent routing method according to which a central routing processor periodically (every path update interval) estimates the offered traffic matrix for the following interval based on real-time measurements, hence the designation of state-dependent, and then it calculates the new routing tables that will be used in the network until the following path update instant.

The MODR method applies to networks with alternative routing and a single alternative path. Thus, the ordered set of paths that can be used at a given time instant t from the source node i to the destination node j for service s is defined by $P_{ij}^{ts} = \left\{p_{ij}^{1s}, p_{ij}^{2s} : p_{ij}^{2s} \in \mathcal{P}_{ij}^{s} \setminus \left\{p_{ij}^{1s}\right\}\right\}$, where p_{ij}^{1s} is the fixed first-choice path constituted by the direct link, when it exists, and p_{ij}^{2s} is periodically updated.

The notation introduced in section 3.3.1 is herein extended with the purpose of formulating the MODR routing problem. Let d^s be the bandwidth required by a service s connection on each link, $B_{ij}^{s} = B_{p_{ij}^{1s}} B_{p_{ij}^{2s}}$ be the average end-to-end blocking probability that is experienced by a service s connection being routed from node i to node j and $A_o^s = \sum_{i,j \in N} a_{ij}^{s}$ be the total load that is offered to the network by service s. Then, $B_m^s = (A_o^s)^{-1} \sum_{i,j \in N} a_{ij}^{s} B_{ij}^{s}$ is the mean service s blocking probability and $A_c^s = A_o^s (1 - B_m^s)$ is the total load that is carried by service s. Given the complexity of the multiobjective alternative routing problem at hands, the MODR routing problem is formulated as a hierarchy with two optimization levels: the network level (NL) objective functions have higher priority and aim to maximize the expected network revenue W_T and minimize the maximal service mean blocking probability B_{Mm}; whereas the service level (SL) objective functions have lower priority and aim to minimize the mean service blocking probabilities B_m^s and the maximal point-to-point blocking probability for each service B_M^s. Fairness objectives are explicitly incorporated as objective functions at the network level (minimization of the maximal mean blocking probability of all service types) and service level (minimization of the maximal blocking probability of all traffic flows of each service type), in parallel with other objective functions (maximization of the total expected revenue and minimization of mean service blocking probabilities). Then, the formalization of the routing problem for MODR is the following:

(Problem $\quad \mathrm{P}_S$)

$$NL : \min_{\overline{\mathcal{P}}} -W_T = -\sum_{s\in S} d^s A_c^s = -\sum_{s\in S} d^s A_o^s (1 - B_m^s) \tag{4.1}$$

$$\min_{\overline{\mathcal{P}}} B_{Mm} = \max_{s\in S} B_m^s \tag{4.2}$$

$$SL : \min_{\overline{\mathcal{P}^s}} B_m^s = (A_o^s)^{-1} \sum_{i,j\in N} a_{ij}^s B_{ij}^s, \quad s = s_1, \ldots, s_{|S|} \tag{4.3}$$

$$\min_{\overline{\mathcal{P}^s}} B_M^s = \max_{i,j\in N} B_{ij}^s, \quad s = s_1, \ldots, s_{|S|} \tag{4.4}$$

s.t. eq. 3.3-3.6 of the traffic model in section 3.3.1.

The purpose of MODR is thus to periodically find the "best" set of single alternative paths that represent a compromise solution between the objective functions, according to the state of the network.

The resolution of the P_S problem relies on a heuristic based on two consecutive mechanisms: *i*) a biobjective shortest path algorithm, designated as Modified Multiobjective Routing Algorithm (MMRA), to obtain candidate alternative paths for flows, as described in 3.4.2.1, *ii*) a procedure to update the routing plan in each iteration.

In summary, as depicted in Figure 4.1, the MODR analytical model is based on fixed-point iterators to compute the link metrics associated with each service, the blocking probabilities $\overline{B}$ and the implied costs $\bar{c}$, for a given network topology G, offered traffic $\overline{A}^t$, links capacity $\overline{C}$ and routing plan $\overline{P}^{t-1}$. The MODR heuristic further identifies whose alternative paths are updated in each iteration among the set of solutions discovered by MMRA, in the sense that a compromise solution is reached in terms of the network global performance (W_T and B_{Mm}) and the lower priority service performance criteria (B_m^s and B_M^s).

As stated in [28, 50], bi-stability may be observed when alternative routing is used in fully meshed networks without a bandwidth reservation mechanism. The MODR heuristic includes a different direct traffic protection strategy designated

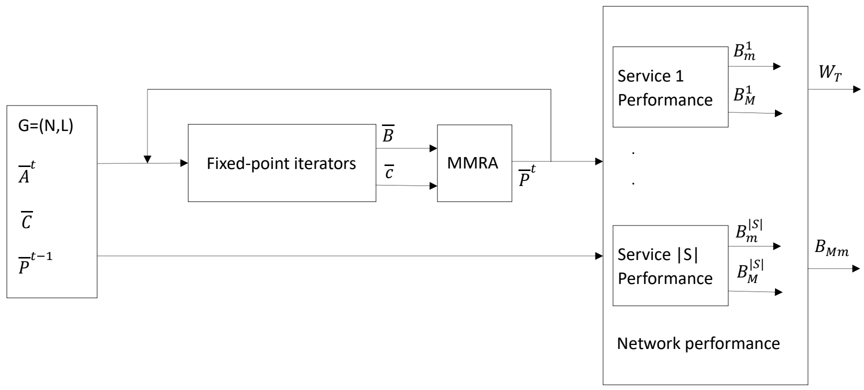

Figure 4.1: Functional relations in MODR model.

by Alternative Path Removal (APR) which is based on alternative path elimination because, from [20] and simulation experiments in [52], it achieves better global network performance than bandwidth reservation schemes. In MODR an alternative path for service s, p^{2s}, is eliminated whenever the following condition stands:

$$m^1_{p^{2s}} > d^s z_{APR} \ \wedge \ \ m^2_{p^{2s}} > -\log(1-0.3)\, z_{APR} \tag{4.5}$$

where $m^1_{p^{2s}}$ and $m^2_{p^{2s}}$ are the values obtained for each of the objectives of the P^2 problem defined in eq. 3.32. The first factor of the condition in $m^1_{p^{2s}}$ corresponds to a path with an implied cost higher than the revenue that it generates (which, in this context, is equivalent to the value of d^s), and the first factor of the condition in $m^2_{p^{2s}}$ corresponds to a path with a blocking probability higher than 0.3. On the other hand, z_{APR} is a parameter which dynamically varies between 0 and 1 under the original MODR heuristic.

Assuming quasi-stationary traffic in successive path update periods, the work in [25] shows that the single objective alternative routing problem is NP-complete in the strong sense. Given that the P$_S$ routing problem has a multiobjective formulation and taking into account the interdependencies between B^s_m (eq. 4.3) and B^s_M (eq. 4.4) and their dependencies on the paths that are used (via B^s_{ij} and eq. 3.3-3.6 in section 3.3.1), these are strong indications of the extreme intractability of the problem, which is solved in [52, 53] using a computationally heavy heuristic. This thesis proposes a simplified heuristic more suitable for application in real networks as its computational effort is very much reduced, while it is still able to fulfill as much as possible the original objectives of the multiobjective dynamic routing problem.

4.4 Simplified MODR (SMODR)

The simplified MODR periodically updates the alternative paths of only a subset of sequentially chosen node pairs, instead of updating the entire routing plan, as in the original MODR heuristic. The number of node pairs whose paths are updated in each path update interval influences the speed at which the network adapts to changes in its offered traffic. As explained in [52], neither the update of the entire routing plan nor the update of a single alternative path in each update interval are good approaches. Updating the alternative paths for all node pairs based on a given state of the network causes the best links in a given time interval to become the worse links in the following interval as a result of being used by a higher number of alternative paths. On the other hand, updating the alternative path for a single pair of nodes in each update interval slows down the process of determining the best paths for the entire network and it prevents the network to adjust to fast traffic fluctuations. Additionally, the experimentation has shown that a direct traffic protection mechanism as a way to prevent the excessive use of (longer) alternative paths in overloaded networks is at least as important as the routing method itself. These two different but related aspects of the problem are addressed within the definition of two simplified heuristics, hereinafter designated as Heuristic 1 and Heuristic 2.

4.4.1 Heuristic 1

The first aspect to consider is the determination of the number of node pairs whose paths are to be updated in each path update interval. For the particular case of the six-nodes test networks in this study (defined in Appendix A.1), Heuristic 1 updates the alternative paths for $\alpha = |N|/2$ sequential node pairs, which results in updating the entire routing plan every $|N| * (|N| - 1)/\alpha$ path update periods.

Different values of α may have to be considered in other network topologies for this routing method.

Heuristic 1 is depicted in Algorithm 4.1. Every time instant $t = nT$ $(n = 1, 2, ...)$, where T is the path update interval, the two link metrics $\overline{B}$ and $\overline{c}$ are calculated considering the set of initial paths $\overline{P}^n$ and a moving average traffic matrix estimate for the following time interval, $\overline{A}^n$. The pseudocode considers the following initial values $i \leftarrow 1$, $j \leftarrow 1$. Then, the solution $\overline{P}^a$ contains the update of the alternative paths for the set of α sequential node pairs, according to MMRA and an improved direct traffic protection mechanism, to be detailed in section 4.4.3.

Algorithm 4.1 - Heuristic 1

1. $\overline{P}^a \leftarrow \overline{P}^n$
2. Calculate $\overline{B}$, $\overline{c}$, for $\overline{P}^a$ using the $\overline{A}^n$ estimate
3. *counter* $\leftarrow 0$
4. While (*counter* $< \alpha$) do
   (a) $j \leftarrow j + 1$
   (b) If $(j = |N|{+}1\ )$ $i \leftarrow i + 1$, $j \leftarrow 1$
   (c) If $(i = |N|{+}1)$ $i \leftarrow 1$, $j \leftarrow 2$
   (d) If $(i = j \wedge j \neq |N|)$ $j \leftarrow j + 1$
   (e) If $(i = j \wedge j = |N|)$ $i \leftarrow 1$, $j \leftarrow 2$
   (f) For (s=1 until s=$|S|$) do
      i. $\overline{P}^a = \overline{P}^a \backslash p_{ij}^{2s} \cup p_{ij}^{MMRA}$, where MMRA determines the alternative path for pair (i, j) and service s in the new solution
      ii. Selective elimination of the alternative path p_{ij}^{2s} in $\overline{P}^a$ (according to one of the direct traffic protection conditions to be defined in section 4.4.3)
   (g) *counter* $\leftarrow$ *counter* $+1$
5. $\overline{P}^{n+1} \leftarrow \overline{P}^a$

It is possible to define a numerical complexity value for MODR in terms of the upper bound of the number of alternative routing solutions that may be analyzed in each path update interval. The complexity of the original MODR heuristic is of the order of $|S|\,(|N| * (|N|-1))^2$. On the other hand, the simplified Heuristic 1 only analyzes $\alpha\,|S|$ solutions. For the six-nodes test networks with $|S| = 3$ that are used in this experimental study, the original MODR heuristic analyzes $3 * (30)^2 = 2700$ solutions, while the simplified Heuristic 1 analyzes $3 * 3 = 9$ solutions, hence leading to a quite significant complexity reduction.

4.4.2 Heuristic 2

The α attribute that is used in Heuristic 1 to quantify the number of node pairs that update their alternative paths at each update time may depend on the network. The proposal of this second heuristic, herein designated as Heuristic 2, intends to overcome this limitation.

Algorithm 4.2 - Heuristic 2

1. $\overline{P}^a \leftarrow \overline{P}^n$
2. Calculate $\overline{B}$, $\overline{c}$, for $\overline{P}^a$ using the $\overline{A}^n$ estimate
3. For ($j = 1$ until $j < |N|$+1) do
   (a) If ($i \neq j$)
      i. $\overline{P}^a = \overline{P}^a \backslash p_{ij}^2 \cup p_{ij}^{MMRA}$, where MMRA determines the alternative path for pair (i, j) and service s in the new solution
      ii. Selective elimination of the alternative path p_{ij}^{2s} in $\overline{P}^a$ (according to one of the direct traffic protection conditions to be defined in section 4.4.3)
4. $s \leftarrow s + 1$
5. If ($s = |S|$) $s \leftarrow 1$, $i \leftarrow i + 1$
6. If ($i = |N|$+1) $i \leftarrow 1$
7. $\overline{P}^{n+1} \leftarrow \overline{P}^a$

Heuristic 2 updates, in each path update instant, the alternative paths for all destination nodes for a given source node and service. Consequently, the entire routing plan is updated every $|N| * |S|$ periods. Heuristic 2 is described in Algorithm 4.2. Consider that Heuristic 2 begins with service 1 and that, similarly to Heuristic 1, the initial values in the pseudocode are the following: $i \leftarrow 1$, $j \leftarrow 1$. As already stated, the complexity of the original MODR heuristic for the six-nodes networks in this study gives 2700. Heuristic 2 only analyzes $|N| - 1 = 5$ solutions, which is a significant complexity reduction, even when compared to Heuristic 1.

4.4.3 Direct Traffic Protection Mechanism

To prevent the excessive use of alternative routing, the original MODR heuristic eliminates alternative paths whenever condition 4.5 is met, using a dynamic parameter z_{APR} ranging from 0 to 1. The proposed simplified heuristics do not use this dynamic parameter, and therefore the study begins by evaluating the network performance as a result of using different static values. A starting point for this analysis considers $z_{APR} = 1$ (the initial value in the original MODR heuristic). Thus, the alternative path p^{2s} is eliminated if the following condition stands:

$$m^1_{p^{2s}} > d_s \ \wedge \ m^2_{p^{2s}} > -\log(1 - 0.3) \,. \tag{4.6}$$

This 0.3 constant corresponds to a 30% threshold value for the path blocking probability and it is indiscriminately used for all services in the network, regardless of their effective bandwidth. This mechanism tends to eliminate more alternative paths in the services which are more demanding in terms of bandwidth. On the other hand, it may lead to an excessive use of alternative routing in the less bandwidth demanding services.

The variation of z_{APR} in the original MODR heuristic leads to the experimentation of other threshold values. As a first step, a lower value (0.20) is attempted:

$$m^1_{p^{2s}} > d_s \ \wedge \ m^2_{p^{2s}} > -\log(1 - 0.2) \,. \tag{4.7}$$

The simulation study in section 4.5 will show that this lower threshold value achieves better network performance the higher the load situation. On the other hand, both conditions 4.6 and 4.7 offer the same treatment to the various services. A selective service level approach that takes advantage of the different effective bandwidth values may bring additional benefits. As such, new conditions for eliminating alternative paths are proposed under eq. 4.8 and 4.9, which balance the use of alternative routing among the various services:

$$m^1_{p^{2s}} > d_s \ \wedge \ m^2_{p^{2s}} > -\log\left(1 - 0.3\frac{B^s_m}{B_{Mm}}\right) \tag{4.8}$$

$$m^1_{p^{2s}} > d_s \ \wedge \ m^2_{p^{2s}} > -\log\left(1 - 0.2\frac{B^s_m}{B_{Mm}}\right). \tag{4.9}$$

The introduction of the $\frac{B^s_m}{B_{Mm}}$ factor introduces fairness among the services in the alternative path elimination procedure, which is now dependent on each service mean blocking probability value. The smaller the ratio between the given service and the most demanding service mean blocking probability, the lower the threshold value above which the alternative path regarding the service in question is eliminated.

Given the definition of implied cost, it also seems appropriate to consider the elimination of an alternative path when its implied cost value is higher than the corresponding expected revenue, regardless of its blocking probability value. In this context, other similar conditions (defined by eq. 4.10 and 4.11) are proposed with the substitution of the AND by the OR condition:

$$m^1_{p^{2s}} > d_s \ \vee \ m^2_{p^{2s}} > -\log\left(1 - 0.3\frac{B^s_m}{B_{Mm}}\right) \tag{4.10}$$

and

$$m^1_{p^{2s}} > d_s \ \vee \ m^2_{p^{2s}} > -\log\left(1 - 0.2\frac{B^s_m}{B_{Mm}}\right). \tag{4.11}$$

The simulation study in section 4.5 includes experiments with these different path elimination criteria. They will show that, with the increase of the network load, an alternative path elimination at lower threshold values of blocking in $m^2_{p^{2s}}$

is more effective. This leads to the following additional condition:

$$m^1_{p^{2s}} > d_s \ \vee \ m^2_{p^{2s}} > -\log\left(1 - 0.1\frac{B^s_m}{B_{Mm}}\right). \tag{4.12}$$

All the previous conditions for alternative path elimination depend both on path blocking probabilities (responsible for point-to-point blocking balance) and on path implied costs (which tend to benefit the more demanding flows in terms of bandwidth leading to a lower mean network blocking probability and to a maximum of carried traffic in the network, with the increase of the point-to-point blocking probability for the less demanding flows). In an attempt to find a simpler solution, a new condition is suggested where the alternative path is eliminated based only on the path implied cost value. This is written as follows:

$$m^1_{p^{2s}} > d_s. \tag{4.13}$$

In general, this condition translates into intermediate results when compared to the performance of simulations with eq. 4.6 and 4.12.

4.4.4 Howard Costs

The implied costs are already known for improving the network performance in terms of carried traffic. At this point, a simpler metric designated by Howard cost [61] is suggested in an attempt to further reduce the computational effort of the simplified heuristics. The Howard cost has been simplistically adapted to multiservice networks as follows:

$$\Delta(k, j) = \frac{B^s_k}{B^s_{k_j}},\ 0 \leq j \leq C_k \tag{4.14}$$

where $B^s_{k_j} = f(j, \overline{d_k}, \overline{a_k})$ represents the blocking probabilities. Expression 4.14 represents an estimate of the expected increase in future blocked calls on link l_k due to the addition of a call when j calls are already in progress. In this sense, paths with the minimal Howard cost tend to contribute to the maximization of throughput and to load balancing as paths with less calls in progress tend to be chosen. Howard costs are additive therefore the cost of a path p^{2s} is given by:

$$m^1_{p^{2s}} = \sum_{l_k \in p^{2s}} \Delta\left(k, j\right). \tag{4.15}$$

By replacing the implied costs by the Howard costs in the MMRA algorithm used in the simplified heuristics, the new conditions for eliminating alternative paths are now the following ones (by analogy with eq. 4.12 and 4.13):

$$m^1_{p^{2s}} > 1 \ \vee \ m^2_{p^{2s}} > -\log\left(1 - 0.1\frac{B^s_m}{B_{Mm}}\right) \tag{4.16}$$

$$m^1_{p^{2s}} > 1. \tag{4.17}$$

Note that the path elimination criterion based on eq. 4.17 has already been considered in [20].

4.5 Simulation Study

This study evaluates the performance of the simplified MODR. Simulations were carried out taking into account: *i*) the direct traffic protection mechanism, *ii*) the offered traffic estimation, and *iii*) the path update interval value. The replacement of the implied costs by the Howard costs is also analyzed.

The performance of the simplified heuristics was evaluated by implementing them in the discrete-event OMNet++ simulator that was already used in the past to validate the original MODR heuristic. In this simulator, the estimated offered traffic $\tilde{x}$ in the n^{th} time interval for traffic flow f is obtained from an estimate $\tilde{X}_f(n-1)$ of the offered traffic in the previous interval calculated from on-line measurements, for the same traffic flow, by using a first order moving average iteration:

$$\tilde{x}_f(n) = (1-b)\tilde{x}_f(n-1) + b\tilde{X}_f(n-1), \tag{4.18}$$

as suggested in [40], with $b = 0.9$. For each scenario, five independent simulation runs were performed and the presented results are the midpoints of a 95% confidence interval.

Two fully meshed test networks with six nodes are used (networks A and M in Table A.1 in Appendix A.1), the same networks already considered in a previous work [52] to simplify the performance comparison with the original MODR heuristic as its simulation time is very high. These networks were engineered with three services: voice, data and video, with the effective bandwidth $\overline{d} = [1, 6, 10]$ for each service and service durations of 1, 5 and 10 minutes, respectively.

The simulation results for the original MODR heuristic are presented in [52] and can also be consulted in tables A.2 and A.17 in Appendix A for global and service performance, respectively. Note that the assumed "nominal load"in this simulation study is 20% less than in [52]. Such results were obtained with a 1 minute path update interval. For the sake of consistency, the first set of analyzed simulations in the scope of the simplified heuristics uses the same path update interval value.

On the other hand, the simplified Heuristic 1 achieves better global network performance than the simplified Heuristic 2. For this reason, the graphical representation of the simulation results in this chapter solely includes the performance of Heuristic 1. Detailed information concerning the global and service performance for both simplified heuristics can be consulted in Appendix A.

4.5.1 Direct Traffic Protection Mechanism

Figures 4.2 and 4.3 show the comparative global network performance of MODR and SMODR for networks A and M, respectively, highlighting the differences between the original MODR heuristic and the simplified Heuristic 1 used by SMODR with the different path elimination criteria introduced in section 4.4.3.

Firstly, the original MODR heuristic achieves better global network performance than the simplified Heuristic 1 with eq. 4.6, the starting point condition for the alternative path elimination mechanism. Nevertheless, the gain achieved with the speed and simplicity of this new heuristic make it more suitable for realistic environments and it is an incentive for further study in the scope of the

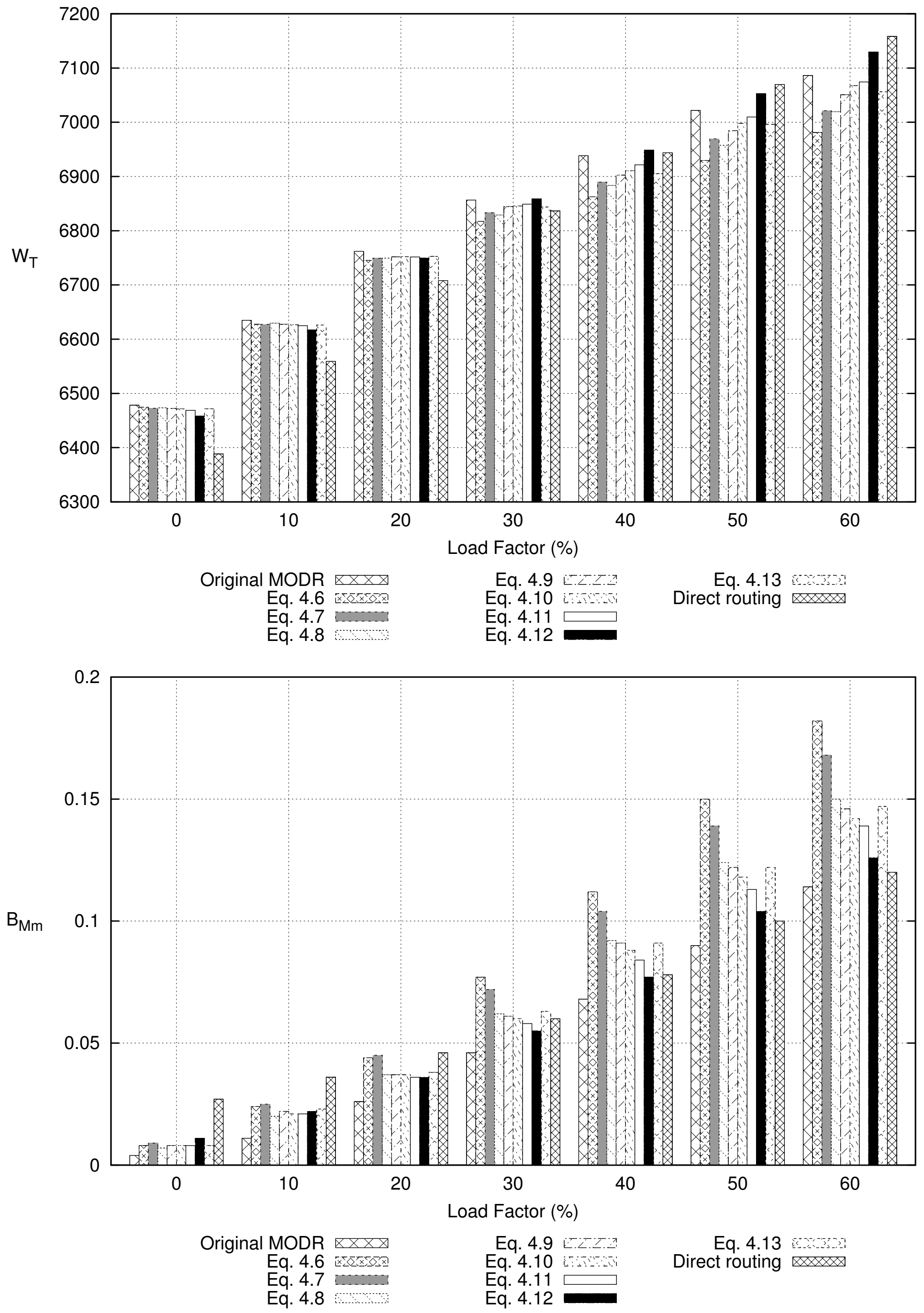

Figure 4.2: Network A - Global performance with different path elimination criteria, $b = 0.9$ and a 1 minute path update interval.

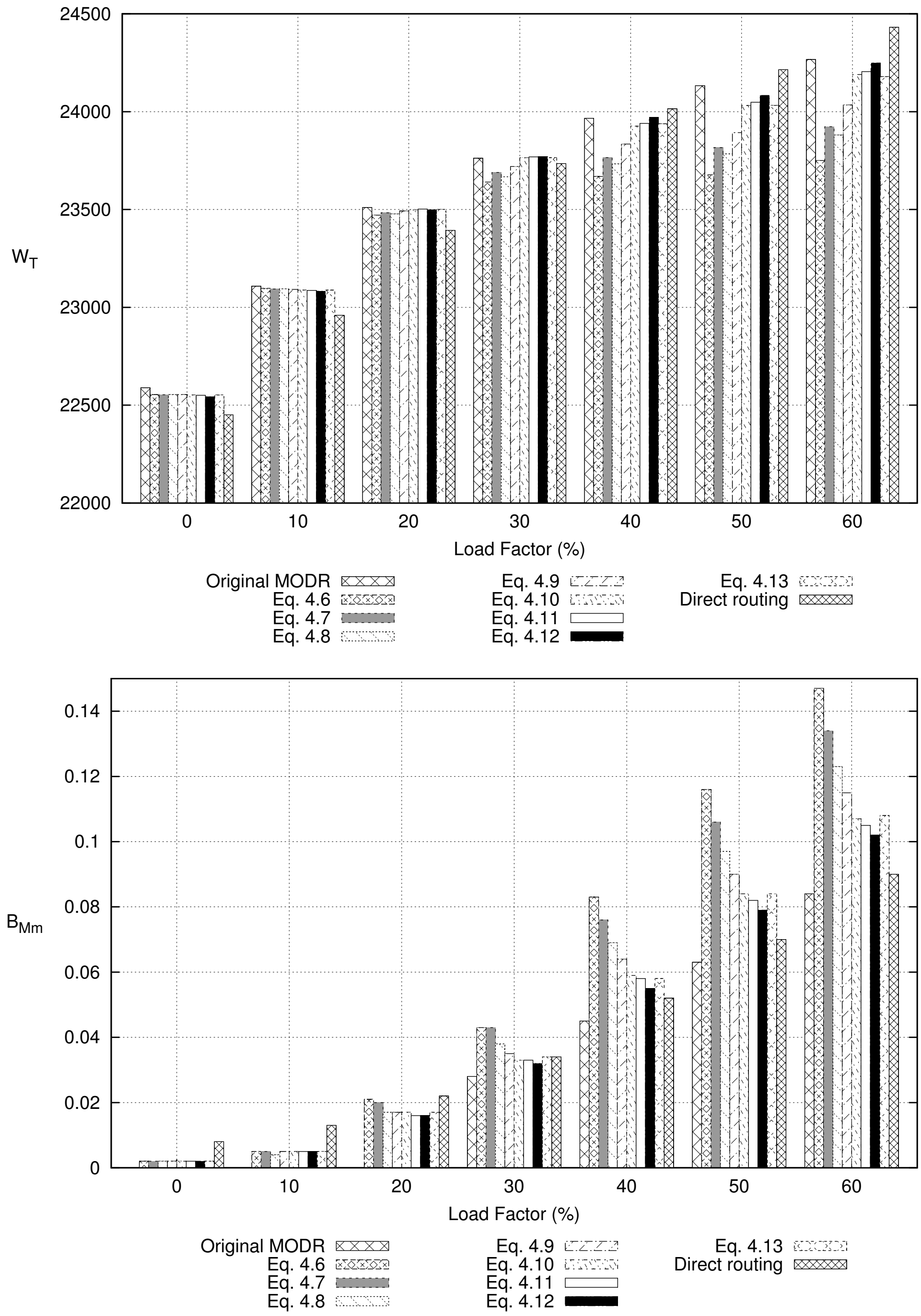

Figure 4.3: Network M - Global performance with different path elimination criteria, $b = 0.9$ and a 1 minute path update interval.

different criteria for the direct traffic protection mechanism analyzed next.

The 30% threshold value for the path blocking probability (eq. 4.6, 4.8 and 4.10) achieves slightly better global performance for lightly loaded situations while the 20% (corresponding to eq. 4.7, 4.9 and 4.11) and 10% (eq. 4.12) threshold values are better for higher loads. On the other hand, using the implied costs as the single criterion in the alternative path removal procedure (eq. 4.13) is never a good approach. [1]

In summary, the condition 4.6 allowing higher blocking probabilities for the less demanding service in terms of bandwidth is better for lightly loaded situations, while condition 4.12 implementing fairness among services in the alternative path removal process and at lower blocking values is the best suited for nominal and higher load situations. Also taking into consideration the performance results of the AND and OR conditions, it is believed that in low load situations the existence of alternative paths is important but, with the increase of the network load, an alternative path elimination mechanism at lower threshold values of blocking probability is more effective. These conclusions are confirmed by the simulation results using the direct routing scheme, in which case there is a fixed single path constituted by the direct link connecting each pair of end nodes (i.e., no alternative routing). In fact, for load factors higher than 40% (see tables A.9 and A.10 in Appendix A.2), direct routing is the best method, with higher expected revenue and lower maximum service mean blocking probability values. This evidence is explained because in the face of a lack of resources in a fully meshed network, alternative routing becomes more inefficient.

Due to the better global network performance in overload situations, it is considered from this moment onward that the SMODR heuristic uses condition 4.12 in the direct traffic protection mechanism.

Besides the network performance, it also matters to assess the performance of the services, as shown in Figures 4.4 and 4.5 for networks A and M, respectively. These results show that the original MODR is the best method in terms of both metrics, in all the network loads, for the most demanding service in terms of bandwidth (service s=3, which in the routing model is the most profitable one).

[1]Service performance results regarding all cases shown in the figures are presented in the Appendix A.3.

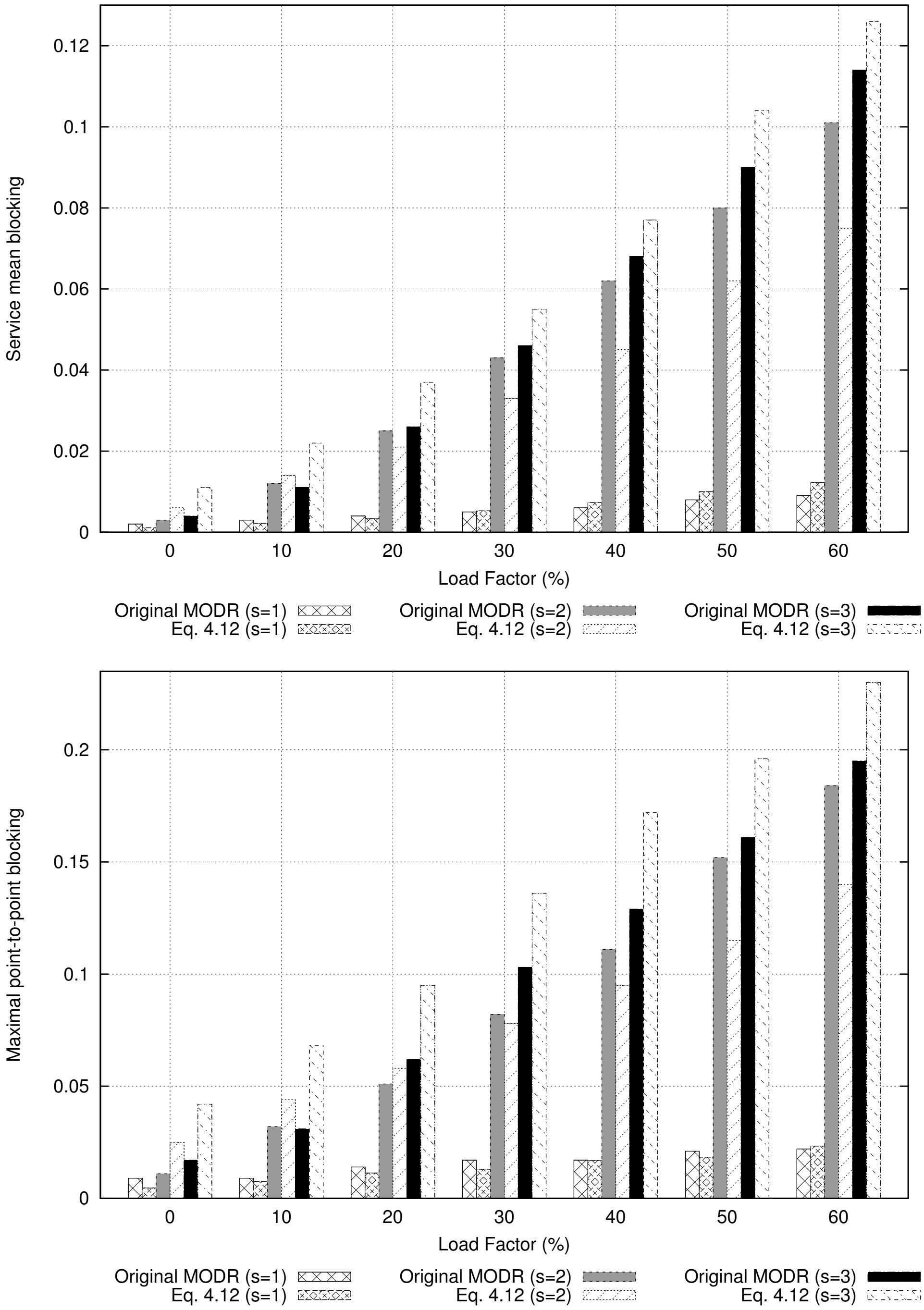

Figure 4.4: Network A - Service performance with different path elimination criteria, $b = 0.9$ and a 1 minute path update interval.

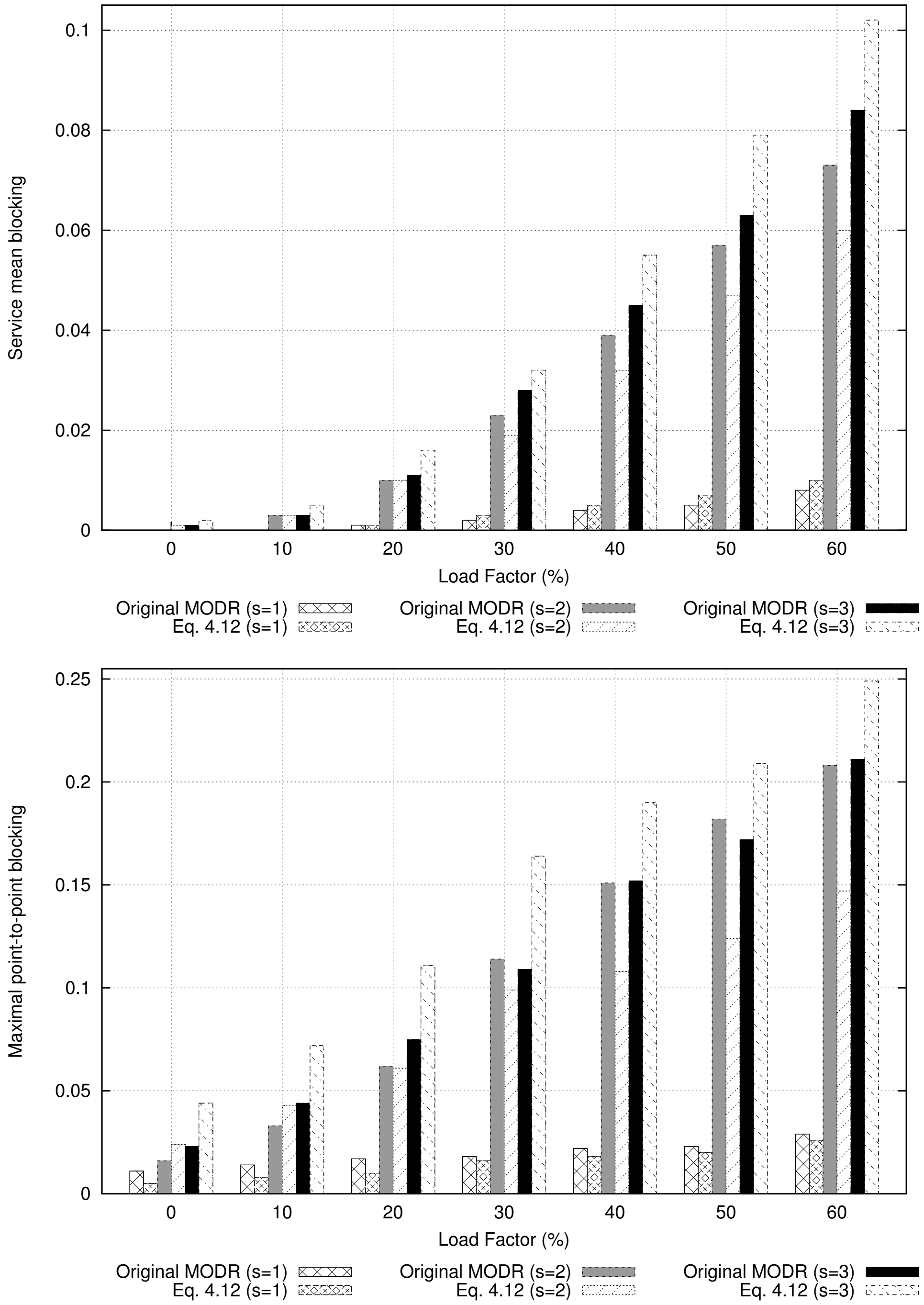

Figure 4.5: Network M - Service performance with different path elimination criteria, $b = 0.9$ and a 1 minute path update interval.

When it comes to service s=2, the original MODR is the best performing method in the biobjective sense for the low load traffic scenarios but, as the network load increases, the SMODR becomes the best method in both metrics. Note that the value for B_m^2 is so low in the nominal load traffic scenario for Network M that it is hardly represented in Figure 4.5. Finally, the service that is less demanding in terms of bandwidth (service s=1) is analyzed. In Network A, the SMODR is the best performing method for the low load traffic scenarios but, as the network load increases, the methods present comparable performance (lower B_m^1 or B_M^1). In Network M, the performance of the methods is comparable in all the traffic scenarios (lower B_m^1 for the original MODR and lower B_M^1 for SMODR). Note further that the values for B_m^1 are so low in the lightly loaded traffic scenarios that they are hardly represented in figures.

4.5.2 Estimation of the Offered Traffic

Another decisive factor with respect to the performance of the routing method is the estimation of the average traffic that is offered to the network by a given flow, which is affected by the value of parameter b in eq. 4.18. A value of b higher than 0.5 gives greater importance to the traffic that was offered during the previous update interval, while a value of b lower than 0.5 puts more weight on the traffic estimate for the previous interval. The value of b originally used is $b = 0.9$, allowing a rapid response to traffic fluctuations and benefiting low load situations, but it can lead to poor routing solutions in overloaded cases. This work considers the additional scenarios of $b = 0.1$ (the value proposed in [32] because while relying in traffic history still allows a slow adaptation in case of changes in the network load) and $b = 0.5$.

As expected, results in tables A.35 and A.36 show that $b = 0.1$ benefits overloaded networks, and $b = 0.5$ results in mid-term performance. Due to the better performance in overload situations, the study continues with $b = 0.1$ from this moment onward. Simulations results concerning the network global performance for the scenarios where $b = 0.9$ and $b = 0.1$ can be observed in figures 4.6 and 4.7. Results for $b = 0.5$, the mid-term case, can only be consulted in tables A.35 and A.36 in Appendix A.2.

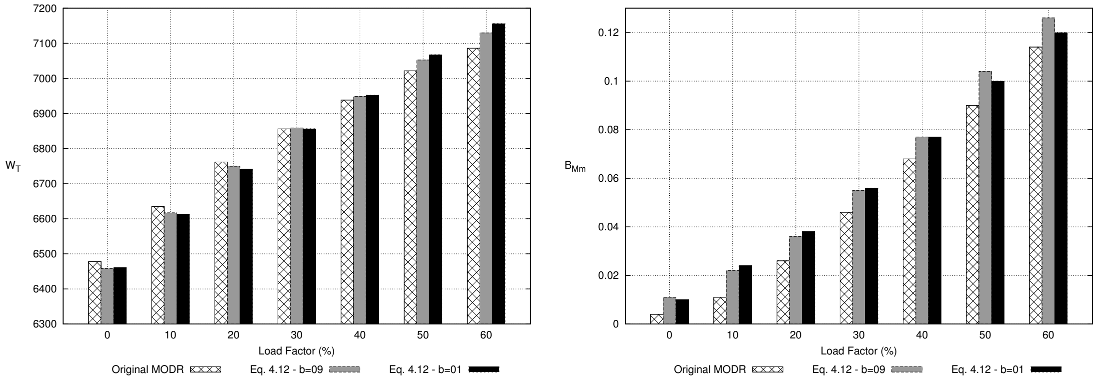

Figure 4.6: Network A - Global performance comparing MODR and SMODR with eq. 4.12, $b = 0.9$ or b=0.1, and a 1 minute path update interval.

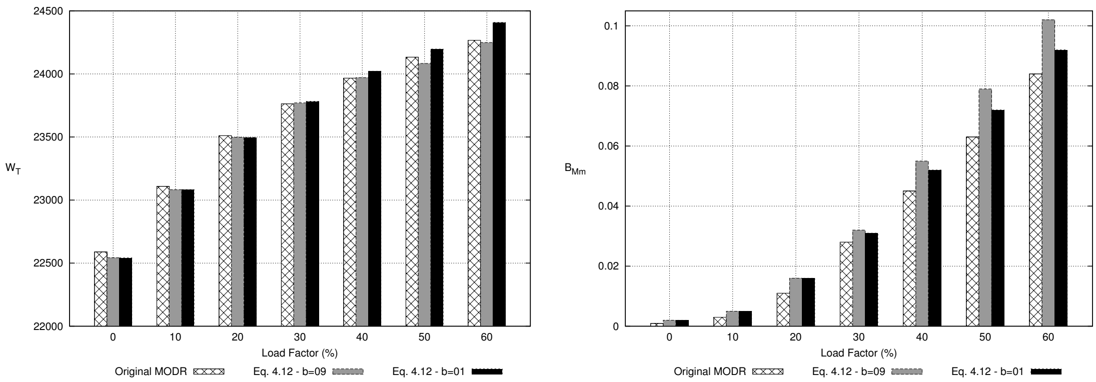

Figure 4.7: Network M - Global performance comparing MODR and SMODR with eq. 4.12, $b = 0.9$ or $b = 0.1$, and a 1 minute path update interval.

4.5.3 Path Update Interval

An additional topic to assess is the influence of the network load on path update intervals. In this context, simulations results are analyzed with a path update interval of 10 seconds (a typical value in voice circuit-switching networks) and 1 minute (previously used in [52] and in the tested scenarios so far). A smaller path update interval achieves a better performance in lightly loaded situations as traffic flows can be better accommodated with the frequent changes in path allocations, while a 1 minute interval has a better performance for overloaded situations.

Figures 4.8 and 4.9 show the comparative global performance results for networks A and M, respectively. The case with a 10 seconds path update time interval is the one with the most appealing global performance (when comparing with the 1 minute path update interval). Note further that the shorter path update interval somehow compensates for the smaller number of pairs of nodes whose paths are periodically updated in the new SMODR method. Results also show that when SMODR uses a 10 seconds path update interval and an alternative path elimination mechanism based on eq. 4.12, it is possible to obtain a performance which is comparable to that of the original MODR method, and even improved in terms of expected revenue in overload situations, achieving other non-dominated solutions in terms of global network performance.

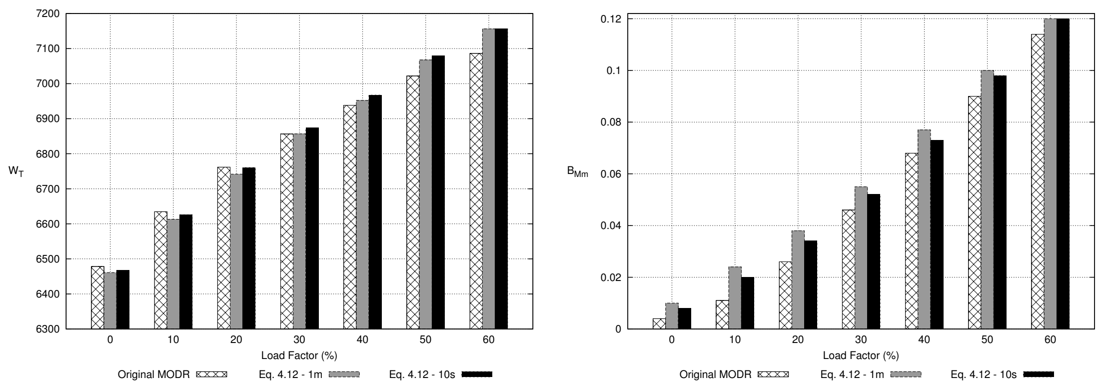

Figure 4.8: Network A - Global performance comparing MODR and SMODR with eq. 4.12, $b = 0.1$, and a 1 minute or 10 seconds path update interval.

The possibility of using different path update intervals, depending on each

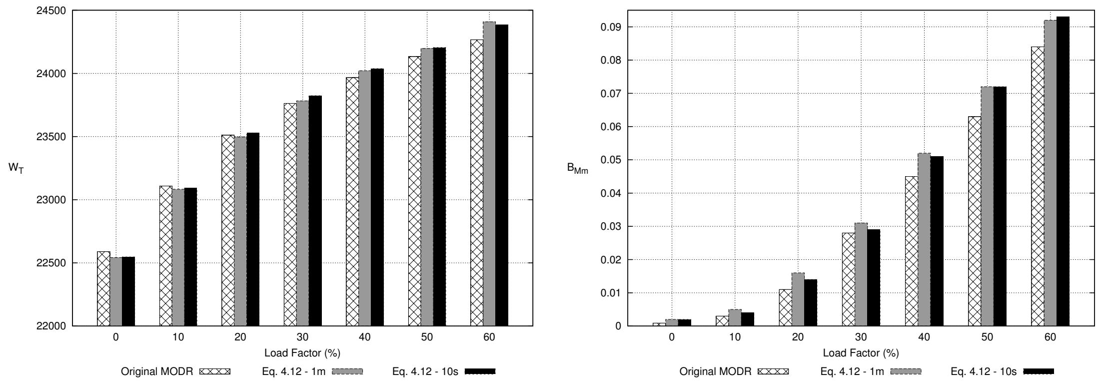

Figure 4.9: Network M - Global performance comparing MODR and SMODR with eq. 4.12, $b = 0.1$, and a 1 minute or 10 seconds path update interval.

service average duration, is also considered. In this scenario, three distinct path update intervals are used at a time: 10 seconds (one sixth of the service 1 average duration), 1 minute (one fifth of the service 3 average duration) and 30 seconds (because service 2 has an average duration with an intermediate value between the value of services 1 and 3), and afterward, 1 minute, 2 minutes and 5 minutes, for services 1, 2 and 3, respectively. None of these scenarios with service dependent path update intervals achieved good results. Tables A.13 and A.14 depict the global performance results in all the tested scenarios for networks A and M, respectively, including the cases with the service dependent path update intervals.

4.5.4 Howard Costs

Figures 4.10 and 4.11 show the performance results for networks A and M, respectively, with path updating periods of 1 minute and 10 seconds, in a variety of path elimination criteria, namely when the Howard costs replace the implied costs in the MMRA algorithm. Results show very clearly that the path elimination criterion based on the Howard costs alone (eq. 4.17) is not a good approach, especially as the network load increases.

On the other hand, network M shows similar performance when using the path elimination criteria 4.12 (with implied costs) and 4.16 (with Howard costs). Nevertheless, the Howard costs lead to worse comparative performance results in other test networks not included in this work, using the same simplified heuristic.

Therefore, any introduction of the Howard costs requires a careful pre-evaluation.

4.5.5 Summary of Key Findings

Here are the main findings in the scope of the study on SMODR in strongly meshed multiservice circuit-switched loss networks:

1. The new proposed SMODR is more suitable than the original MODR for a realistic network environment as it is much lighter in terms of computational effort while maintaining good results in terms of network performance in a multiservice environment;

2. In a heavily loaded meshed network, the network performance can benefit from the direct traffic protection procedure (more than from the alternative routing algorithm itself).

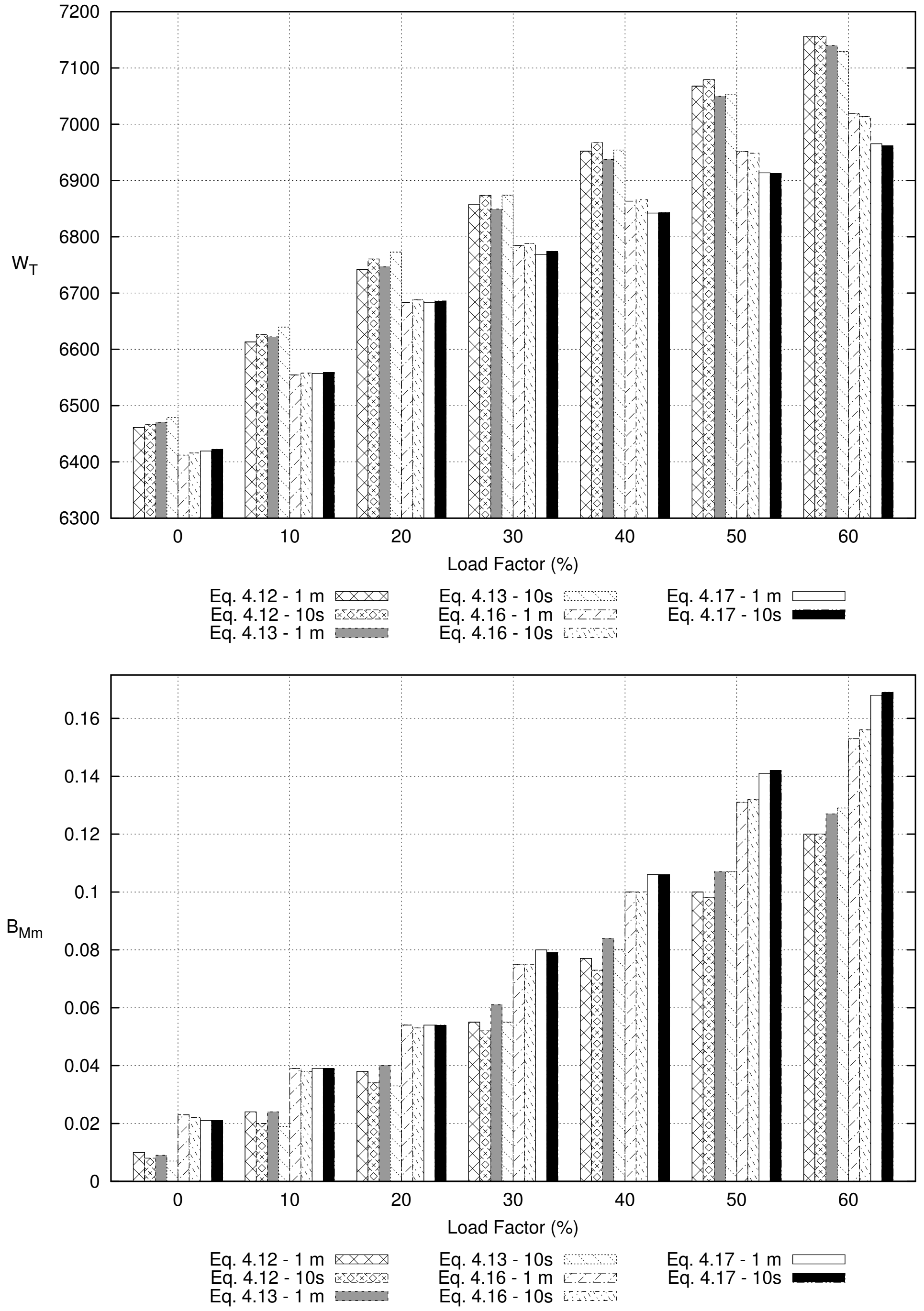

Figure 4.10: Network A - Global performance using implied or Howard costs with different path elimination criteria, $b = 0.1$ and different path update intervals (1 m and 10 s).

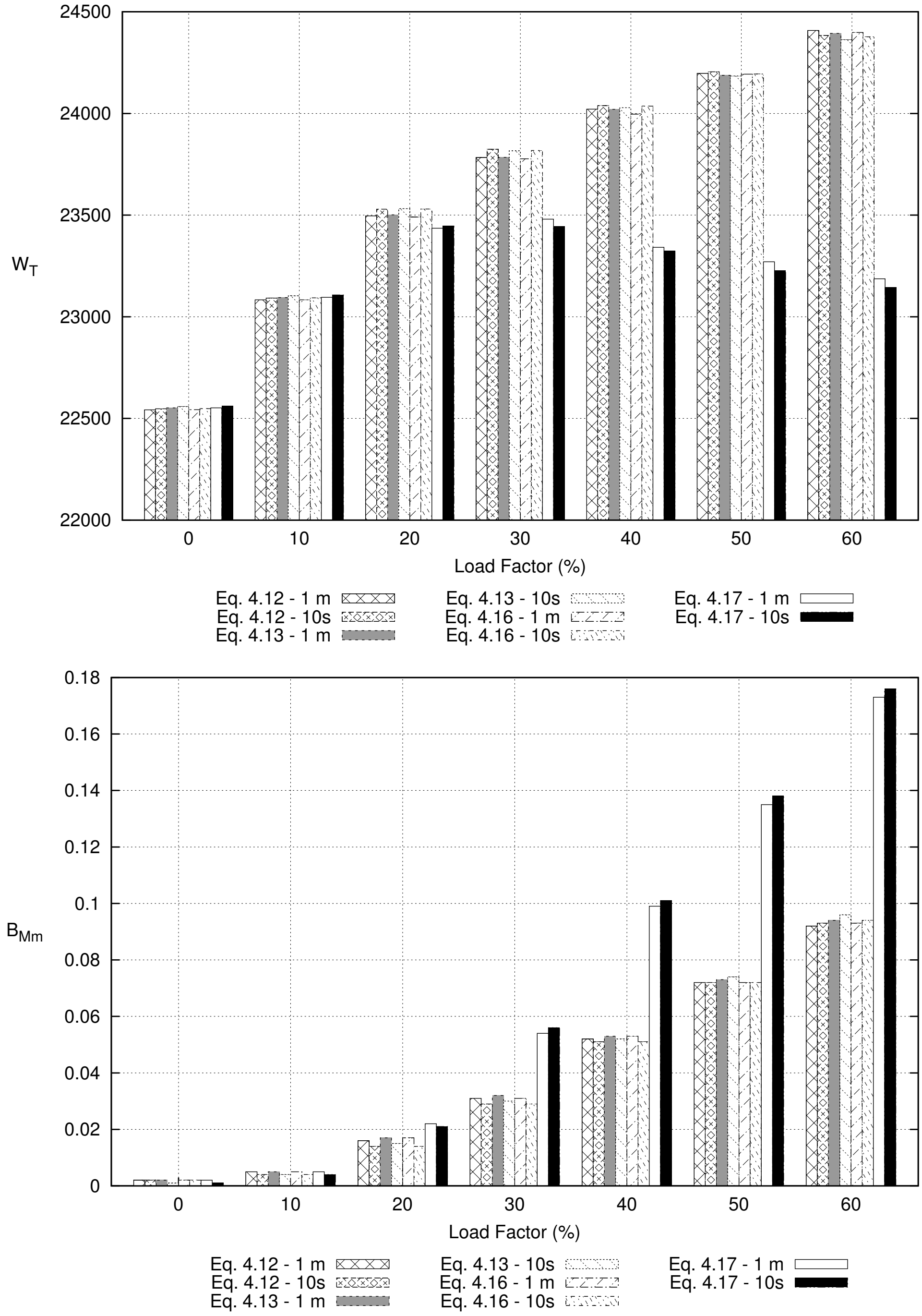

Figure 4.11: Network M - Global performance using implied or Howard costs with different path elimination criteria, $b = 0.1$ and different path update intervals (1 m and 10 s).

Chapter 5

Dynamic Multicriteria Alternative Routing (DMAR)

5.1 Introduction

Real networks are planned and dimensioned for certain traffic patterns which, in operation mode, can vary and lead to situations of traffic imbalance. In such scenario, single alternative paths as in MODR approach may not be sufficient to carry the overflow traffic. A better performing network is expected by allowing the use of multiple alternative paths, instead of a single one, to distribute the overflow traffic.

This chapter proposes a new method, Dynamic Multicriteria Alternative Routing (DMAR), a multiple objective dynamic routing method that applies to single and multiservice reservation-oriented networks with alternative routing. DMAR is inspired by MODR and DAR. DMAR periodically determines a set of alternative paths in a manner similar to MODR, i.e., based on a biobjective heuristic and using the blocking probabilities and the implied costs, for a particular state of the network. Between path update instants, these alternative paths are used in an event-dependent strategy of the DAR type, dependent on the success or blocking

The content of this chapter is partly based on the following publication:

- C. Francisco, L. Martins, D. Medhi. Dynamic Multicriteria Alternative Routing for Single- and Multi-service Reservation-Oriented Networks and Its Performance. Annals of Telecommunications, Springer, pag. 697-715, 2019.

of connections. DMAR is presented in this thesis with formulations for single service and multiservice networks in an attempt to balance the traffic between traffic flows in single service networks and also between services in multiservice environments.

This chapter is structured as follows. Section 5.2 proposes the new method, DMAR. It starts by presenting the analytical model, together with the extension of the notation and concepts already introduced in section 3.3.2 and that apply to multiservice networks implementing alternative routing with multiple alternative paths (the single service networks being a particular case of the multiservice networks). The heuristics that apply to DMAR in single service and multiservice networks are described in subsections 5.2.1 and 5.2.2, respectively. To properly evaluate this new method, the network performance of DMAR is compared and analyzed in section 5.3 against the performance of DAR and MODR in a diversified simulation environment in terms of *i*) network model (single service and multiservice), *ii*) network topology (fully meshed and sparser) and *iii*) traffic matrices (with stationary and dynamic traffic).

5.2 Dynamic Multicriteria Alternative Routing (DMAR)

DMAR is a centralized periodic state-dependent routing scheme where the set of admissible alternative paths to be used between each pair of end nodes (i, j) and for service s is periodically calculated in a centralized processor according to the network state at time instant $t' = T(n-1)$ and can be used until the following path update instant in $t'' = Tn$, where T is the path update interval. The set of admissible paths in the n^{th} path update interval is thus defined by $\mathscr{P}_{ij}^{ns} = \left\{p_{ij}^{1s}, p_{ij}^{2s}, \ldots, p_{ij}^{M_{ij}^{ns}s} : 1 \leq M_{ij}^{ns} \leq M_{ij}^{s}\right\}$. Between path update instants, DMAR behaves like DAR. In each time instant $t \in \left]T(n-1), Tn\right]$, a connection request for service s from the source node i to the destination node j can use two paths: p_{ij}^{1s} which is the fixed direct link (or a fixed shortest path, as in Adaptive Alternative Routing (AAR) [37]) and an alternative path p_{ij}^{ms} in $\mathscr{P}_{ij}^{ns} \backslash \left\{p_{ij}^{1s}\right\}$. The first-choice path p_{ij}^{1s} is tried first; in case of blocking, the alternative path

p_{ij}^{ms} is attempted. This alternative path is maintained until it leads to a blocked connection, in which case a new alternative path in $\mathscr{P}_{ij}^{ns} \backslash \left\{p_{ij}^{1s}\right\}$ is randomly chosen to be used with future connection requests. This so called 'sticky random' routing strategy ensures fairness in the alternative routing as paths with lower blocking probability are used more often.

5.2.1 Single Service DMAR

Classical dynamic alternative routing schemes like DAR typically attempt to maximize a single objective function: the carried traffic (which is equivalent to minimizing the mean network blocking probability). This approach commonly leads to a higher maximal point-to-point blocking probability value in single service networks. DMAR aims to solve this problem by using multiple alternative paths in association with an event-dependent routing strategy in order to better adjust to the offered traffic conditions, in the sense that a compromise solution among the objective functions is reached. The problem formulation for single service DMAR is described hereinafter in section 5.2.1.1.

5.2.1.1 Biobjective Routing Problem Formulation

Consider a single service network model where $S = \{s_1\}$ (for the sake of simplicity, the services index is suppressed from the notation in this section).

The set of paths that is chosen under the DMAR method intends to simultaneously minimize the mean network blocking probability and the maximal point-to-point blocking probability (thus offering a more equitable quality of service to the different flows). Let a_{ij} be the offered load from source node i to destination node j, $A_o = \sum_{i,j \in N} a_{ij}$ be the total load that is offered to the network and B_{ij} be the average end-to-end blocking probability that is experienced by a connection request being routed from node i to node j. Then, the formalization of the routing problem for DMAR in single service networks is the following:

(Problem P_1)

$$\min_{\overline{\mathcal{P}}} B = (A_o)^{-1} \sum_{i,j \in N} a_{ij} B_{ij} \tag{5.1}$$

$$\min_{\overline{\mathcal{P}}} B_{max} = \max_{i,j \in N} B_{ij} \tag{5.2}$$

s.t. equations 3.13-3.18 of the traffic model in section 3.3.2.

The purpose of DMAR in single service networks is thus to periodically find the set of alternative paths that represent a good compromise solution in terms of the mean network blocking probability B and the maximal point-to-point blocking probability B_{max}.

5.2.1.2 Single Service Heuristic

Determining the best solution under the DMAR problem can be computationally demanding. In the case of a fully meshed network, each pair of nodes can have $\sum_{i=0}^{|N|-2} C(|N|-2, i)$ possible sets of disjoint alternative paths, where $C(n,p) = n!/(p!(n-p)!)$ and $|N|$ is the number of nodes in the network. The solutions space includes the set of alternative paths for all $|N| * (|N|-1)$ node pairs. Consequently, the solutions space for the routing problem at hand includes $\left(\sum_{i=0}^{|N|-2} C(|N|-2, i)\right)^{|N|*(|N|-1)}$ different solutions.

To cope with the complexity of the proposed model, the routing problem of DMAR is solved through a heuristic based on the biobjective shortest path algorithm designated by BSPA, described in section 3.4.2.2. A crucial aspect of solving the DMAR routing problem is the use of BSPA with the link metrics implied costs and blocking probabilities. In fact, minimizing the path implied costs tends to minimize the mean network blocking probability while minimizing the blocking in paths tends to minimize the maximal point-to-point blocking probability.

The heuristic that is used in the context of DMAR for the periodic calculation of paths is described hereinafter and depicted in Algorithm 5.1. Every time instant $t = \{nT : n = 1, 2, ...\}$, where T is the path update interval, the heuristic begins by calculating the two link metrics, the blocking probabilities $\overline{B}$ and the

Algorithm 5.1 - DMAR

1. $\overline{\mathscr{P}}^a \leftarrow \overline{\mathscr{P}}^n$, $\overline{\mathscr{P}}^* \leftarrow \overline{\mathscr{P}}^n$

2. Calculate $\overline{B}$, $\overline{c}$, B and B_{max}, for $\overline{\mathscr{P}}^a$ using the $\overline{A}^n$ estimate

3. $minB \leftarrow B$, $minB_{max} \leftarrow B_{max}$, $cycle \leftarrow 0$, $change \leftarrow 0$

4. Identify $\mathcal{K}$, the set of pairs of nodes for which there is no two-links path with enough available bandwidth to carry all the blocked traffic in case of fixed routing (direct routing, for a fully meshed network)

5. While ($cycle < change$+2) do

   (a) $continue \leftarrow 0$

   (b) While ($continue == 0$) do

      (i) $\forall i, j \in N$, calculate $maxCost_{ij} = \max_{p^m \in \mathscr{P}^a_{ij} \setminus \{p^1\}} c_{p^m}$

      (ii) Calculate $maxCost = \max_{i,j \in N} maxCost_{ij}$

      (iii) If ($maxCost \geq d$)

         (A) Identify the pair (i, j) which is responsible for the value of $maxCost$

         (B) Calculate the new $\overline{\mathscr{P}}^a$ by eliminating from $\mathscr{P}^a_{ij}$ and $\mathscr{P}^a_{ji}$ the alternative path that is responsible for the value of $maxCost$

         (C) Calculate $\overline{B}$, $\overline{c}$, B and B_{max}, for $\overline{A}^n$ and the new $\overline{\mathscr{P}}^a$

         (D) $ratio_B$= $(minB - B) / minB$

         (E) $ratio_{B_{max}}$= $(minB_{max} - B_{max}) / minB_{max}$

         (F) If ($ratio_B + ratio_{B_{max}} > 0$)

            - $minB \leftarrow B$, $minB_{max} \leftarrow B_{max}$
            - $change \leftarrow cycle$, $\overline{\mathscr{P}}^* \leftarrow \overline{\mathscr{P}}^a$

      (iv) Else $continue \leftarrow 1$

   (c) Sort the pairs of nodes in descending order of B_{ij}, where B_{ij} is calculated according to eq. 3.13

   (d) For ($order = 1$ until $order \leq |N| * (|N| - 1)/2$) do

      (i) Identify the pair of nodes (i, j) for which B_{ij} has the $order^{\text{th}}$ highest value

Algorithm 5.1 - DMAR (cont.)

5. (d) (ii) $nAltPath \leftarrow |N|$ - 2
   (iii) If $(B_{ij} \leq B \wedge (i,j) \notin \mathcal{K})$
   - $nAltPath \leftarrow M_{ij}^{n}$ - 1
   - If($nAltPath$==0) $nAltPath \leftarrow 1$

   (iv) $\overline{\mathscr{P}}^{a} \leftarrow \overline{\mathscr{P}}^{a} \setminus \{\mathscr{P}_{ij} \cup \mathscr{P}_{ji}\} \cup \{\mathscr{P}_{ij}^{BSPA} \cup \mathscr{P}_{ji}^{BSPA}\}$, where the new alternative paths for pair (i,j) are defined according to the BSPA algorithm
   (v) Eliminate from $\mathscr{P}_{ij}^{a}$ and $\mathscr{P}_{ji}^{a}$ the alternative paths with an implied cost value greater than or equal to d
   (vi) If $(nAltPath < \left|\mathscr{P}_{ij}^{a}\right| - 1)$ Eliminate from $\mathscr{P}_{ij}^{a}$ the paths in a position higher than $nAltPath$+1
   (vii) If $(nAltPath < \left|\mathscr{P}_{ji}^{a}\right| - 1)$ Eliminate from $\mathscr{P}_{ji}^{a}$ the paths in a position higher than $nAltPath$+1
   (viii) Calculate $\overline{B}$, $\overline{c}$, B and B_{max}, for $\overline{A}^{n}$ and the new $\overline{\mathscr{P}}^{a}$
   (ix) $ratio_{B} = (minB - B)/minB$
   (x) $ratio_{B_{max}} = (minB_{max} - B_{max})/minB_{max}$
   (xi) If $(ratio_{B} + ratio_{B_{max}} > 0)$
   - $minB \leftarrow B$, $minB_{max} \leftarrow B_{max}$
   - $change \leftarrow cycle$, $\overline{\mathscr{P}}^{*} \leftarrow \overline{\mathscr{P}}^{a}$

   (e) $cycle \leftarrow cycle + 1$

6. $\overline{\mathscr{P}}^{n+1} \leftarrow \overline{\mathscr{P}}^{*}$

---

implied costs $\overline{c}$, and afterward the network performance metrics, B and B_{max}, according to the set of initial paths $\overline{\mathscr{P}}^{n}$ for the n^{th} path update time instant and a traffic matrix estimate $\overline{A}^{n}$ for the following time interval (steps 1 and 2 in Algorithm 5.1). By definition, using a path with an implied cost value higher than the revenue that it generates is not desirable from the point of view of the carried traffic. Therefore, the alternative paths in such condition are removed in descending order of their implied cost (steps 5.(a) and 5.(b)). The implied costs are already known to improve the network performance in terms of carried traffic, although usually to the detriment of the point-to-point blocking probability. In this context, the next step of the heuristic searches for new alternative paths for all pairs of end nodes (i, j) in the network, with the pairs of nodes being sorted in descending order of their point-to-point blocking probabilities B_{ij} (step 5.(c)).

Consider now that $nAltPath$ is the maximum number of alternative paths allowed for pair (i, j). As a first approach (step 5.(d).(ii)), $nAltPath = |N| - 2$, allowing all the two-links alternative paths, in the case of a fully meshed network. Next (step 5.(d).(iii)), it is verified whether the pair (i, j) belongs to $\mathcal{K}$, previously determined in step 4, which is constituted by the set of pairs of nodes for which there is no two-links path with enough available bandwidth to carry all the blocked traffic in a hypothetical scenario of fixed routing. In such case, it is important to allow this pair to have as many alternative paths as possible to spread the overflow traffic. On the other hand, for pairs that do not belong to $\mathcal{K}$ and that present a point-to-point blocking probability lower than the mean network blocking probability (already enjoying a fair treatment), the value of $nAltPath$ is only allowed to be equal to the number of alternative paths in the current solution ($M_{ij}^n - 1$), or 1 (if the current solution does not allow alternative routing for this pair).

In this context, the calculation of new paths is made according to the BSPA procedure (step 5.(d).(iv)) which returns an ordered set of alternative paths for pair (i, j), being followed by the removal of the paths with an implied cost value higher than the generated revenue (step 5.(d).(v)). The solution to be tested includes the first $nAltPath$ alternative paths, if they exist, in the ordered set (steps 5.(d).(vi) and 5.(d).(vii)).

Each new solution is compared to the "best"solution obtained so far ($\overline{\mathscr{P}}^*$), and replaces it if the improvement ratio in one of the network performance metrics is higher than the degradation of the other (steps 5.(b).(iii).(F) and 5.(d).(xi)). With this criterion and considering only the last solution found during the heuristic execution time, it is possible to reach a situation where the initial and final solutions are non-dominated, while a solution that dominates the initial solution has been found by the heuristic. This is the case in the following sequence of solutions found by the heuristic: $(B^1, B^1_{max}) = (0.03, 0.3), (B^2, B^2_{max}) = (0.032, 0.27), (B^3, B^3_{max}) = (0.029, 0.29)$. In this scenario, DMAR chooses the second solution (while the third solution dominates the first solution). This limitation is acknowledged and accepted for the sake of simplicity. A possible improvement to the heuristic would be to save all the non-dominated solutions that are discovered during the heuristic execution time and, at the end, to choose the final solution based on a given criterion (ex: weighted euclidean distance to the ideal optimal solution).

5.2.2 Multiservice DMAR

Most classical routing methods attempt to maximize the carried traffic in order to maximize the profit. In multiservice multirate networks where the bandwidth is shared by all services this approach does not guarantee fairness in terms of the quality of service provided to the individual services, which can be measured by the service mean blocking probability. The multiservice DMAR attempts to solve this routing problem according to the problem formulation presented hereinafter in section 5.2.2.1.

5.2.2.1 Biobjective Routing Problem Formulation

Consider that $A_o^s = \sum_{i,j \in N} a_{ij}^s$ is the total load that is offered to the network by service s and that $B^s = \sum_{i,j \in N} a_{ij}^s B_{ij}^s / A_o^s$ is the mean network blocking probability experienced by a service s connection. In this context, the set of paths intends to minimize the bandwidth denial rate BDR [69] (which takes into consideration the multirate services accessing the same network resources) and the maximal service mean blocking probability $maxB$. The biobjective multiservice DMAR routing problem is therefore formulated as follows:

(Problem P_S)

$$\min_{\overline{\mathcal{P}}} BDR = \frac{\sum_{s \in S} \sum_{i,j \in N} a_{ij}^s B_{ij}^s d^s}{\sum_{s \in S} A_o^s d^s} \tag{5.3}$$

$$\min_{\overline{\mathcal{P}}} maxB = \max_{s \in S} B^s \tag{5.4}$$

s.t. equations 3.13-3.18 of the traffic model in section 3.3.2.

The purpose of the multiservice DMAR is thus to periodically find the set of alternative paths that results in the best compromise solution in terms of BDR and $maxB$ for a given state of the network. Note that the routing problem formulations of DMAR and MODR/SMODR are equivalent at the network performance level (minimization of the BDR and $maxB$) but MODR/SMODR consider an additional lower priority service level as well.

5.2.2.2 Multiservice Heuristic

Algorithm 5.2 describes the heuristic for DMAR-S and it results from the extension of the Algorithm 5.1 to a multiservice network, by replacing B by BDR and B_{max} by $maxB$.

Algorithm 5.2 - DMAR-S

1. steps 1-4 in Algorithm 5.1, considering all services
2. While ($cycle < change$+2) do
   (a) For ($s = 1$ until $s \leq |S|$) do // runs through all services $s \in S$
      i. steps 5(a) - 5(e) in Algorithm 5.1 for service s
3. step 6 in Algorithm 5.1

5.3 Simulation Study

The performance of DMAR is now evaluated in a biojective sense by comparison with DAR and MODR. The performance of the methods is measured in terms of B and B_{max} in single service networks and in terms of BDR and $maxB$ in multiservice networks.

The routing methods differ in three major aspects:

- first-choice traffic protection mechanism. DAR uses a bandwidth reservation mechanism in each link l_k ($\sqrt{C_k}/2$) [37]) while both DMAR and MODR rely on an alternative path elimination strategy;
- number of alternative paths for each pair of nodes and service type. MODR allows a single alternative path while DMAR and DAR allow the use of multiple alternative paths that are used in an event-dependent strategy.

This comparison highlights the difference in terms of performance over the potential use of a single or multiple alternative paths to share overflow traffic;

- alternative paths establishment. The set of alternative paths for each pair of nodes and service type remains fixed throughout the simulation time for the DAR method ($\mathscr{P}_{ij}^{ns} = \mathcal{P}_{ij}^{s}, \forall n \in \mathbb{N}$), while it is periodically updated through a biobjective routing heuristic and according to the state of the network in the case of DMAR and MODR. The difference between DMAR and MODR is that while MODR applies to alternative routing with a single alternative path, DMAR allows multiple alternative paths to be used by an event-dependent routing strategy, potentially representing an added value.

The performance of the several routing methods is evaluated in a diversified simulation environment which includes *i*) single service and multiservice networks, *ii*) different topologies such as fully meshed and sparser networks, *iii*) stationary and dynamic traffic.

Alternative routing is often associated with fully meshed networks where the first-choice path is the direct link and there are $|N|$-2 alternative paths with a two links length. However, in sparser topologies, the direct link may not exist and the number of admissible alternative paths as well as their maximum length may be difficult to define. To understand the impact of these differences on the performance of the methods both topology types are considered in this study. The test networks in use are described in Appendix B.2, being that networks A, B and C are single service and networks D and E multiservice.

Dynamic routing schemes are key to achieve a good network performance in the presence of the intrinsic traffic dynamics in real network environments. However, these schemes are typically tested in the literature by using scenarios with stationary traffic patterns, which do not allow a realistic performance evaluation. As a reference point, this study also includes the evaluation of the network performance of the methods with stationary traffic. In this context, traffic matrices representing global congestion situations validate the routing methods when the available bandwidth is scarce and it is necessary to prevent the excess of alternative paths. Furthermore, the routing schemes are tested in the presence of dynamic traffic patterns validating how the different characteristics of the methods allow the adaptation to the traffic oscillations. The traffic patterns used in the simulation study in the single and multiservice environments, with stationary and dynamic traffic, are described in Appendix B.1.

The routing methods are evaluated in a discrete-event CSIM simulator [55, 68], where they were implemented. For each of the scenarios, 5 independent simulation runs were conducted. The simulator in use provides generators of stationary and dynamic traffic and, within the scope of this simulation study, the dynamic traffic is represented by sine waves.

A typical value in circuit-switched networks for the path update interval is 10 seconds. However, to reduce the computational effort in this study, DMAR and MODR periodically calculate, every 1 minute, the set of paths to be used in the following time interval according to an estimated offered traffic matrix (calculated as described in eq. 4.18 with $b = 0.9$). The test scenarios being considered in the scope of this simulation study as well as the corresponding performance results are discussed next.

5.3.1 Single Service Network

The single service study includes several traffic matrices with stationary and dynamic traffic, inspired by 24-hours of voice traffic provided by Sprint [56]. These traffic patterns are tested in three ten-nodes networks, designated as Network A, B and C. Network A is depicted in Table B.4 and it is a fully meshed network whose dimensioning was adjusted to the traffic matrix for one of the busiest hours in the Sprint network. Network B is a sparser network, described in Table B.5, and it results from the removal of five of the links from Network A. Network C, depicted in Table B.6, is a fully meshed network that was dimensioned for several peak hours of the voice service. Further details on the dimensioning of these networks can be consulted in Appendix B.2.

The single service networks are engineered with a service with the required bandwidth $d = 1$ and an average call duration of 1 minute.

5.3.1.1 Stationary Traffic

The biobjective nature of the routing problem in question allows the representation of the simulations results through Cartesian graphs, using an axis to represent each of the two defined objective functions. In the case of the single service networks, the network performance is measured in terms of B and B_{max}, and the presented result values are the midpoints of the confidence intervals calculated with a 95% confidence level and obtained using the method of independent replications.

This study begins by comparing the performance of DMAR, DAR and MODR in test networks A and B for a reference traffic matrix, subsequently identified as the nominal traffic situation (see "BH" traffic in Table B.1 in Appendix B.1.1). The simulations results presented in figures 5.1 and 5.2 show the network performance of the methods in the nominal load and in two additional traffic scenarios of global congestion where the offered load to each pair of nodes has a 10% and a 20% load increase.

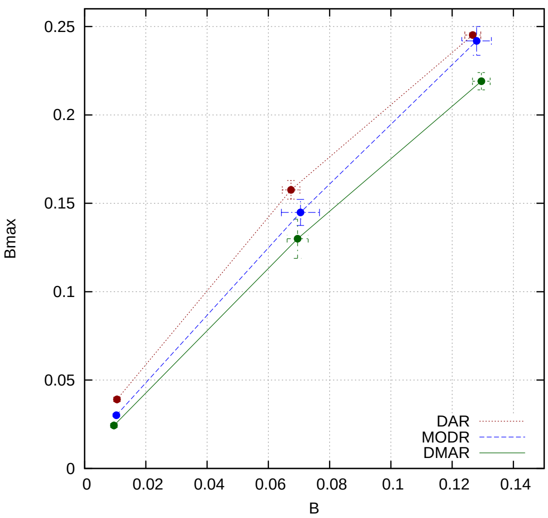

Figure 5.1: Network A - Nominal load and global congestion (10% and 20%).

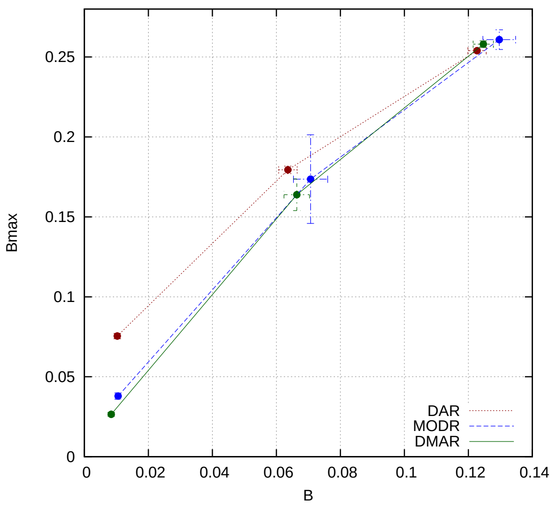

Figure 5.2: Network B - Nominal load and global congestion (10% and 20%).

In the nominal load traffic scenario, DMAR has better performance (lower B and B_{max}) than DAR and MODR in both fully meshed (A) and sparser (B) networks.

It is also important to understand how the methods behave in abnormal situations where the whole load in the network increases for a specified amount. Alternative routing is especially important in lightly loaded networks; however, the study of global congestion situations for dynamic alternative routing schemes is critical because if the excessive use of alternative paths is not avoided the network may experience performance degradation. Figures 5.1 and 5.2 also present the results for 10% and 20% extra load situations for networks A and B, respectively. Note that the 20% extra load situation shows a network which is already out of order (a B value higher than 10%). It is possible to observe that the values of B_{max} obtained with DMAR are significantly lower than the ones obtained with DAR and the B values of DMAR are slightly higher than the corresponding values of DAR. However, the B values of DMAR are within the 95% confidence interval of the B values for DAR and so they are comparable. The MODR method never shows better values for B nor B_{max} in any of the scenarios.

5.3.1.2 Dynamic Traffic

So far the tested scenarios include stationary traffic only. Dynamic traffic is evaluated next, and it is modulated by sinusoidal curves of the type described in Appendix B.1.2. Figure 5.3 shows the offered traffic curves for a scenario where the traffic that is offered to each of the node pairs in the network follows a sinusoidal waveform with the average (Avg) value of "BH", a peak amplitude (A) of 5% of that value and wave periods (T) of 117, 101 and 128 minutes, sequentially assigned according to the ordered list of the node pairs, as defined in Table B.3 in Appendix B.1.2. The legend in Figure 5.3 shows the total offered load and the pairs of nodes offering on average more traffic to the network in this scenario. Figure 5.4 shows the comparative total offered load curve for two traffic cases, herein designated by "A=5%,10%", where the peak amplitude variation is 5% and 10%.

In the presence of dynamic traffic, it is not possible to use Cartesian graphs to represent performance results. Instead, the figures showing performance results include several hours of simulation where the values of the performance metrics B and B_{max} are calculated every 15 minutes and the curves in the figures result

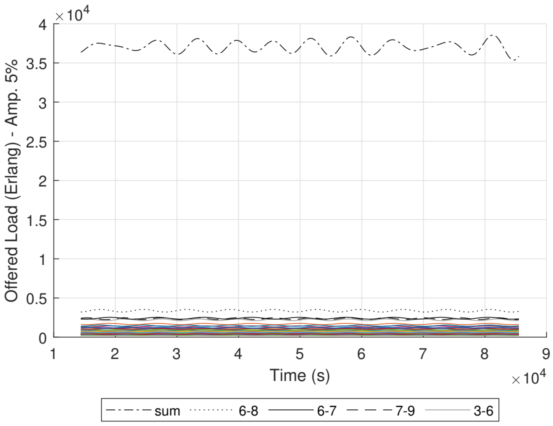

Figure 5.3: Offered traffic curves (per pair of nodes and total value) for the dynamic traffic with A=5%.

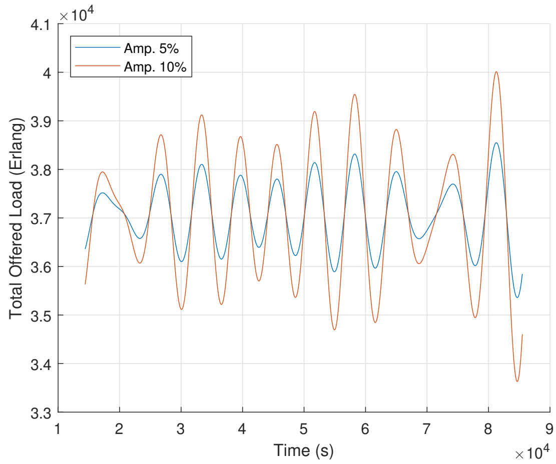

Figure 5.4: Offered traffic curves for the dynamic traffic with both A=5% and A=10%.

from linear interpolation between the mean values of B and B_{max}, respectively, from 5 simulation runs. Note that the first 4 hours (the warmup period) are discarded and, consequently, not considered in the results analysis.

Figures 5.5-5.6 and 5.7-5.8 show the performance results for Networks A and B, respectively, for the two above mentioned traffic scenarios in the]4, 24]h period. The legend of the B_{max} curve includes, for each individual routing method, the identification of the pair of nodes corresponding to the value of B_{max}. DMAR is the best performing method in the two traffic scenarios (in both 5% and 10% peak amplitude situations) in the fully meshed Network A. In the sparser Network B, DMAR is the method with the best B_{max} value. However, the curve of B is slightly better for DAR in the peak values (although at the expenses of much worse B_{max} values).

Next, the performance of the methods is analyzed in a more realistic scenario in which the curves of the traffic that is offered to the network concerning the "7 BH" period (]10,17]h) of the Sprint network are mapped into sinusoidal waves. This traffic scenario is tested in Network C and Figure 5.9 represents the curve of the corresponding traffic that is offered by each pair of nodes to the network (as well as the respective sum). The legend of the Figure 5.9 also highlights the three pairs of nodes that offer, in average, more traffic to the network.

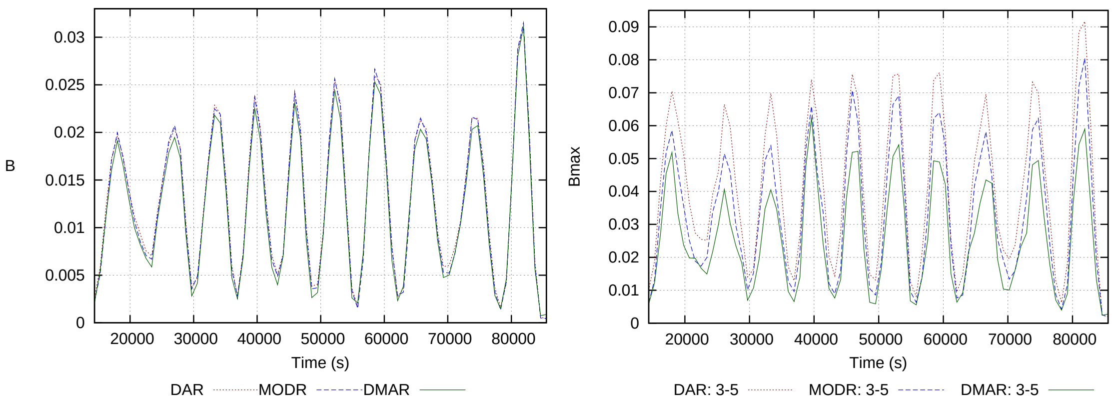

Figure 5.5: Network A - dynamic traffic (Avg="BH"; A=5%; T(min)= 101, 117 and 128).

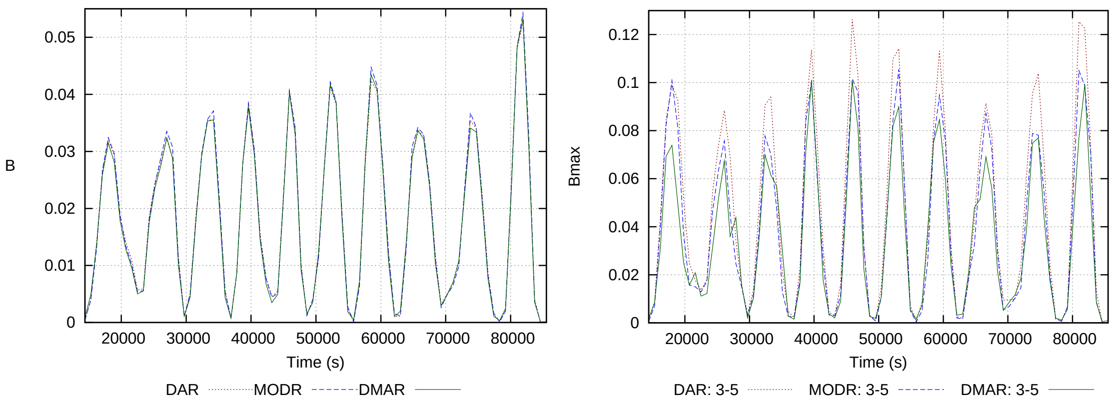

Figure 5.6: Network A - dynamic traffic (Avg="BH"; A=10%; T(min)= 101, 117 and 128).

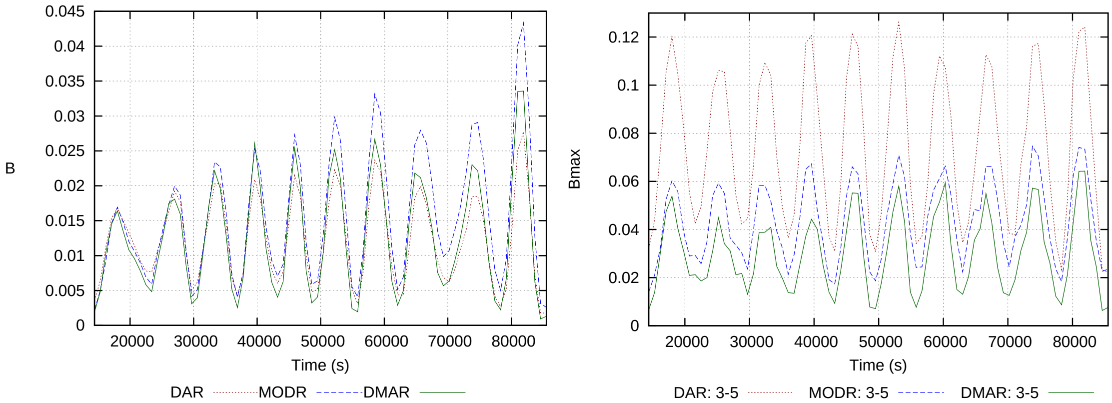

Figure 5.7: Network B - dynamic traffic (Avg="BH"; A=5%; T(min)= 101, 117 and 128).

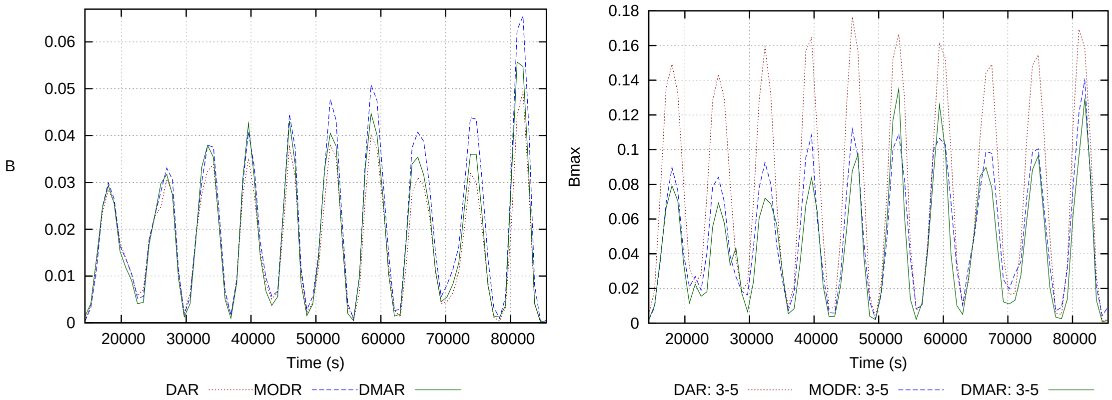

Figure 5.8: Network B - dynamic traffic (Avg="BH"; A=10%; T(min)= 101, 117 and 128).

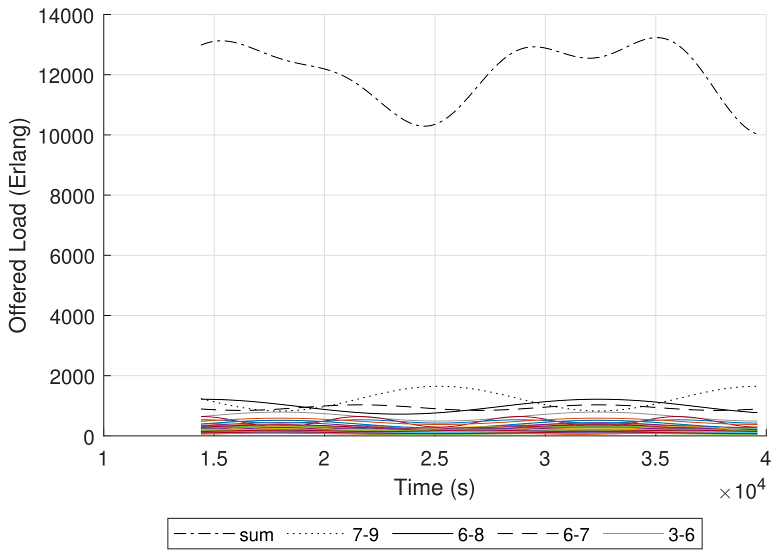

Figure 5.9: Offered traffic curves (per pair of nodes and total value) for the "7 BH" traffic.

The simulation results in Figure 5.10 show that DMAR is the best performing method throughout the simulation time. The analysis of the simulation results also shows a particularity in the performance curve of B for the MODR method for some time intervals. In the time intervals [14400,16200]s, [21600,28800]s and [36900,38700]s the values of B are much worse for the MODR when comparing with the other methods. These intervals correspond to the periods in which the curve of the traffic that is offered by pair 7-9 (the pair which offers on average more traffic to the network and which is responsible for the B_{max} curve in this scenario) reaches its maximum values.

This worse performance of MODR was investigated. Assuming direct routing in the fully meshed network, it was analyzed the available bandwidth in each link for each of the traffic matrices corresponding to the time intervals in which the MODR presents the worse performance in Figure 5.10. Considering now that this network would allow alternative routing to pair 7-9, it would be necessary to simultaneously use almost all of the alternative paths with two-links to additionally carry the amount of traffic corresponding to the traffic overflowing from pair 7-9 in the problematic time intervals. However, MODR only allows a single alternative path for each node pair which justifies, in the cited time intervals, the poorer performance.

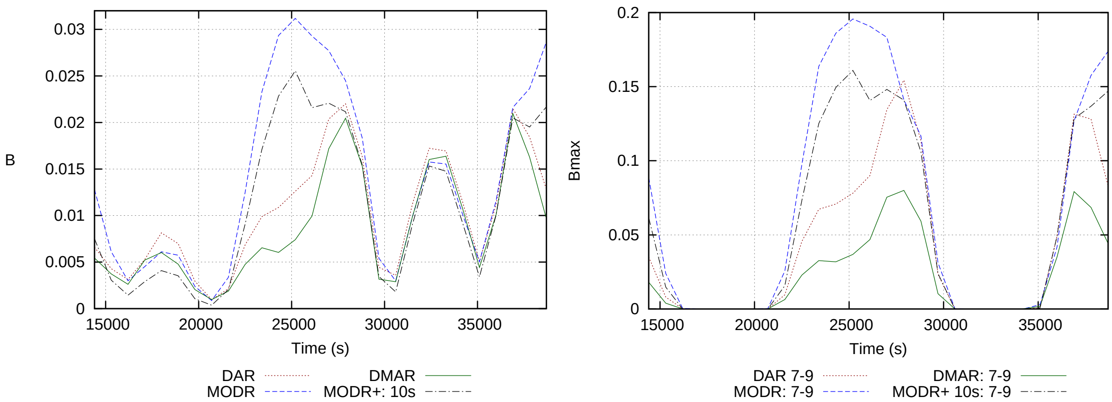

Figure 5.10: Network C - dynamic traffic (“7 BHs”).

This hypothesis was tested through a surgical change in the MODR method, hereinafter referred to as MODR+. The MODR+ routing method works in the same way as MODR with the following modification: in the beginning of each path update instant, the links whose occupation is higher than a configured threshold (99%) are marked as being congested. The use of these congested links for alternative routing is then prohibited until the next path update instant.

The MODR+ method was tested using short path update intervals of 10 seconds [15]. The raised hypothesis is confirmed by the simulation results in Figure 5.10 since the performance of MODR+ is now more similar to that of the other methods. This finding strengthens the DMAR proposal and the use of multiple alternative paths to spread overflow traffic. For the sake of consistency throughout the work, the results of the MODR presented in Figure 5.10 correspond to simulations using path update intervals of 1 minute. It should be noted, however, that the performance of the MODR method using path update intervals of 1 minute and 10 seconds are comparable.

5.3.2 Multiservice Network

The multiservice study also includes stationary and dynamic traffic matrices. These traffic matrices are tested in two ten-nodes multiservice networks, designated as Network D (in Table B.7) and E (in Table B.8), which are dimensioned in a similar manner to the corresponding single service networks A and C, respectively, assuming that all offered traffic is single service.

The multiservice networks are inspired by the work in [69] and they are engineered with three services with the required bandwidth $d = [1, 6, 10]$ and average call duration $h = [1, 5, 10]$ minutes for services s_1, s_2 and s_3.

The MODR method for multiservice networks is replaced in this study by its lighter version proposed in Chapter 4, the SMODR.

5.3.2.1 Stationary Traffic

In multiservice networks the performance of the routing methods is measured in terms of BDR and $maxB$. The analysis for the stationary traffic scenarios compares the performance of the methods in Network D in the presence of "BH" traffic (extended to multiservice as described in the Appendix B.1.1) and in the corresponding 10% and 20% extra load situations. The results in Figure 5.11 show that DMAR outperforms both DAR and SMODR in terms of a biobjective approach (lower BDR and $maxB$ values) in the three traffic scenarios. Figure 5.11 also shows that the DMAR ensures greater fairness in terms of the comparative quality of service between the various services, as evidenced by the lower value of the $maxB$ in each of the presented traffic scenarios. On the other hand, DAR benefits services s_1 and s_2 with lower service mean blocking probability values in detriment of service s_3 with a higher value. In fact, the mean blocking probability values for service s_1, B_m^1, in the various scenarios are so low with the DAR method that they are hardly represented in the figure presenting the service performance results.

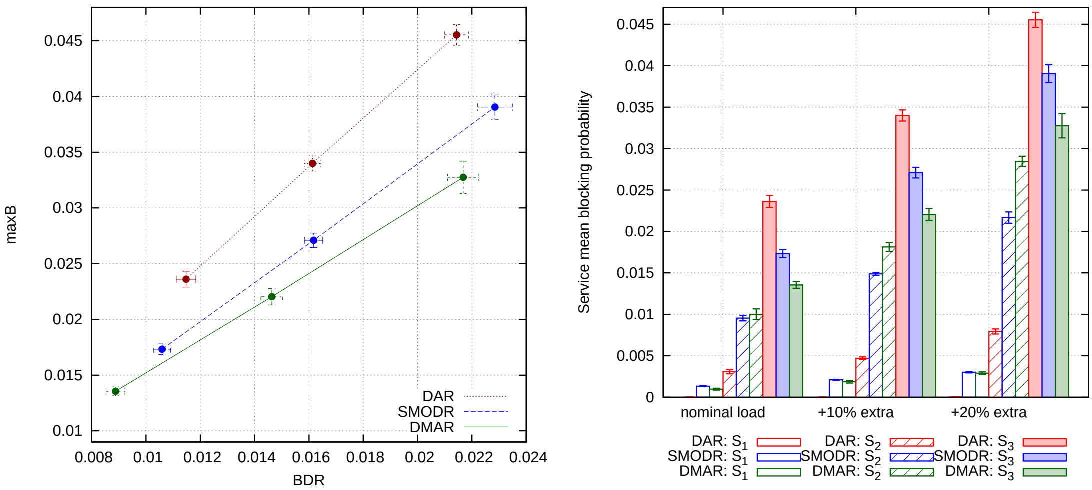

Figure 5.11: Nominal load and global congestion (10% and 20%).

5.3.2.2 Dynamic Traffic

Dynamic traffic patterns in multiservice networks represent more realistic environments and pose even more demanding scenarios in terms of network performance. Figure 5.12 shows the comparative performance of the methods in Network E for a traffic scenario based on the seven busiest hours of the single service voice traffic of the Sprint network, extended to multiservice as described in the Appendix B.1.2. The legend in the $maxB$ curve includes the identification of the service that is responsible for that value in each of the methods.

DMAR presents better performance than SMODR throughout the entire sim-

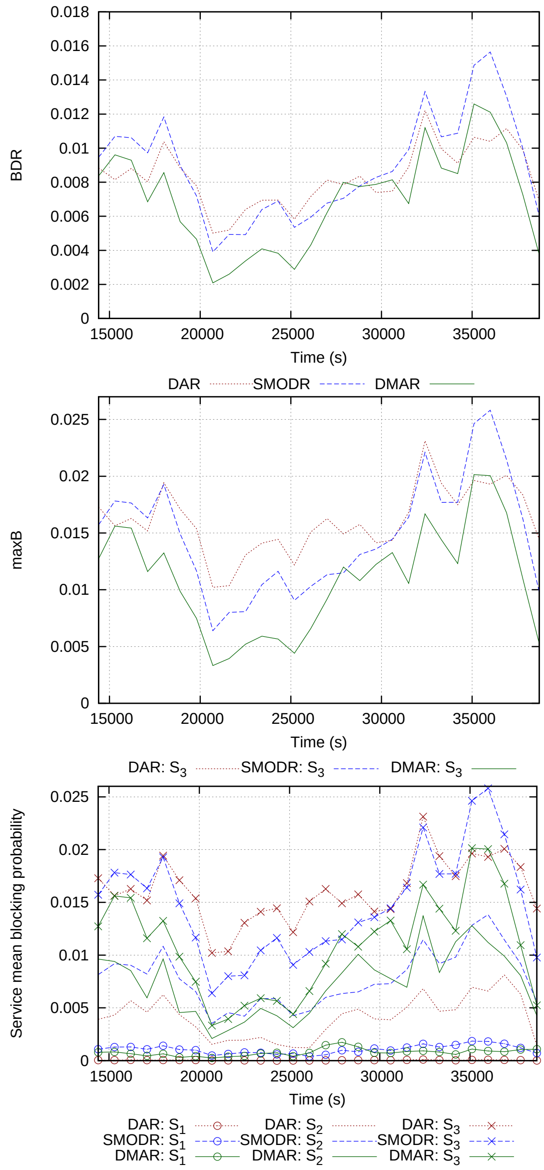

Figure 5.12: Network E - multiservice dynamic traffic.

ulation time. This is also the case in general when comparing with DAR, with the exception of time intervals near $t = 15000$s, $t = 30000$s and $t = 35000$s, in which there are big variations in the traffic that is offered to the network at consecutive time intervals and near peak traffic, making it more difficult to obtain adequate traffic estimates. It is also possible to conclude that DMAR is the method which guarantees greater fairness among the different services.

5.3.3 Summary of Key Findings

From the presented comprehensive work, it is possible to summarize the following key findings:

1. The proposal of DMAR, a new dynamic alternative routing method with a multicriteria formulation;

2. DMAR is presented for single service and extended to multiservice networks;

3. DMAR applies to generic topologies;

4. DMAR was evaluated against DAR, MODR and SMODR in a diversified simulation environment including several load scenarios like global congestion situations and dynamic traffic patterns:

   (a) In single service networks with stationary traffic:

      i. DMAR performs better than DAR or MODR for nominal load;

      ii. DMAR, MODR and DAR are comparable in 10% to 20% overloaded situations;

   (b) In single service networks with dynamic traffic:

      i. DMAR performs better for fully meshed networks;

      ii. DMAR and DAR are comparable for strongly meshed networks in certain situations;

      iii. The proposal of an improved version of MODR, designated by MODR+, gives strength to the new DMAR method (and the use of multiple alternative paths spreading overflow traffic);

   (c) In multiservice networks, DMAR is the best performing method in both stationary and dynamic traffic scenarios;

5. The results show that DMAR efficiently adjusts to network changes while ensuring the satisfaction of QoS requirements.

Chapter 6

Dynamic Alternative Routing with local Multiple paths Protection (DARMP)

6.1 Introduction

Real-time services have become increasingly popular on the Internet imposing tight requirements in terms of packet loss and delay and a stringent recovery time in case of failure.

Dynamic alternative routing is already known to improve the network survivability because, in case of failure in a first-choice path, a second chance may be given to incoming connections which can attempt alternative paths. However, ongoing traffic in affected paths at the failure time instant is lost. This traffic can be saved by a pair of disjoint paths (primary and backup).

MPLS was designed to fulfill the needs of real-time services and a local protection mechanism (Fast Reroute (FRR)) providing recovery in SONET time (50 ms) was proposed by the IETF MPLS working group [63]. In MPLS FRR,

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The content of this chapter is partly based on the following publication:

- C. Francisco, L. Martins, J. Redol, P. Monteiro, Dynamic alternative routing with local protection paths in MPLS networks. ICUMT 2010, International Congress on Ultra Modern Telecommunications and Control Systems and Workshops, Moscow, Russia, 18-20 October, 2010.

each protected LSP traversing a given facility (link or node) has a pre-configured backup path originating at the node immediately upstream to that facility, providing a fast recovery in case of failure because the decision on the recovery is strictly local.

Typical MPLS FRR approaches are fixed, non-adaptive or periodically optimized. On the other hand, the bandwidth for protection is usually guaranteed by reserving extra bandwidth on backup paths resulting in a waste of resources in the absence of failures. Additionally, current implementations use a (possibly shared) single backup path to carry both ongoing and incoming traffic affected by a failure on a protected LSP, potentially leading to increased local congestion in the event of a failure.

The contribution of this thesis consists of associating a local protection mechanism with no bandwidth reservation with a dynamic alternative routing method. This approach improves not only the network performance but also the network survivability by saving not only incoming connections, which is typical of alternative source routing, but also ongoing connections traversing a failing link, which is the new achievement of this proposal. This new method, designated by Dynamic Alternative Routing with local Multiple paths Protection (DARMP), is effective in saving real-time traffic in the same topologies where alternative routing is efficient. DARMP is proposed and tested in the scope of this work using the well-known DAR scheme.

This chapter is structured as follows: section 6.2 presents the DARMP formulation for a single service network, in which the local link protection mechanism is formally described. Section 6.3 describes the simulation environment used in the validation of the DARMP method. Two routing methods with local protection against failures are additionally implemented to allow a comparative analysis of their performances.

6.2 Dynamic Alternative Routing with local Multiple paths Protection (DARMP)

There are two approaches to implement MPLS FRR. In the one-to-one backup method the point of local repair (PLR), which is the node responsible for redirecting traffic for the backup path, configures a distinct backup LSP, the detour LSP, to each protected LSP. In the facility backup method, a single bypass tunnel configured in a PLR can protect multiple LSPs, offering a scalability advantage. For this reason, the facility backup method is chosen in this thesis.

In the facility backup method, a single bypass tunnel may protect multiple LSPs. However, in the event of a link failure, if the single protection path runs out of available bandwidth, connections are automatically lost. This is particularly critical for networks based on the fixed routing paradigm, which is often the case in MPLS networks.

This problem may be solved by extending the traffic splitting concept to local protection, in an attempt to increase the network load balancing and the likelihood of a connection being saved in case of link failure in a diversity of traffic scenarios. This technique has already been applied to global protection in [22]. Using traffic splitting in the local protection facility backup method, the PLR is allowed to split the traffic of affected LSPs into multiple pre-assigned bypass tunnels, in the sense that global QoS be satisfied. Note that although connections traversing a failing link can be protected by different bypass tunnels, each individual connection is routed over a single bypass tunnel, which can be supported with the use of RSVP.

On the other hand, a dynamic alternative routing strategy can be used to improve the network survivability in strongly meshed networks. This topology is typical of core networks, where MPLS is often used and survivability is critical. Dynamic alternative routing already offers more than one path possibility to incoming connections. In fact, in the event of a link failure in first-choice paths, ongoing connections traversing the failed link are lost but incoming connections may be offered to alternative paths.

This thesis proposes the association of a dynamic alternative routing strategy with a local protection mechanism with multiple protection paths, and without increasing the bandwidth needs for protection purposes. In this context, just as the network is suitable for alternative routing, it is also suitable for having multiple bypass tunnels. In the event of a link failure, the multiple bypass tunnels spread the ongoing traffic across the network, allowing the alternative routing scheme to route incoming connections according to the new network condition. In contrast, a single bypass tunnel could potentially lead to a situation of traffic imbalance in the network and alternative routing would not be so effective.

The DARMP model is presented next, together with the extension of the notation and concepts already introduced in section 3.2. For simplicity, the DARMP formulation is presented for single service networks and the services index is suppressed from this chapter.

6.2.1 Routing and Protection in the DARMP method

DARMP is proposed with the DAR routing scheme which originally applies to fully meshed networks. Alternative routing is also known to improve the network performance in strongly meshed methods. DARMP also applies to such topologies where the first-choice path may not be the direct link and alternative paths may not be equally sized. For the sake of resources optimization, it is assumed that all paths have a maximum length $D = 3$ which means that the alternative paths have 2 or 3 links in length. At path reselection time instants, the probability $prob_{p_{ij}^m}$ of using the alternative path p_{ij}^m, with $m = 2, \ldots, M_{ij}$ is determined giving preference to shorter paths, i.e., paths with 2 links length will be chosen with a probability that is twice the probability of choosing paths with 3 links length, while paths with the same length have the same probability of usage.

DARMP combines DAR with a local protection mechanism implementing a facility backup technique with multiple bypass tunnels. Assume that l_k is the failed link at failure time instant t_f and that M_{l_k} is the number of bypass tunnels protecting traffic in link l_k. Then, a loopless bypass tunnel for traffic traversing link $l_k = (i, j, C_k)$, b_{l_k}, consists of a sequence of adjacent links such that the first link is $l_n = (i, q, C_n)$ and the last link is $l_p = (r, j, C_p)$, without repetition of nodes (except in adjacent links), where $i, q, r, j \in N$. On the other hand, the bypass tunnel domain for link l_k, $\mathcal{BD}_{l_k}$, is constituted by the set of bypass tunnels protecting traffic in link l_k, such that $\mathcal{BD}_{l_k} = \left\{b_{l_k}^1, \ldots, b_{l_k}^{M_{l_k}}\right\}$.

In the scenario of a failure in link l_k, the bypass tunnel domain $\mathcal{BD}_{l_k}$ must have been configured prior to the failure so that the protection is immediate as soon as the upstream node realizes the link failure. Assume that the set of ongoing connections needing to be saved (i.e., whose first or alternative path traverse the failed link l_k) is $F_{l_k}^{t_f}$. Then, the probability $prob_{b_{l_k}^n}$ of using the bypass tunnel $b_{l_k}^n$, with $n = 1, \ldots, M_{l_k}$, to protect a connection belonging to $F_{l_k}^{t_f}$ is determined in the same way as $prob_{p_{ij}^m}$, giving preference to shorter paths.

The use of a bypass tunnel to save ongoing traffic in a failed link increases the end-to-end path in length. Longer paths result in less available capacity in the network which may even result in a lower number of saved connections or in increased network congestion. The use of shortest paths is thus desired.

The end-to-end path resulting from the activation of local protection after the detection of a failure in link l_k results from the union of the working path beginning at the source node s until node i, followed by the bypass tunnel until node j, and finally a sequence of nodes belonging to the original working path since node j until the destination node d.

The mode of operation of the DARMP method is depicted in Figure 6.1. Upon a failure in link $l_k = (B, C, C_k)$, the traffic in protected LSPs traversing the failed link l_k is saved through its spreading among multiple bypass tunnels ($\mathcal{BD}_{B,C} = \{(B - G - C), (B - F - C)\}$) with equal probabilities in this case, and incoming connections from the source node A to the destination node C are carried by an alternative path ((A-D-C) or (A-E-C)). The use of dynamic alternative routing for forwarding incoming requests presents two major advantages: *i*) it is done according to the sticky random strategy, promoting the adaptation of the network to its new condition, *ii*) allows the use of potentially shorter paths during the link failure, instead of the longer end-to-end paths resulting from the union of the operational links in the protected LSPs with the bypass tunnels activated by the local protection mechanism. In the cited example, an incoming connection from node A to node C would be carried by a two-links length alternative path ((A-D-C) or (A-E-C)), instead of using a longer end-to-end path ($(A - B - F - C)$ or $(A - B - G - C)$). These longer end-to-end paths remain active until the subscribers terminate the connections. This time is independent of the link recovery time.

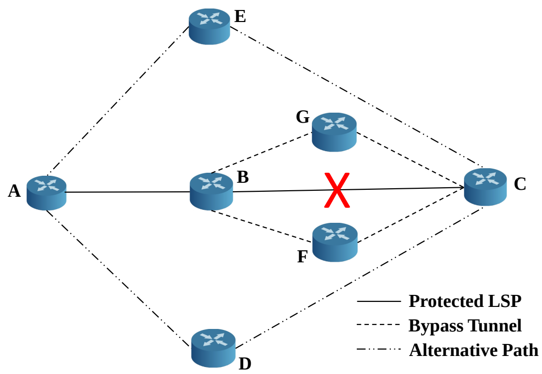

Figure 6.1: DARMP mode of operation.

6.3 Simulation Study

The performance of DARMP is evaluated in this work using a simulation platform. To allow a performance comparative analysis, two further strategies based on fixed routing (FR) in association with a local protection mechanism have been implemented. FR can be used in association with several local protection mechanisms. If a typical facility backup method is used to protect against link failures, each PLR configures a single bypass tunnel (which is shared by all protected LSPs) around each protected link. This method is herein designated as Fixed Routing with Single Protection (FRSP), and the single bypass tunnel is the second shortest path (using hop count metric) between the failure end nodes. On the other hand, if traffic splitting is applied to the facility backup method, each PLR configures multiple bypass tunnels. This method is herein designated as Fixed Routing with Multiple Protection (FRMP), and the computation of the bypass tunnel domain is done as in DARMP. In both FRSP and FRMP strategies, the end-to-end paths resulting from the activation of the local protection mechanism are simultaneously used to carry the ongoing connections in the failure time instant and also incoming connections until the failure gets resolved. This approach lacks flexibility and it leads to a higher consumption of network resources as these end-to-end paths tend to be longer.

This study evaluating the comparative network performance of DARMP, FRMP and FRSP includes simulations in three situations: in the absence of failures and in the case of a link failure (with and without a protection mechanism). In the absence of failures, or with a link failure but without protection, DARMP forwards traffic like DAR, using $\sqrt{C_k}/2$ as the bandwidth reservation level for each link l_k [37]. As FRSP and FRMP employ a fixed routing strategy they present the same performance in these scenarios and they are equally treated. In brief, when there is no protection, fixed routing and DAR are compared.

On the other hand, upon a link failure in a network with an active protection mechanism, the following topics are analyzed:

- the comparison between FRSP and FRMP evaluates the potential gain through the use of multiple bypass tunnels (instead of a single one) allowing the distribution of the protected traffic across the network;
- the comparison between FRMP and DARMP evaluates the effect of using alternative routing (with potentially shorter paths that adapt in real-time to the new network condition) to carry the incoming traffic for the failure time duration.

The discrete-event simulator based on OMNeT++ used in Chapter 4 is herein extended to support link failures. For each simulation scenario, 10 independent simulation runs were conducted, and the presented results are within a 97.5% confidence interval.

To understand the impact of the network topology on the performance of each of the methods, two test networks with different topologies are used in this study. The first test network derives from Network I in [69]. Network I, on the other hand, is derived from an actual MPLS service provider and it comprises 15 nodes, connected by 58 links (see Table C.1 in Appendix C.1.1), where all sources of traffic are connected by direct links and there are several lightly loaded links that are only used in alternative paths. The work in [69] applies to a multiservice MPLS network while DARMP is tested in single service networks therefore some adjustments were made. More detailed information on this dimensioning can be consulted in Appendix C.1.1.

The resulting network is designated in this chapter by Network A and it can be consulted in Table C.4 in Appendix C.1.1. In the absence of failures, Network A presents a mean network blocking probability of 5.6% with DARMP, which is a situation where the network is already under stress (for this reason this traffic case is designated henceforward as HIGH_LOAD). Given that the objective of this work is to evaluate the performance of the methods in link failure situations for networks that have not been dimensioned taking into account possible failure cases, it is important that traffic scenarios with less load be foreseen so that the protection mechanism can be more efficient. In this context, the LOW_LOAD traffic scenario considers a 17% decrease in the average value for the traffic that is offered to the network by each pair of nodes, obtaining a mean network blocking probability of 1% with DARMP. The VERY_LOW_LOAD traffic scenario designates a situation with a traffic matrix with a 10% load reduction when comparing to the reference situation (LOW_LOAD).

The second test network, herein designated as Network B, is a ten-nodes fully meshed network with 45 links (see Table C.5 in Appendix C.1.2). This network was chosen because DAR, as well as other classical alternative routing methods, was designed for fully meshed circuit-switched networks. In Network B, the same average traffic load was offered to all pairs of nodes. Link capacities were not engineered by any algorithm. Instead, they were adjusted by simulation in order to obtain a 1% mean blocking probability for DARMP (LOW_LOAD traffic case). A load factor reduction of 15% is considered in the VERY_LOW_LOAD situation. This difference in the two networks on the load factor reduction relates to the purpose of achieving a similar average link usage in both network cases. A traffic scenario of the HIGH_LOAD type was not considered for Network B because in situations of overload traffic little benefit is obtained from a protection mechanism that takes advantage of the available bandwidth on the network.

Finally, note that none of the networks was dimensioned considering protection against failures. In fact, the overall network bandwidth is not increased because the goal is to avoid the waste of resources in the absence of failures and to understand how the three methods behave in networks that were not dimensioned for link failures scenarios.

6.3.1 Routing and Protection Framework

The first step includes the configuration of the network routing domain $\mathcal{P}_G$ and of the bypass tunnel domain for each link l_k, $\mathcal{BD}_{l_k}$. To prevent congestion due to the use of longer paths, the following parameters are adjusted depending on the network connectivity degree. Consider that $M_{ij} \leq M, \forall i, j \in N$. In terms of routing domain, for Network A, M=8 and D=3 while, for Network B, M=9 and D=2. In terms of protection for each link l_k, $M_{l_k} \leq M$ for both networks and the maximum number of arcs in a bypass tunnel is 3 in the case of Network A and 2 in the case of Network B.

These paths were obtained through the MPS variant proposed in [33] and consist of the k-shortest paths (using hop count metric) with a maximum length. A remark must be made at this point: an initial approach accepted link-disjoint paths only (which would be particularly effective in protecting traffic against link failures). However, it resulted in a very bad performance because the number of both alternative and protection paths presented a significant decrease, and so this approach was abandoned.

Therefore, in DARMP, each router has a multi-path routing table with the following properties:

- for each pair of end nodes (i, j), a first-choice path p_{ij}^1 (which is the direct link or a fixed shortest path);
- for each pair of end nodes (i, j), a list of alternative paths $\mathcal{P}_{ij} \backslash \left\{p_{ij}^1\right\}$ (and their usage probabilities $prob_{p_{ij}^m} : 2 \leq m \leq M_{ij}$);
- for each one of the adjacent links l_k, its bypass tunnel domain $\mathcal{BD}_{l_k}$ (and the respective usage probabilities $prob_{b_{l_k}^n} : n \leq M_{l_k}$).

In FRSP and FRMP, $\mathcal{P}_{ij} = \left\{p_{ij}^1\right\}, \forall i, j \in N$, where p_{ij}^1 is the same first-choice path as in DARMP. In FRSP, $\mathcal{BD}_{l_k} = \left\{b_{l_k}^1\right\}$, where $b_{l_k}^1$ is the second shortest path between the failure end nodes. As mentioned before, FRMP allows the use of multiple bypass tunnels and $\mathcal{BD}_{l_k}$ is the same as in DARMP.

6.3.2 Analysis of Simulation Results

The evaluation of the network performance in this study relies on different metrics: the mean network blocking probability (in the absence of failures B and during the failure B_F) and the convergence time $Conv$ which is the number of seconds, after the failure resolution, that the network takes to reach a stable value which is 1% apart from the original mean blocking probability (before the failure occurrence).

The two test networks, Network A and Network B, are engineered with a single service with the required bandwidth d = 1 and an average service duration of 3 minutes. A single link failure of 5 minutes (the necessary time for a reboot) is simulated in links 3-9 and 1-3 for networks A and B, respectively. These links were chosen because they are one of the biggest links in terms of both carried traffic and capacity in each network.

6.3.2.1 Absence of failures

Simulations results in Table 6.1 show that, in this scenario, regardless of the network and load situation, DARMP scheme consistently presents a better performance (lower mean network blocking probability (B)) than FRSP/FRMP. This was the expected behavior and it is due to the fact that fixed routing offers one possibility alone to each incoming request (without any flexibility), while DAR improves the network performance because of its ability to forward traffic to alternative paths in case of blocking in the first-choice paths.

Table 6.1: Mean network blocking probability - absence of failures.

	FRSP/FRMP	DARMP
	Network A	
B (VERY_LOW_LOAD)	$0.0518 \pm 1.2 \times 10^{-4}$	$0.0012 \pm 3.4 \times 10^{-5}$
B (LOW_LOAD)	$0.0610 \pm 1.4 \times 10^{-4}$	$0.0106 \pm 7.3 \times 10^{-5}$
B (HIGH_LOAD)	$0.1155 \pm 2.8 \times 10^{-4}$	$0.0556 \pm 2.2 \times 10^{-4}$
	Network B	
B (VERY_LOW_LOAD)	$0.0008 \pm 2.6 \times 10^{-5}$	$0.00001 \pm 2.3 \times 10^{-6}$
B (LOW_LOAD)	$0.0195 \pm 1.7 \times 10^{-4}$	$0.0101 \pm 1.6 \times 10^{-4}$

6.3.2.2 Link Failure - Without a Protection Mechanism

When a link failure occurs in a network using the FRSP/FRMP methods but without an activated protection mechanism there is a total loss of both ongoing and incoming traffic in all the affected LSPs. In this failure scenario, a dynamic alternative routing scheme improves the network survivability by giving a second chance to incoming connections whose first-choice paths are denied (but the ongoing traffic in affected LSPs is irreparably lost).

Table 6.2: Link failure without a protection mechanism.

	Network A		Network B	
	FRSP/FRMP	DARMP	FRSP/FRMP	DARMP
	VERY_LOW_LOAD			
B_F	$0.0793 \pm 2.1 \times 10^{-3}$	$0.0012 \pm 1.2 \times 10^{-4}$	$0.0233 \pm 1.1 \times 10^{-3}$	$0.0022 \pm 4.1 \times 10^{-4}$
$Conv$	307.1 ± 15.2	721.2 ± 400.5	1636.7 ± 1120.52	1118.9 ± 1706.31
O_F	$C_{A3} \pm 4.4$	$1.29 \times C_{A3} \pm 5.2$	$C_{B3} \pm 9.2$	$C_{B3} \pm 9.2$
F_F	$C_{A3} \pm 4.4$	$1.29 \times C_{A3} \pm 5.2$	$C_{B3} \pm 9.2$	$C_{B3} \pm 9.2$
S_F	0	0	0	0
	LOW_LOAD			
B_F	$0.0900 \pm 3.0 \times 10^{-3}$	$0.0116 \pm 1.6 \times 10^{-3}$	$0.0422 \pm 2.2 \times 10^{-3}$	$0.0268 \pm 2.6 \times 10^{-3}$
$Conv$	306.1 ± 3.5	577.5 ± 324.7	415.4 ± 193.2	582.5 ± 277.4
O_F	$C_{A2} \pm 9.6$	$1.46 \times C_{A2} \pm 12.3$	$C_{B2} \pm 12.3$	$1.04 \times C_{B2} \pm 13.1$
F_F	$C_{A2} \pm 9.6$	$1.46 \times C_{A2} \pm 12.3$	$C_{B2} \pm 12.3$	$1.04 \times C_{B2} \pm 13.1$
S_F	0	0	0	0
	HIGH_LOAD			
B_F	$0.1438 \pm 1.1 \times 10^{-3}$	$0.0684 \pm 2.9 \times 10^{-3}$		
$Conv$	300.46 ± 40.5	293.46 ± 76.9		
O_F	$C_{A1} \pm 17.2$	$1.44 \times C_{A1} \pm 22.3$		
F_F	$C_{A1} \pm 17.2$	$1.44 \times C_{A1} \pm 22.3$		
S_F	0	0		

Table 6.2 shows the performance of networks A and B as a result of a 5 minutes failure in links 3-9 and 1-3, respectively. Consider further that O_F is the number of ongoing connections traversing the failed link in the failure time instant and that S_F and F_F are the number of connections that in the failure time instant are saved and failed, respectively. Finally, C_{xy} represents the number of ongoing connections in Network $x = \{A, B\}$ routed by FRSP/FRMP methods in load situation $y = \{1(HIGH\_LOAD), 2(LOW\_LOAD), 3(VERY\_LOW\_LOAD)\}$ and

traversing the failed link in the failure time instant.

The analysis starts with Network A in the HIGH_LOAD traffic scenario. The value of the mean network blocking probability during the failure rises approximately 25% for FRSP/FRMP when comparing to the case without failures. This increase is justified by the fact that these methods have a fixed single path for each pair of nodes, which translates into a complete loss of traffic both at the time instant of the failure and during the failure for all paths that traverse the failed link. The value of the mean network blocking probability during the failure rises 23% in the case of DARMP, with the absolute value of B_F being lower (about half) than that obtained for FRSP/FRMP. Regarding the convergence time values, FRSP/FRMP take about 300 seconds and DARMP takes about 293 seconds.

A similar analysis can be done for the two lighter load network situations (LOW_LOAD and VERY_LOW_LOAD) in networks A and B, based on results also shown in Table 6.2. Note further that the absolute value of B_F in any of the traffic load scenarios in both networks is much lower when using the DARMP scheme, as expected. Indeed, there is virtually no change in the mean blocking probability value during the failure for the VERY_LOW_LOAD scenario in Network A because fewer connections (when compared to higher load traffic cases) are at risk in the failure time instant and the routing scheme is capable of taking advantage of the extra available capacity elsewhere in the network to route incoming connections that otherwise would be denied due to the failed link.

6.3.2.3 Link Failure - With a Protection Mechanism

Table 6.3 shows the performance results in Network A in the case of a link failure when the methods implement the protection mechanism. The first observation is that, comparing these blocking probability values during failure B_F with the results obtained without an implemented protection (in Table 6.2), both FRSP and FRMP present a decrease while DARMP presents an increase.

When Network A uses the FRSP scheme, in the event of a failure, a single bypass tunnel attempts to save all the traffic that was being carried through the failed link. Consequently, a single path becomes congested and none of the

Table 6.3: Network A - Failure with a protection mechanism.

	FRSP	FRMP	DARMP
		VERY_LOW_LOAD	
B_F	$0.0200 \pm 2.2 \times 10^{-3}$	$0.0045 \pm 2.1 \times 10^{-4}$	$0.0029 \pm 4.6 \times 10^{-4}$
$Conv$	401.2 ± 5.6	402.3 ± 5.1	1421.2 ± 706.9
O_F	$C_{A3} \pm 4.4$	$C_{A3} \pm 4.4$	$1.29 \times C_{A3} \pm 5.2$
F_F	$0.30 \times C_{A3} \pm 0.02$	$0.02 \times C_{A3} \pm 0.04$	$0.03 \times C_{A3} \pm 0.07$
S_F	$0.70 \times C_{A3} \pm 0.02$	$0.98 \times C_{A3} \pm 0.04$	$1.26 \times C_{A3} \pm 0.07$
		LOW_LOAD	
B_F	$0.0884 \pm 3.4 \times 10^{-3}$	$0.0707 \pm 3.4 \times 10^{-4}$	$0.0135 \pm 1.7 \times 10^{-5}$
$Conv$	306.1 ± 3.5	305.2 ± 2.9	711.3 ± 634.9
O_F	$C_{A2} \pm 9.6$	$C_{A2} \pm 9.6$	$1.46 \times C_{A2} \pm 12.3$
F_F	$0.42 \times C_{A2} \pm 0.02$	$0.22 \times C_{A2} \pm 0.03$	$0.50 \times C_{A2} \pm 0.05$
S_F	$0.58 \times C_{A2} \pm 0.02$	$0.78 \times C_{A2} \pm 0.03$	$0.96 \times C_{A2} \pm 0.05$
		HIGH_LOAD	
B_F	$0.1437 \pm 1.1 \times 10^{-3}$	$0.13335 \pm 3.1 \times 10^{-3}$	$0.0737 \pm 3.5 \times 10^{-3}$
$Conv$	300.47 ± 12.8	312.614 ± 15.8	437.1 ± 236.9
O_F	$C_{A1} \pm 17.2$	$C_{A1} \pm 17.2$	$1.44 \times C_{A1} \pm 22.3$
F_F	$0.52 \times C_{A1} \pm 2.23$	$0.49 \times C_{A1} \pm 0.03$	$0.90 \times C_{A1} \pm 2.72$
S_F	$0.48 \times C_{A1} \pm 2.23$	$0.51 \times C_{A1} \pm 0.03$	$0.54 \times C_{A1} \pm 2.72$

incoming connections (that do not use neither the failed link nor any of the links that constitute the bypass tunnel) are affected. On the other hand, when the FRMP scheme is used in a link failure situation, the extra load coming from the ongoing traffic on the failed link is spread among multiple bypass tunnels reducing the local congestion that otherwise (with FRSP) would be focused on a single path. Accordingly, when compared to FRSP, a decrease for the FRMP blocking probability during failure was already expected.

When it comes to DARMP, it behaves in the same manner as FRMP in the failure time instant. The main difference relies on the number of connections that each scheme has to save. As shown in Table 6.3, DARMP has to rescue more connections than FRSP or FRMP. This can be explained by the lower mean network blocking probability in the absence of failures, which results in more carried traffic for the same traffic pattern and, consequently, in more traffic needing to be saved with less available bandwidth. The sudden increase in the bypass tunnels occupation in the failure time instant also contributes to the increase in the mean network blocking during failure. Despite that, regardless of the network load, DARMP always saves more connections than FRSP or FRMP, while still maintaining the lowest blocking probability during failure.

The network survivability is now evaluated in Network B which, conversely to Network A, is load balanced and it does not have several lightly loaded links that are only used for alternative routing (which is an advantage in Network A). FRSP presents a very bad comparative performance in terms of both the blocking probability during the failure and the number of saved connections in the failure time instant because the single bypass tunnel does not have enough available capacity to rescue all the traffic affected by the failed LSPs. On the other hand, FRMP takes advantage of the multiple bypass tunnels to distribute the traffic at risk, saving almost 100% of the connections traversing the failed link for the VERY_LOW_LOAD situation. Finally, DARMP saves a slightly lower number of connections when compared to FRMP due to the fact that in the failure time instant the network carries more traffic which results in less available capacity. Nevertheless, DARMP is still the scheme with the lowest blocking probability during failure in both traffic scenarios.

Table 6.4: Network B - Failure with a protection mechanism.

	FRSP	FRMP	DARMP
		VERY_LOW_LOAD	
B_F	$0.0200 \pm 1.4 \times 10^{-3}$	$0.0045 \pm 1.3 \times 10^{-3}$	$0.00003 \pm 1.5 \times 10^{-6}$
$Conv$	1597.42 ± 906.708	2043.92 ± 1602.81	3272.32 ± 1924.04
O_F	$C_{B3} \pm 9.2$	$C_{B3} \pm 9.2$	$C_{B3} \pm 9.2$
F_F	$0.71 \times C_{B3} \pm 2.2$	$0.03 \times C_{B3} \pm 7.1$	$0.04 \times C_{B3} \pm 8.2$
S_F	$0.29 \times C_{B3} \pm 2.2$	$0.97 \times C_{B3} \pm 7.1$	$0.96 \times C_{B3} \pm 8.2$
		LOW_LOAD	
B_F	$0.0421 \pm 2.5 \times 10^{-3}$	$0.0390 \pm 2.6 \times 10^{-3}$	$0.0285 \pm 3.0 \times 10^{-3}$
$Conv$	405.7 ± 190.6	415.4 ± 193.2	582.2 ± 282.6
O_F	$C_{B2} \pm 12.3$	$C_{B2} \pm 12.3$	$1.04 \times C_{B2} \pm 13.1$
F_F	$0.90 \times C_{B2} \pm 3.5$	$0.31 \times C_{B2} \pm 8.1$	$0.44 \times C_{B2} \pm 10.4$
S_F	$0.10 \times C_{B2} \pm 3.5$	$0.69 \times C_{B2} \pm 8.1$	$0.60 \times C_{B2} \pm 10.4$

6.3.2.4 Summary of Key Findings

From the presented comprehensive work, it is possible to summarize the following key findings:

1. The proposal of a local protection mechanism without bandwidth reservation (eliminating the bandwidth waste in the absence of failures) that is suitable for networks with dynamic alternative routing;

2. The increase of network adaptability and load balancing because, in the failure time instant, ongoing traffic in protected LSPs is split among multiple bypass tunnels and, during the failure, incoming connections are routed by alternative paths according to the new network condition in terms of load and topology;

3. The proposed strategy was evaluated in a simulation study using DAR, given its simplicity. However, it is valid in association with other dynamic alternative routing methods, such as the ones proposed in this thesis (SMODR and DMAR);

4. The simulation environment considered single service networks only. However, this approach also applies to multiservice networks;

5. In the absence of bandwidth reservation for protection purposes, there is no guarantee that all traffic can be saved. However, in a multiservice network where there is priority traffic (for example, real-time services), the network can be dimensioned to give different services different priorities under the protection mechanism, so that the most important services are saved.

Chapter 7

Conclusions

This thesis extends to MPLS a multiobjective dynamic alternative routing method, the MODR method, originally suitable for strongly meshed multiservice circuit-switched loss networks. MPLS networks with explicit routing can be modeled as circuit-switched loss networks at traffic level, as long as using the concept of effective bandwidth. This work further details the requirements for the use of dynamic alternative routing in MPLS networks.

In its multiservice formulation, MODR attempts to maximize the profit while promoting fairness among the multiple services and between traffic flows of each service type. The purpose is thus to periodically find the "best" set of single alternative paths representing a compromise solution between the objective functions, according to the state of the network. This routing problem is originally solved by a computationally heavy heuristic, making it difficult to apply in realistic network environments. This thesis replaces the original heuristic by a new simplified one that periodically updates the single alternative paths for a subset of sequentially chosen node pairs and it introduces a selective alternative path removal procedure to prevent the network to be overtaken by alternative routing in situations of traffic overload. Within the scope of the Simplified MODR (SMODR) method, it is possible to conclude that, in heavily loaded meshed networks, it is more important to control the excess of alternative routing than the routing algorithm itself.

However, in situations of traffic imbalance unforeseen when planning the network, single alternative paths may not have available the necessary resources to carry all the overflow traffic. This problem is solved by proposing a new method, Dynamic Multicriteria Alternative Routing (DMAR), which allows the use of multiple alternative paths, instead of a single one, to distribute the overflow traffic. DMAR combines an event-dependent strategy with the periodic update of multiple alternative paths according to a biobjective heuristic using the blocking probabilities and the implied costs. This work proposes the heuristics in charge of the path computation in both single service and multiservice environments, and it describes the analytical model supporting DMAR, namely the extension of the implied costs concept to allow the use of multiple alternative paths. A simulation study shows that DMAR efficiently balances the network traffic in single service networks and also between the different services in multiservice environments, leading to an improved overall network performance.

On the other hand, MPLS networks have been designed to meet the needs of real-time applications and, for that reason, rapid recovery upon failure becomes crucial. Dynamic alternative routing already improves the network survivability by allowing incoming connections to attempt alternative paths in case there is a failure. However, traffic in progress in failed links is lost. This thesis proposes Dynamic Alternative Routing with local Multiple paths Protection (DARMP), the association of a dynamic alternative routing strategy with a local protection mechanism with multiple protection paths and no bandwidth reservation. DARMP is tested with DAR but it is suitable to use with other dynamic alternative routing methods as well. DARMP improves the network performance also in case of a link failure because *i*) there is no bandwidth reservation for protection purposes, and *ii*) the network traffic is better distributed in case of a failure, i.e., in the failure time instant the protected traffic is spread among multiple protection paths taking advantage of the available bandwidth in the network, and during the failure the incoming connections are routed according to an event-dependent behavior and taking into account the new network status in the sense that QoS be satisfied. Although not guaranteeing a 100% protection rate (given that there is no bandwidth reservation for protection), DARMP is suitable for real networks carrying real-time applications because premium traffic would be given higher priority in the protection mechanism and faulty connections would belong to lower priority and therefore less important services.

Finally, this thesis highlights the potential advantages of using a multiobjective dynamic routing method in realistic network environments to take into consideration the multidimensional issues affecting QoS and cost factors, as well as the importance of designing a protection mechanism in alignment with any implemented dynamic alternative routing method to improve the network performance while minimizing the resources usage also in case of a link failure.

Appendix A

SMODR

Appendix A presents supplementary material to the work presented in Chapter 4 concerning the proposal of SMODR. Section A.1 describes the six-nodes fully meshed test networks that are used in the SMODR simulation study. These are the same networks that have already been used in a past work [52], to simplify the performance comparison with the original MODR method since its simulation time is very high. Section A.2 presents global performance simulations results in three scenarios: *i*) original MODR, as presented in [52], *ii*) SMODR (with Heuristics 1 and 2), using the blocking probabilities and the implied costs in the biobjective shortest path algorithm (MMRA), *iii*) SMODR (with Heuristic 1), using the Howard costs as substitutes for the implied costs in the MMRA algorithm. Section A.3 presents the corresponding service performance results, in the same three situations.

A.1 Test Networks

Table A.1: Networks A and M.

	Network A				Network M			
O-D	Link	Offered Traffic			Link	Offered Traffic		
Pair	Capacity	$s = 1$	$s = 2$	$s = 3$	Capacity	$s = 1$	$s = 2$	$s = 3$
1-2	812	27*5	27*2	27	851	27.47*3	27.47*2	27.47
1-3	183	6*5	6*2	6	195	6.97*3	6.97*2	6.97
1-4	776	25*5	25*2	25	6585	257.81*3	257.81*2	257.81
1-5	631	20*5	20*2	20	616	20.47*3	20.47*2	20.47
1-6	605	20*5	20*2	20	937	29.11*3	29.11*2	29.11
2-3	782	25*5	25*2	25	688	25.11*3	25.11*2	25.11
2-4	293	10*5	10*2	10	2602	101.61*3	101.61*2	101.61
2-5	963	30*5	30*2	30	3013	76.78*3	76.78*2	76.78
2-6	603	20*5	20*2	20	2288	82.56*3	82.56*2	82.56
3-4	341	11*5	11*2	11	342	11.92*3	11.92*2	11.92
3-5	239	8*5	8*2	8	192	6.86*3	6.86*2	6.86
3-6	397	13*5	13*2	13	356	13.25*3	13.25*2	13.25
4-5	266	9*5	9*2	9	2212	79.42*3	79.42*2	79.42
4-6	603	20*5	20*2	20	2187	83.0*3	83.0*2	83.0
5-6	355	12*5	12*2	12	3456	127.11*3	127.11*2	127.11

A.2 Global Performance

A.2.1 Original MODR

Table A.2: Global performance simulations results for the original MODR method in both networks, as presented in [52] (see Service performance in table A.17).

Overload Factor	Original MODR - ΔT=1m Network A	Network M
	$W_T \pm \Delta$	
0%	6478.24 ± 24.09	22588.7 ± 31.67
10%	6634.84 ± 18.82	23108.3 ± 25.43
20%	6761.94 ± 15.22	23510.8 ± 46.66
30%	6856.39 ± 7.35	23762.7 ± 32.61
40%	6938.33 ± 15.66	23966.6 ± 36.00
50%	7021.92 ± 16.93	24133.2 ± 39.35
60%	7086.22 ± 26.64	24266.5 ± 48.92
	$B_{Mm} \pm \Delta$	
0%	$0.004 \pm 1.8 \times 10^{-3}$	$0.0009 \pm 2.9 \times 10^{-4}$
10%	$0.011 \pm 2.9 \times 10^{-3}$	$0.0030 \pm 5.4 \times 10^{-4}$
20%	$0.026 \pm 3.6 \times 10^{-3}$	$0.011 \pm 2.0 \times 10^{-3}$
30%	$0.046 \pm 4.3 \times 10^{-3}$	$0.028 \pm 1.1 \times 10^{-3}$
40%	$0.068 \pm 4.8 \times 10^{-3}$	$0.045 \pm 1.7 \times 10^{-3}$
50%	$0.090 \pm 7.2 \times 10^{-3}$	$0.063 \pm 2.6 \times 10^{-3}$
60%	$0.114 \pm 1.0 \times 10^{-2}$	$0.084 \pm 1.9 \times 10^{-3}$

A.2.2 SMODR, using Implied Costs in MMRA

Table A.3: Network A - Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criteria according to eq. 4.6 and 4.7, and $b = 0.9$ (see Service performance in tables A.18 and A.19).

Overload Factor	SMODR (Eq. 4.6) - ΔT=1m Heuristic 1	SMODR (Eq. 4.6) - ΔT=1m Heuristic 2	SMODR (Eq. 4.7) - ΔT=1m Heuristic 1	SMODR (Eq. 4.7) - ΔT=1m Heuristic 2
	$W_T \pm \Delta$		$W_T \pm \Delta$	
0%	6474.52 ± 22.26	6473.09 ± 21.72	6472.69 ± 21.66	6471.89 ± 23.00
10%	6627.61 ± 15.25	6623.55 ± 11.63	6627.37 ± 14.28	6624.33 ± 13.83
20%	6745.3 ± 14.66	6734.92 ± 16.34	6749.20 ± 12.10	6737.89 ± 09.59
30%	6817.31 ± 18.54	6814.09 ± 23.57	6833.11 ± 19.16	6827.93 ± 14.12
40%	6862.6 ± 23.45	6864.06 ± 19.86	6889.62 ± 20.85	6884.76 ± 26.63
50%	6929.55 ± 31.57	6932.25 ± 17.97	6969.45 ± 17.51	6962.25 ± 28.78
60%	6981.02 ± 25.98	6975.15 ± 34.83	7021.43 ± 31.15	7015.21 ± 24.83
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$	
0%	$0.008 \pm 3.3 \times 10^{-3}$	$0.008 \pm 2.6 \times 10^{-3}$	$0.009 \pm 3.5 \times 10^{-3}$	$0.009 \pm 3.6 \times 10^{-3}$
10%	$0.024 \pm 5.9 \times 10^{-3}$	$0.025 \pm 5.1 \times 10^{-3}$	$0.025 \pm 5.8 \times 10^{-3}$	$0.026 \pm 4.7 \times 10^{-3}$
20%	$0.044 \pm 2.2 \times 10^{-3}$	$0.047 \pm 3.2 \times 10^{-3}$	$0.045 \pm 2.2 \times 10^{-3}$	$0.047 \pm 1.9 \times 10^{-3}$
30%	$0.077 \pm 8.8 \times 10^{-3}$	$0.077 \pm 8.2 \times 10^{-3}$	$0.072 \pm 7.7 \times 10^{-3}$	$0.074 \pm 7.0 \times 10^{-3}$
40%	$0.112 \pm 6.4 \times 10^{-3}$	$0.112 \pm 9.2 \times 10^{-3}$	$0.104 \pm 5.5 \times 10^{-3}$	$0.107 \pm 8.5 \times 10^{-3}$
50%	$0.150 \pm 9.2 \times 10^{-3}$	$0.151 \pm 4.2 \times 10^{-3}$	$0.139 \pm 6.9 \times 10^{-3}$	$0.143 \pm 6.7 \times 10^{-3}$
60%	$0.182 \pm 4.5 \times 10^{-3}$	$0.183 \pm 5.4 \times 10^{-3}$	$0.168 \pm 7.0 \times 10^{-3}$	$0.173 \pm 3.0 \times 10^{-3}$

Table A.4: Network M: Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criteria according to eq. 4.6 and 4.7, and $b = 0.9$ (see Service performance in tables A.20 and A.21).

Overload Factor	SMODR (Eq. 4.6) - ΔT=1m Heuristic 1	SMODR (Eq. 4.6) - ΔT=1m Heuristic 2	SMODR (Eq. 4.7) - ΔT=1m Heuristic 1	SMODR (Eq. 4.7) - ΔT=1m Heuristic 2
	$W_T \pm \Delta$		$W_T \pm \Delta$	
0%	22554.2 ± 61.12	22555.6 ± 61.36	22553.4 ± 60.89	22553.7 ± 60.97
10%	23097.2 ± 47.80	23092.9 ± 45.58	23094.0 ± 46.81	23090.1 ± 48.48
20%	23471.4 ± 24.85	23463.3 ± 12.01	23483.4 ± 15.56	23487.1 ± 14.06
30%	23640.5 ± 79.33	23617.6 ± 39.08	23689.5 ± 37.57	23671.9 ± 46.60
40%	23668.9 ± 50.48	23650.2 ± 55.38	23765.4 ± 61.60	23753.4 ± 63.04
50%	23677.4 ± 95.66	23687.9 ± 57.76	23816.7 ± 67.32	23805.5 ± 53.47
60%	23750.3 ± 34.26	23706.5 ± 20.12	23923.1 ± 23.91	23899.6 ± 30.10
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$	
0%	$0.002 \pm 7.6 \times 10^{-4}$	$0.001 \pm 6.4 \times 10^{-4}$	$0.002 \pm 8.1 \times 10^{-4}$	$0.002 \pm 6.3 \times 10^{-4}$
10%	$0.005 \pm 1.2 \times 10^{-3}$	$0.005 \pm 1.4 \times 10^{-3}$	$0.005 \pm 1.1 \times 10^{-3}$	$0.005 \pm 1.3 \times 10^{-3}$
20%	$0.021 \pm 1.5 \times 10^{-3}$	$0.021 \pm 3.1 \times 10^{-3}$	$0.020 \pm 2.1 \times 10^{-3}$	$0.020 \pm 2.5 \times 10^{-3}$
30%	$0.043 \pm 6.2 \times 10^{-3}$	$0.047 \pm 3.9 \times 10^{-3}$	$0.043 \pm 3.5 \times 10^{-3}$	$0.044 \pm 4.0 \times 10^{-3}$
40%	$0.083 \pm 3.8 \times 10^{-3}$	$0.084 \pm 2.4 \times 10^{-3}$	$0.076 \pm 4.2 \times 10^{-3}$	$0.077 \pm 3.1 \times 10^{-3}$
50%	$0.116 \pm 7.9 \times 10^{-3}$	$0.116 \pm 8.2 \times 10^{-3}$	$0.106 \pm 7.3 \times 10^{-3}$	$0.108 \pm 8.0 \times 10^{-3}$
60%	$0.147 \pm 1.0 \times 10^{-3}$	$0.150 \pm 2.4 \times 10^{-3}$	$0.134 \pm 2.8 \times 10^{-3}$	$0.136 \pm 2.8 \times 10^{-3}$

Table A.5: Network A - Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criteria according to eq. 4.8 and 4.9, and $b = 0.9$ (see Service performance in tables A.22 and A.23).

Overload Factor	SMODR (Eq. 4.8) - ΔT=1m Heuristic 1	Heuristic 2	SMODR (Eq. 4.9) - ΔT=1m Heuristic 1	Heuristic 2
	$W_T \pm \Delta$		$W_T \pm \Delta$	
0%	6473.38 ± 22.70	6472.37 ± 19.70	6472.07 ± 21.92	6471.47 ± 22.49
10%	6629.52 ± 10.57	6624.43 ± 16.90	6627.32 ± 8.17	6623.78 ± 14.51
20%	6749.51 ± 17.40	6740.13 ± 13.05	6751.79 ± 19.33	6744.11 ± 9.66
30%	6829.03 ± 15.28	6826.72 ± 16.27	6844.49 ± 15.76	6837.33 ± 18.57
40%	6883.65 ± 24.15	6891.65 ± 27.73	6902.43 ± 26.39	6906.83 ± 19.35
50%	6957.64 ± 28.19	6960.11 ± 25.53	6984.48 ± 24.41	6980.89 ± 11.51
60%	7019.43 ± 33.06	7016.80 ± 31.35	7050.68 ± 34.42	7048.74 ± 26.88
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$	
0%	$0.007 \pm 3.1 \times 10^{-3}$	$0.008 \pm 2.0 \times 10^{-3}$	$0.008 \pm 3.5 \times 10^{-3}$	$0.008 \pm 2.7 \times 10^{-3}$
10%	$0.020 \pm 4.7 \times 10^{-3}$	$0.022 \pm 4.6 \times 10^{-3}$	$0.022 \pm 5.5 \times 10^{-3}$	$0.023 \pm 5.1 \times 10^{-3}$
20%	$0.037 \pm 2.9 \times 10^{-3}$	$0.040 \pm 1.6 \times 10^{-3}$	$0.037 \pm 3.1 \times 10^{-3}$	$0.041 \pm 1.8 \times 10^{-3}$
30%	$0.062 \pm 6.8 \times 10^{-3}$	$0.064 \pm 7.6 \times 10^{-3}$	$0.061 \pm 8.0 \times 10^{-3}$	$0.065 \pm 6.7 \times 10^{-3}$
40%	$0.092 \pm 4.4 \times 10^{-3}$	$0.092 \pm 3.4 \times 10^{-3}$	$0.091 \pm 4.6 \times 10^{-3}$	$0.092 \pm 5.3 \times 10^{-3}$
50%	$0.124 \pm 8.0 \times 10^{-3}$	$0.127 \pm 5.8 \times 10^{-3}$	$0.122 \pm 6.6 \times 10^{-3}$	$0.126 \pm 7.8 \times 10^{-3}$
60%	$0.150 \pm 5.7 \times 10^{-3}$	$0.152 \pm 5.0 \times 10^{-3}$	$0.146 \pm 4.0 \times 10^{-4}$	$0.151 \pm 6.3 \times 10^{-3}$

Table A.6: Network M - Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criteria according to eq. 4.8 and 4.9, and $b = 0.9$ (see Service performance in tables A.24 and A.25).

Overload Factor	SMODR (Eq. 4.8) - ΔT=1m Heuristic 1	Heuristic 2	SMODR (Eq. 4.9) - ΔT=1m Heuristic 1	Heuristic 2
	$W_T \pm \Delta$		$W_T \pm \Delta$	
0%	22553.8 ± 61.30	22555.2 ± 61.46	22553.7 ± 61.26	22553.8 ± 61.60
10%	23094.8 ± 47.09	23092.3 ± 49.10	23091.6 ± 47.66	23089.0 ± 50.61
20%	23477.6 ± 15.59	23477.1 ± 9.85	23492.3 ± 20.02	23495.2 ± 19.28
30%	23667.5 ± 62.68	23647.7 ± 40.14	23719.5 ± 35.80	23714.3 ± 38.09
40%	23733.4 ± 66.25	23708.4 ± 66.58	23834.3 ± 66.78	23814.2 ± 55.29
50%	23784.0 ± 65.22	23783.8 ± 64.72	23892.8 ± 62.85	23902.3 ± 55.27
60%	23881.0 ± 31.95	23866.3 ± 28.85	24034.0 ± 21.04	24013.3 ± 33.19
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$	
0%	$0.002 \pm 8.4 \times 10^{-4}$	$0.002 \pm 6.4 \times 10^{-4}$	$0.002 \pm 7.5 \times 10^{-4}$	$0.002 \pm 6.5 \times 10^{-4}$
10%	$0.004 \pm 1.2 \times 10^{-3}$	$0.004 \pm 1.0 \times 10^{-3}$	$0.005 \pm 1.1 \times 10^{-3}$	$0.005 \pm 1.0 \times 10^{-3}$
20%	$0.017 \pm 2.0 \times 10^{-3}$	$0.017 \pm 2.3 \times 10^{-3}$	$0.017 \pm 1.7 \times 10^{-3}$	$0.016 \pm 2.3 \times 10^{-3}$
30%	$0.038 \pm 4.1 \times 10^{-3}$	$0.040 \pm 2.4 \times 10^{-3}$	$0.035 \pm 3.4 \times 10^{-3}$	$0.036 \pm 3.2 \times 10^{-3}$
40%	$0.069 \pm 3.7 \times 10^{-3}$	$0.071 \pm 4.4 \times 10^{-3}$	$0.064 \pm 4.3 \times 10^{-3}$	$0.065 \pm 2.8 \times 10^{-3}$
50%	$0.097 \pm 6.7 \times 10^{-3}$	$0.098 \pm 5.8 \times 10^{-3}$	$0.090 \pm 5.3 \times 10^{-3}$	$0.092 \pm 5.6 \times 10^{-3}$
60%	$0.123 \pm 2.3 \times 10^{-3}$	$0.125 \pm 2.6 \times 10^{-3}$	$0.115 \pm 2.3 \times 10^{-3}$	$0.117 \pm 3.7 \times 10^{-3}$

Table A.7: Network A - Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criteria according to eq. 4.10 and 4.11, and $b = 0.9$ (see Service performance in tables A.26 and A.27).

Overload Factor	SMODR (Eq. 4.10) - ΔT=1m Heuristic 1	SMODR (Eq. 4.10) - ΔT=1m Heuristic 2	SMODR (Eq. 4.11) - ΔT=1m Heuristic 1	SMODR (Eq. 4.11) - ΔT=1m Heuristic 2
	$W_T \pm \Delta$		$W_T \pm \Delta$	
0%	6471.40 ± 21.89	6470.30 ± 22.55	6468.77 ± 20.23	6467.19 ± 22.04
10%	6626.51 ± 13.17	6621.57 ± 14.94	6624.98 ± 10.62	6620.45 ± 15.94
20%	6752.08 ± 15.32	6744.78 ± 11.01	6751.65 ± 15.62	6745.60 ± 8.85
30%	6845.56 ± 13.33	6839.62 ± 12.87	6849.05 ± 14.80	6848.47 ± 14.38
40%	6910.28 ± 21.84	6913.36 ± 21.51	6921.51 ± 19.28	6919.70 ± 17.59
50%	6997.98 ± 18.41	6993.79 ± 20.57	7009.86 ± 25.67	7007.19 ± 21.41
60%	7067.61 ± 33.03	7058.29 ± 22.56	7074.27 ± 36.84	7074.78 ± 31.01
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$	
0%	$0.008 \pm 3.5 \times 10^{-3}$	$0.008 \pm 2.5 \times 10^{-3}$	$0.008 \pm 2.7 \times 10^{-3}$	$0.008 \pm 2.3 \times 10^{-3}$
10%	$0.021 \pm 4.1 \times 10^{-3}$	$0.023 \pm 3.7 \times 10^{-3}$	$0.021 \pm 4.8 \times 10^{-3}$	$0.023 \pm 4.1 \times 10^{-3}$
20%	$0.037 \pm 2.5 \times 10^{-3}$	$0.039 \pm 1.2 \times 10^{-3}$	$0.036 \pm 2.6 \times 10^{-3}$	$0.038 \pm 1.7 \times 10^{-3}$
30%	$0.060 \pm 7.8 \times 10^{-3}$	$0.063 \pm 6.4 \times 10^{-3}$	$0.058 \pm 6.3 \times 10^{-3}$	$0.058 \pm 6.1 \times 10^{-3}$
40%	$0.088 \pm 4.0 \times 10^{-3}$	$0.089 \pm 5.7 \times 10^{-3}$	$0.084 \pm 4.7 \times 10^{-3}$	$0.086 \pm 6.5 \times 10^{-3}$
50%	$0.118 \pm 4.6 \times 10^{-3}$	$0.122 \pm 8.4 \times 10^{-3}$	$0.113 \pm 7.0 \times 10^{-3}$	$0.116 \pm 6.6 \times 10^{-3}$
60%	$0.142 \pm 5.0 \times 10^{-3}$	$0.146 \pm 3.2 \times 10^{-3}$	$0.139 \pm 5.3 \times 10^{-3}$	$0.139 \pm 5.7 \times 10^{-3}$

Table A.8: Network M - Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criteria according to eq. 4.10 and 4.11, and $b = 0.9$ (see Service performance in tables A.28 and A.29).

Overload Factor	SMODR (Eq. 4.10) - ΔT=1m Heuristic 1	SMODR (Eq. 4.10) - ΔT=1m Heuristic 2	SMODR (Eq. 4.11) - ΔT=1m Heuristic 1	SMODR (Eq. 4.11) - ΔT=1m Heuristic 2
	$W_T \pm \Delta$		$W_T \pm \Delta$	
0%	22552.1 ± 61.99	22551.5 ± 62.83	22550.9 ± 61.57	22548.8 ± 61.37
10%	23088.1 ± 45.04	23082.2 ± 45.54	23086.2 ± 47.82	23082.2 ± 47.86
20%	23497.4 ± 16.12	23499.9 ± 18.10	23502.2 ± 21.46	23506.4 ± 16.34
30%	23763.8 ± 52.15	23755.9 ± 34.71	23768.7 ± 41.44	23759.2 ± 43.03
40%	23926.0 ± 61.94	23928.1 ± 48.06	23940.2 ± 49.66	23932.2 ± 49.76
50%	24031.3 ± 52.57	24053.3 ± 56.66	24048.1 ± 53.75	24057.0 ± 44.76
60%	24189.6 ± 35.66	24199.4 ± 27.29	24204.3 ± 31.93	24211.7 ± 34.29
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$	
0%	$0.002 \pm 7.8 \times 10^{-4}$	$0.002 \pm 6.0 \times 10^{-4}$	$0.002 \pm 7.8 \times 10^{-4}$	$0.002 \pm 6.8 \times 10^{-4}$
10%	$0.005 \pm 1.3 \times 10^{-3}$	$0.005 \pm 1.3 \times 10^{-3}$	$0.005 \pm 1.3 \times 10^{-3}$	$0.005 \pm 1.1 \times 10^{-3}$
20%	$0.017 \pm 1.5 \times 10^{-3}$	$0.017 \pm 1.5 \times 10^{-3}$	$0.016 \pm 1.3 \times 10^{-3}$	$0.016 \pm 2.3 \times 10^{-3}$
30%	$0.033 \pm 2.7 \times 10^{-3}$	$0.035 \pm 3.1 \times 10^{-3}$	$0.033 \pm 2.3 \times 10^{-3}$	$0.034 \pm 3.4 \times 10^{-3}$
40%	$0.059 \pm 3.5 \times 10^{-3}$	$0.060 \pm 2.0 \times 10^{-3}$	$0.058 \pm 3.2 \times 10^{-3}$	$0.060 \pm 2.2 \times 10^{-3}$
50%	$0.084 \pm 5.1 \times 10^{-3}$	$0.085 \pm 5.9 \times 10^{-3}$	$0.082 \pm 5.5 \times 10^{-3}$	$0.084 \pm 5.5 \times 10^{-3}$
60%	$0.107 \pm 2.8 \times 10^{-3}$	$0.108 \pm 2.1 \times 10^{-3}$	$0.105 \pm 3.2 \times 10^{-3}$	$0.107 \pm 2.5 \times 10^{-3}$

Table A.9: Network A - Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion according to eq. 4.12 and $b = 0.9$, and a direct routing scheme (see Service performance in tables A.30 and A.32).

Overload Factor	SMODR (Eq. 4.12) - ΔT=1m Heuristic 1	Heuristic 2	Direct routing
	$W_T \pm \Delta$		$W_T \pm \Delta$
0%	6458.25 ± 21.54	6456.14 ± 19.31	6388.33 ± 22.95
10%	6617.16 ± 9.35	6611.98 ± 13.23	6559.05 ± 10.23
20%	6749.57 ± 15.84	6741.99 ± 14.11	6707.99 ± 11.08
30%	6858.94 ± 15.36	6856.37 ± 13.08	6836.46 ± 19.02
40%	6948.69 ± 21.01	6945.79 ± 21.80	6943.85 ± 26.39
50%	7052.48 ± 22.22	7048.80 ± 21.41	7069.78 ± 26.80
60%	7129.71 ± 32.50	7126.34 ± 32.04	7158.07 ± 27.65
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$
0%	$0.011 \pm 3.0 \times 10^{-3}$	$0.011 \pm 2.8 \times 10^{-3}$	$0.027 \pm 3.4 \times 10^{-3}$
10%	$0.022 \pm 3.8 \times 10^{-3}$	$0.024 \pm 3.6 \times 10^{-3}$	$0.036 \pm 3.7 \times 10^{-3}$
20%	$0.036 \pm 2.1 \times 10^{-3}$	$0.039 \pm 1.9 \times 10^{-3}$	$0.046 \pm 1.8 \times 10^{-3}$
30%	$0.055 \pm 5.5 \times 10^{-3}$	$0.057 \pm 6.8 \times 10^{-3}$	$0.060 \pm 5.3 \times 10^{-3}$
40%	$0.077 \pm 3.6 \times 10^{-3}$	$0.079 \pm 5.5 \times 10^{-3}$	$0.078 \pm 3.1 \times 10^{-3}$
50%	$0.104 \pm 4.6 \times 10^{-3}$	$0.107 \pm 4.1 \times 10^{-3}$	$0.100 \pm 4.8 \times 10^{-3}$
60%	$0.126 \pm 6.3 \times 10^{-3}$	$0.128 \pm 5.5 \times 10^{-3}$	$0.120 \pm 4.8 \times 10^{-3}$

Table A.10: Network M - Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion according to eq. 4.12 and $b = 0.9$, and a direct routing scheme (see Service performance in tables A.31 and A.32).

Overload Factor	SMODR (Eq. 4.12) - ΔT=1m Heuristic 1	Heuristic 2	Direct routing
	$W_T \pm \Delta$		$W_T \pm \Delta$
0%	22543.1 ± 59.31	22543.0 ± 59.08	22450.9 ± 52.36
10%	23082.4 ± 45.40	23071.7 ± 48.26	22959.3 ± 49.70
20%	23497.9 ± 17.96	23499.2 ± 21.44	23393.5 ± 23.94
30%	23770.4 ± 32.72	23774.2 ± 40.75	23734.3 ± 43.41
40%	23971.0 ± 48.44	23962.4 ± 52.62	24014.8 ± 60.05
50%	24082.9 ± 49.04	24105.2 ± 48.05	24214.3 ± 69.90
60%	24249.0 ± 36.10	24269.3 ± 32.01	24431.3 ± 21.44
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$
0%	$0.002 \pm 8.0 \times 10^{-4}$	$0.002 \pm 8.7 \times 10^{-4}$	$0.008 \pm 1.4 \times 10^{-3}$
10%	$0.005 \pm 1.1 \times 10^{-3}$	$0.006 \pm 1.0 \times 10^{-3}$	$0.013 \pm 1.5 \times 10^{-3}$
20%	$0.016 \pm 1.8 \times 10^{-3}$	$0.016 \pm 1.9 \times 10^{-3}$	$0.022 \pm 1.5 \times 10^{-3}$
30%	$0.032 \pm 2.2 \times 10^{-3}$	$0.032 \pm 2.6 \times 10^{-3}$	$0.034 \pm 2.1 \times 10^{-3}$
40%	$0.055 \pm 2.4 \times 10^{-3}$	$0.056 \pm 3.0 \times 10^{-3}$	$0.052 \pm 2.2 \times 10^{-3}$
50%	$0.079 \pm 5.4 \times 10^{-3}$	$0.080 \pm 5.8 \times 10^{-3}$	$0.070 \pm 4.7 \times 10^{-3}$
60%	$0.102 \pm 2.6 \times 10^{-3}$	$0.102 \pm 2.2 \times 10^{-3}$	$0.090 \pm 2.3 \times 10^{-3}$

Table A.11: Global performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion according to eq. 4.13 for both networks, with $b = 0.9$ (see Service performance in tables A.33 and A.34).

Overload Factor	SMODR (Network A) - ΔT=1m Heuristic 1	Heuristic 2	SMODR (Network M) - ΔT=1m Heuristic 1	Heuristic 2
	$W_T \pm \Delta$		$W_T \pm \Delta$	
0%	6471.63 ± 21.52	6433.66 ± 23.20	22552.3 ± 60.01	22552.6 ± 61.70
10%	6626.04 ± 11.83	6598.90 ± 11.05	23087.7 ± 47.53	23083.0 ± 46.37
20%	6752.42 ± 10.00	6734.45 ± 16.38	23500.8 ± 13.43	23502.5 ± 18.82
30%	6843.74 ± 29.12	6846.66 ± 18.31	23764.9 ± 33.96	23753.4 ± 48.03
40%	6905.16 ± 28.38	6927.13 ± 23.40	23938.0 ± 48.71	23927.7 ± 40.33
50%	6996.16 ± 24.69	7021.76 ± 16.95	24031.7 ± 59.21	24044.4 ± 43.33
60%	7056.12 ± 33.08	7084.11 ± 31.27	24179.3 ± 33.12	24199.3 ± 41.57
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$	
0%	$0.008 \pm 3.1 \times 10^{-3}$	$0.016 \pm 2.4 \times 10^{-3}$	$0.002 \pm 1.0 \times 10^{-3}$	$0.002 \pm 7.6 \times 10^{-4}$
10%	$0.023 \pm 3.9 \times 10^{-3}$	$0.027 \pm 3.5 \times 10^{-3}$	$0.005 \pm 1.3 \times 10^{-3}$	$0.005 \pm 1.2 \times 10^{-3}$
20%	$0.038 \pm 8.7 \times 10^{-4}$	$0.039 \pm 2.4 \times 10^{-3}$	$0.017 \pm 2.0 \times 10^{-3}$	$0.017 \pm 2.3 \times 10^{-3}$
30%	$0.063 \pm 4.5 \times 10^{-3}$	$0.058 \pm 5.3 \times 10^{-3}$	$0.034 \pm 2.6 \times 10^{-3}$	$0.036 \pm 3.7 \times 10^{-3}$
40%	$0.091 \pm 6.4 \times 10^{-3}$	$0.083 \pm 4.1 \times 10^{-3}$	$0.058 \pm 4.0 \times 10^{-3}$	$0.061 \pm 1.8 \times 10^{-3}$
50%	$0.122 \pm 7.7 \times 10^{-3}$	$0.111 \pm 5.6 \times 10^{-3}$	$0.084 \pm 5.5 \times 10^{-3}$	$0.085 \pm 5.2 \times 10^{-3}$
60%	$0.147 \pm 5.2 \times 10^{-3}$	$0.136 \pm 5.8 \times 10^{-3}$	$0.108 \pm 2.5 \times 10^{-3}$	$0.108 \pm 2.3 \times 10^{-3}$

Table A.12: Global performance simulations results for SMODR (Heuristic 1) using path elimination criterion according to eq. 4.12, for both networks, with $b = 0.1$ and $b = 0.5$ (see Service performance in tables A.35 and A.36).

Overload Factor	SMODR (Network A) - Eq. 4.12 $b = 0.1$	$b = 0.5$	SMODR (Network M) - Eq. 4.12 $b = 0.1$	$b = 0.5$
	$W_T \pm \Delta$		$W_T \pm \Delta$	
0%	6460.92 ± 22.82	6459.97 ± 20.59	22542.1 ± 60.68	22543.2 ± 60.7717
10%	6613.05 ± 13.72	6617.44 ± 9.47	23083.2 ± 47.80	23082.4 ± 46.5483
20%	6741.81 ± 16.01	6750.35 ± 11.89	23496.5 ± 19.71	23501.1 ± 14.3926
30%	6856.84 ± 16.95	6862.76 ± 21.76	23782.8 ± 51.33	23786.2 ± 46.6335
40%	6952.16 ± 28.87	6949.85 ± 26.74	24021.3 ± 58.41	23982.6 ± 53.9371
50%	7067.66 ± 24.20	7056.21 ± 26.13	24197.2 ± 56.45	24127.5 ± 65.7952
60%	7156.44 ± 28.43	7140.52 ± 29.04	24408.4 ± 22.07	24320.7 ± 26.0396
	$B_{Mm} \pm \Delta$		$B_{Mm} \pm \Delta$	
0%	$0.010 \pm 2.9 \times 10^{-3}$	$0.010 \pm 2.6 \times 10^{-3}$	$0.002 \pm 7.1 \times 10^{-4}$	$0.002 \pm 7.7 \times 10^{-4}$
10%	$0.024 \pm 4.3 \times 10^{-3}$	$0.023 \pm 3.4 \times 10^{-3}$	$0.005 \pm 1.0 \times 10^{-3}$	$0.005 \pm 9.7 \times 10^{-4}$
20%	$0.038 \pm 2.2 \times 10^{-3}$	$0.036 \pm 2.1 \times 10^{-3}$	$0.016 \pm 1.7 \times 10^{-3}$	$0.016 \pm 1.7 \times 10^{-3}$
30%	$0.056 \pm 5.3 \times 10^{-3}$	$0.054 \pm 4.0 \times 10^{-3}$	$0.031 \pm 1.9 \times 10^{-3}$	$0.031 \pm 1.9 \times 10^{-3}$
40%	$0.077 \pm 2.8 \times 10^{-3}$	$0.077 \pm 3.2 \times 10^{-3}$	$0.052 \pm 2.7 \times 10^{-3}$	$0.054 \pm 2.3 \times 10^{-3}$
50%	$0.100 \pm 5.8 \times 10^{-3}$	$0.104 \pm 3.2 \times 10^{-3}$	$0.072 \pm 4.5 \times 10^{-3}$	$0.076 \pm 5.2 \times 10^{-3}$
60%	$0.120 \pm 5.4 \times 10^{-3}$	$0.124 \pm 5.4 \times 10^{-3}$	$0.092 \pm 1.7 \times 10^{-3}$	$0.098 \pm 2.2 \times 10^{-3}$

Table A.13: Network A - Global performance simulations results for SMODR (Heuristic 1) using path elimination criterion according to eq. 4.12, $b = 0.1$ and different path update intervals (see Service performance for ΔT=10s in table A.37).

Overload Factor	SMODR (Eq. 4.12) - Heuristic 1 ΔT=1m	ΔT=10s	ΔT=10s,30s,1m	ΔT=1m,2m,5m
	$W_T \pm \Delta$			
0%	6460.92 ± 22.82	6466.89 ± 23.09	6462.70 ± 22.21	6458.90 ± 22.21
10%	6613.05 ± 13.72	6626.00 ± 11.04	6622.68 ± 13.89	6613.07 ± 13.89
20%	6741.81 ± 16.01	6760.52 ± 14.38	6755.66 ± 11.77	6739.80 ± 11.77
30%	6856.84 ± 16.95	6873.55 ± 14.82	6865.77 ± 16.25	6856.84 ± 16.25
40%	6952.16 ± 28.87	6967.26 ± 27.81	6956.43 ± 24.68	6950.44 ± 24.68
50%	7067.66 ± 24.20	7079.24 ± 23.75	7067.00 ± 23.28	7066.36 ± 23.28
60%	7156.44 ± 28.43	7156.41 ± 28.19	7151.16 ± 27.71	7153.68 ± 27.71
	$B_{Mm} \pm \Delta$			
0%	$0.010 \pm 2.9 \times 10^{-3}$	$0.008 \pm 2.4 \times 10^{-3}$	$0.009 \pm 2.8 \times 10^{-3}$	$0.011 \pm 2.7 \times 10^{-3}$
10%	$0.024 \pm 4.3 \times 10^{-3}$	$0.020 \pm 3.1 \times 10^{-3}$	$0.021 \pm 3.2 \times 10^{-3}$	$0.024 \pm 3.5 \times 10^{-3}$
20%	$0.038 \pm 2.2 \times 10^{-3}$	$0.034 \pm 2.2 \times 10^{-3}$	$0.034 \pm 2.1 \times 10^{-3}$	$0.038 \pm 1.7 \times 10^{-3}$
30%	$0.055 \pm 5.3 \times 10^{-3}$	$0.052 \pm 6.3 \times 10^{-3}$	$0.053 \pm 5.8 \times 10^{-3}$	$0.055 \pm 4.7 \times 10^{-3}$
40%	$0.077 \pm 2.9 \times 10^{-3}$	$0.073 \pm 2.6 \times 10^{-3}$	$0.075 \pm 2.5 \times 10^{-3}$	$0.076 \pm 3.5 \times 10^{-3}$
50%	$0.100 \pm 5.8 \times 10^{-3}$	$0.098 \pm 4.3 \times 10^{-3}$	$0.100 \pm 4.7 \times 10^{-3}$	$0.101 \pm 3.8 \times 10^{-3}$
60%	$0.120 \pm 5.4 \times 10^{-3}$	$0.120 \pm 5.7 \times 10^{-3}$	$0.120 \pm 6.0 \times 10^{-3}$	$0.120 \pm 4.6 \times 10^{-3}$

Table A.14: Network M - Global performance simulations results for SMODR (Heuristic 1) using path elimination criterion according to eq. 4.12, $b = 0.1$ and different path update intervals (see Service performance for ΔT=10s in table A.37).

Overload Factor	SMODR (Eq. 4.12) - Heuristic 1 ΔT=1m	ΔT=10s	ΔT=10s,30s,1m	ΔT=1m,2m,5m
	$W_T \pm \Delta$			
0%	22542.1 ± 60.68	22547.4 ± 61.69	22546.3 ± 60.35	22545.1 ± 62.63
10%	23083.2 ± 47.80	23091.6 ± 50.96	23087.2 ± 50.62	23082.3 ± 47.54
20%	23496.5 ± 19.71	23529.2 ± 20.38	23517.8 ± 16.13	23494.0 ± 26.80
30%	23782.8 ± 51.33	23823.6 ± 39.78	23813.0 ± 40.29	23782.1 ± 36.66
40%	24021.3 ± 58.41	24037.7 ± 52.91	24026.9 ± 54.72	24017.2 ± 44.30
50%	24197.2 ± 56.45	24204.9 ± 62.01	24176.7 ± 48.02	24196.5 ± 63.87
60%	24408.4 ± 22.07	24383.6 ± 17.25	24362.2 ± 35.06	24404.1 ± 19.84
	$B_{Mm} \pm \Delta$			
0%	$0.002 \pm 6.7 \times 10^{-4}$	$0.002 \pm 6.9 \times 10^{-4}$	$0.002 \pm 5.8 \times 10^{-4}$	$0.002 \pm 6.4 \times 10^{-4}$
10%	$0.005 \pm 1.1 \times 10^{-3}$	$0.004 \pm 7.0 \times 10^{-4}$	$0.005 \pm 6.0 \times 10^{-4}$	$0.005 \pm 1.1 \times 10^{-3}$
20%	$0.016 \pm 1.6 \times 10^{-3}$	$0.014 \pm 1.5 \times 10^{-3}$	$0.014 \pm 1.8 \times 10^{-3}$	$0.016 \pm 2.2 \times 10^{-3}$
30%	$0.031 \pm 1.9 \times 10^{-3}$	$0.029 \pm 2.1 \times 10^{-3}$	$0.029 \pm 2.7 \times 10^{-3}$	$0.031 \pm 2.6 \times 10^{-3}$
40%	$0.052 \pm 2.9 \times 10^{-3}$	$0.051 \pm 2.1 \times 10^{-3}$	$0.051 \pm 3.4 \times 10^{-3}$	$0.052 \pm 2.9 \times 10^{-3}$
50%	$0.072 \pm 4.8 \times 10^{-3}$	$0.072 \pm 4.4 \times 10^{-3}$	$0.072 \pm 5.4 \times 10^{-3}$	$0.072 \pm 4.7 \times 10^{-3}$
60%	$0.092 \pm 1.9 \times 10^{-3}$	$0.093 \pm 1.5 \times 10^{-3}$	$0.094 \pm 2.4 \times 10^{-3}$	$0.092 \pm 1.3 \times 10^{-3}$

A.2.3 SMODR, using Howard Costs in MMRA

Table A.15: Network A - Global performance for SMODR (Heuristic 1), $b = 0.1$ and ΔT=1m or ΔT=10s (see Service performance in tables A.38 and A.39).

Overload Factor	SMODR - ΔT=1m Eq. 4.16	SMODR - ΔT=1m Eq. 4.17	SMODR - ΔT=10s Eq. 4.16	SMODR - ΔT=10s Eq. 4.17
	$W_T \pm \Delta$			
0%	6412.1 ± 24.28	6419.2 ± 25.02	6415.7 ± 25.63	6422.2 ± 24.98
10%	6554.4 ± 9.91	6557.2 ± 8.64	6557.7 ± 13.29	6558.9 ± 5.92
20%	6683.2 ± 19.14	6683.4 ± 20.29	6687.8 ± 18.03	6686.0 ± 21.12
30%	6784.3 ± 8.07	6768.8 ± 12.91	6788.4 ± 12.04	6774.1 ± 16.33
40%	6863.4 ± 20.82	6842.2 ± 14.32	6865.9 ± 20.58	6843.4 ± 19.45
50%	6951.3 ± 23.97	6913.6 ± 22.80	6948.7 ± 28.52	6912.5 ± 19.27
60%	7019.4 ± 31.65	6965.5 ± 27.01	7013.9 ± 26.89	6961.6 ± 36.93
	$B_{Mm} \pm \Delta$			
0%	$0.023 \pm 5.4 \times 10^{-3}$	$0.021 \pm 6.1 \times 10^{-3}$	$0.022 \pm 5.0 \times 10^{-3}$	$0.021 \pm 5.4 \times 10^{-3}$
10%	$0.039 \pm 3.0 \times 10^{-3}$	$0.039 \pm 4.0 \times 10^{-3}$	$0.038 \pm 2.9 \times 10^{-3}$	$0.039 \pm 4.4 \times 10^{-3}$
20%	$0.054 \pm 3.6 \times 10^{-3}$	$0.054 \pm 4.3 \times 10^{-3}$	$0.053 \pm 3.2 \times 10^{-3}$	$0.054 \pm 4.2 \times 10^{-3}$
30%	$0.075 \pm 7.8 \times 10^{-3}$	$0.080 \pm 7.2 \times 10^{-3}$	$0.075 \pm 7.0 \times 10^{-3}$	$0.079 \pm 6.7 \times 10^{-3}$
40%	$0.100 \pm 5.1 \times 10^{-3}$	$0.106 \pm 6.2 \times 10^{-3}$	$0.100 \pm 4.3 \times 10^{-3}$	$0.106 \pm 5.6 \times 10^{-3}$
50%	$0.131 \pm 6.1 \times 10^{-3}$	$0.141 \pm 4.5 \times 10^{-3}$	$0.132 \pm 5.3 \times 10^{-3}$	$0.142 \pm 5.8 \times 10^{-3}$
60%	$0.153 \pm 4.6 \times 10^{-3}$	$0.168 \pm 4.8 \times 10^{-3}$	$0.156 \pm 4.8 \times 10^{-3}$	$0.169 \pm 6.6 \times 10^{-3}$

Table A.16: Network M - Global performance for SMODR (Heuristic 1), $b = 0.1$ and ΔT=1m or ΔT=10s (see Service comparison results in tables A.40 and A.41).

Overload Factor	SMODR - ΔT=1m Eq. 4.16	SMODR - ΔT=1m Eq. 4.17	SMODR - ΔT=10s Eq. 4.16	SMODR - ΔT=10s Eq. 4.17
	$W_T \pm \Delta$			
0%	22542.8 ± 59.97	22552.3 ± 61.99	22548.1 ± 61.4	22561.3 ± 64.4
10%	23083.5 ± 47.32	23095.5 ± 43.51	23093.1 ± 47.6	23107.5 ± 50.5
20%	23490.2 ± 14.80	23435.3 ± 26.26	23530.0 ± 16.0	23446.4 ± 34.8
30%	23776.8 ± 44.66	23480.3 ± 54.13	23818.1 ± 41.5	23444.0 ± 75.4
40%	23996.5 ± 56.76	23341.6 ± 57.65	24036.3 ± 57.6	23323.5 ± 60.2
50%	24193.4 ± 53.14	23270.6 ± 69.87	24193.7 ± 66.0	23226.1 ± 91.6
60%	24398.3 ± 20.49	23186.8 ± 40.33	24376.8 ± 17.1	23144.5 ± 20.9
	$B_{Mm} \pm \Delta$			
0%	$0.002 \pm 7.6 \times 10^{-4}$	$0.002 \pm 5.8 \times 10^{-4}$	$0.002 \pm 6.7 \times 10^{-4}$	$0.001 \pm 4.4 \times 10^{-4}$
10%	$0.005 \pm 1.1 \times 10^{-3}$	$0.005 \pm 1.2 \times 10^{-3}$	$0.004 \pm 7.8 \times 10^{-4}$	$0.004 \pm 9.0 \times 10^{-4}$
20%	$0.017 \pm 1.7 \times 10^{-3}$	$0.022 \pm 1.9 \times 10^{-3}$	$0.014 \pm 1.8 \times 10^{-3}$	$0.021 \pm 3.1 \times 10^{-3}$
30%	$0.031 \pm 2.4 \times 10^{-3}$	$0.054 \pm 5.1 \times 10^{-3}$	$0.029 \pm 2.3 \times 10^{-3}$	$0.056 \pm 6.9 \times 10^{-3}$
40%	$0.053 \pm 2.4 \times 10^{-3}$	$0.099 \pm 5.5 \times 10^{-3}$	$0.051 \pm 2.4 \times 10^{-3}$	$0.101 \pm 4.5 \times 10^{-3}$
50%	$0.072 \pm 4.6 \times 10^{-3}$	$0.135 \pm 7.5 \times 10^{-3}$	$0.072 \pm 4.7 \times 10^{-3}$	$0.138 \pm 9.2 \times 10^{-3}$
60%	$0.093 \pm 2.0 \times 10^{-3}$	$0.173 \pm 2.9 \times 10^{-3}$	$0.094 \pm 2.1 \times 10^{-3}$	$0.176 \pm 2.7 \times 10^{-3}$

A.3 Service Performance

A.3.1 Original MODR

Table A.17: Service performance simulations results for the original MODR in both networks, as presented in [52].

Overload Factor	Original MODR - ΔT=1m			
	Network A		Network M	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.002 \pm 2.6 \times 10^{-4}$	$0.009 \pm 2.8 \times 10^{-3}$	$< 10^{-3}$	$0.011 \pm 2 \times 10^{-3}$
10%	$0.003 \pm 6.3 \times 10^{-4}$	$0.009 \pm 1.6 \times 10^{-3}$	$< 10^{-3}$	$0.014 \pm 2.8 \times 10^{-3}$
20%	$0.004 \pm 6.1 \times 10^{-4}$	$0.014 \pm 2.6 \times 10^{-3}$	$0.001 \pm 1.5 \times 10^{-4}$	$0.017 \pm 3.3 \times 10^{-3}$
30%	$0.005 \pm 9.5 \times 10^{-4}$	$0.017 \pm 3.6 \times 10^{-3}$	$0.002 \pm 3.3 \times 10^{-4}$	$0.018 \pm 4 \times 10^{-3}$
40%	$0.006 \pm 4.0 \times 10^{-4}$	$0.017 \pm 2.6 \times 10^{-3}$	$0.004 \pm 1 \times 10^{-3}$	$0.022 \pm 6.9 \times 10^{-3}$
50%	$0.008 \pm 9.3 \times 10^{-4}$	$0.021 \pm 6.4 \times 10^{-3}$	$0.005 \pm 6.2 \times 10^{-4}$	$0.023 \pm 3.5 \times 10^{-3}$
60%	$0.009 \pm 1.2 \times 10^{-3}$	$0.022 \pm 3.3 \times 10^{-3}$	$0.008 \pm 4.2 \times 10^{-3}$	$0.029 \pm 8.8 \times 10^{-3}$
	Service $s = 2$			
0%	$0.003 \pm 1.2 \times 10^{-3}$	$0.011 \pm 3.5 \times 10^{-3}$	$< 10^{-3}$	$0.016 \pm 2.7 \times 10^{-3}$
10%	$0.012 \pm 2.7 \times 10^{-3}$	$0.032 \pm 9.7 \times 10^{-3}$	$0.003 \pm 4.8 \times 10^{-4}$	$0.033 \pm 6 \times 10^{-3}$
20%	$0.025 \pm 4.6 \times 10^{-3}$	$0.051 \pm 7.6 \times 10^{-3}$	$0.01 \pm 1.1 \times 10^{-3}$	$0.062 \pm 5.6 \times 10^{-3}$
30%	$0.043 \pm 4.4 \times 10^{-3}$	$0.082 \pm 7.4 \times 10^{-3}$	$0.023 \pm 2.3 \times 10^{-3}$	$0.114 \pm 2.4 \times 10^{-2}$
40%	$0.062 \pm 4.4 \times 10^{-3}$	$0.111 \pm 1.0 \times 10^{-2}$	$0.039 \pm 1.8 \times 10^{-3}$	$0.151 \pm 1.4 \times 10^{-2}$
50%	$0.080 \pm 6.3 \times 10^{-3}$	$0.152 \pm 1.1 \times 10^{-2}$	$0.057 \pm 2.4 \times 10^{-3}$	$0.182 \pm 1.5 \times 10^{-2}$
60%	$0.101 \pm 6.9 \times 10^{-3}$	$0.184 \pm 2.2 \times 10^{-2}$	$0.073 \pm 3.8 \times 10^{-3}$	$0.208 \pm 1.6 \times 10^{-2}$
	Service $s = 3$			
0%	$0.004 \pm 1.8 \times 10^{-3}$	$0.017 \pm 8.5 \times 10^{-3}$	$0.001 \pm 2.9 \times 10^{-4}$	$0.023 \pm 7.8 \times 10^{-3}$
10%	$0.011 \pm 2.9 \times 10^{-3}$	$0.031 \pm 6.8 \times 10^{-3}$	$0.003 \pm 5.4 \times 10^{-4}$	$0.044 \pm 6.8 \times 10^{-3}$
20%	$0.026 \pm 3.6 \times 10^{-3}$	$0.062 \pm 1.5 \times 10^{-2}$	$0.011 \pm 2 \times 10^{-3}$	$0.075 \pm 1.8 \times 10^{-2}$
30%	$0.046 \pm 4.3 \times 10^{-3}$	$0.103 \pm 2.8 \times 10^{-2}$	$0.028 \pm 1.1 \times 10^{-3}$	$0.109 \pm 1.5 \times 10^{-2}$
40%	$0.068 \pm 4.8 \times 10^{-3}$	$0.129 \pm 1.6 \times 10^{-2}$	$0.045 \pm 1.7 \times 10^{-3}$	$0.152 \pm 1.7 \times 10^{-2}$
50%	$0.090 \pm 7.2 \times 10^{-3}$	$0.161 \pm 2.2 \times 10^{-2}$	$0.063 \pm 2.6 \times 10^{-3}$	$0.172 \pm 1.3 \times 10^{-2}$
60%	$0.114 \pm 1.0 \times 10^{-2}$	$0.195 \pm 2.3 \times 10^{-2}$	$0.084 \pm 1.9 \times 10^{-3}$	$0.211 \pm 3.4 \times 10^{-2}$

A.3.2 SMODR, using Implied Costs in MMRA

Table A.18: Network A - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.6, and $b = 0.9$.

Overload Factor	SMODR (Network A) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$< 10^{-4}$	$0.0008 \pm 2.6 \times 10^{-4}$	$0.0002 \pm 1.0 \times 10^{-4}$	$0.0007 \pm 7.3 \times 10^{-5}$
10%	$0.0005 \pm 1.1 \times 10^{-4}$	$0.0015 \pm 4.6 \times 10^{-4}$	$0.0005 \pm 1.5 \times 10^{-4}$	$0.0014 \pm 3.7 \times 10^{-4}$
20%	$0.0009 \pm 1.3 \times 10^{-4}$	$0.0020 \pm 4.3 \times 10^{-4}$	$0.0009 \pm 9.1 \times 10^{-5}$	$0.0018 \pm 2.7 \times 10^{-4}$
30%	$0.0016 \pm 1.7 \times 10^{-4}$	$0.0027 \pm 3.8 \times 10^{-4}$	$0.0016 \pm 1.3 \times 10^{-4}$	$0.0029 \pm 6.4 \times 10^{-4}$
40%	$0.0025 \pm 2.0 \times 10^{-4}$	$0.0042 \pm 5.4 \times 10^{-4}$	$0.0023 \pm 2.8 \times 10^{-4}$	$0.0039 \pm 5.9 \times 10^{-4}$
50%	$0.0035 \pm 3.9 \times 10^{-4}$	$0.0058 \pm 9.6 \times 10^{-4}$	$0.0033 \pm 2.3 \times 10^{-4}$	$0.0055 \pm 9.9 \times 10^{-4}$
60%	$0.0041 \pm 2.6 \times 10^{-4}$	$0.0059 \pm 3.0 \times 10^{-4}$	$0.0041 \pm 2.9 \times 10^{-4}$	$0.0062 \pm 6.9 \times 10^{-4}$
	Service $s = 2$			
0%	$0.003 \pm 1.1 \times 10^{-3}$	$0.011 \pm 3.3 \times 10^{-3}$	$0.004 \pm 1.3 \times 10^{-3}$	$0.010 \pm 2.0 \times 10^{-3}$
10%	$0.009 \pm 1.3 \times 10^{-3}$	$0.022 \pm 4.3 \times 10^{-3}$	$0.010 \pm 2.0 \times 10^{-3}$	$0.023 \pm 5.9 \times 10^{-3}$
20%	$0.017 \pm 1.7 \times 10^{-3}$	$0.036 \pm 4.9 \times 10^{-3}$	$0.018 \pm 1.4 \times 10^{-3}$	$0.037 \pm 1.6 \times 10^{-3}$
30%	$0.030 \pm 3.1 \times 10^{-3}$	$0.054 \pm 7.2 \times 10^{-3}$	$0.031 \pm 2.6 \times 10^{-3}$	$0.056 \pm 5.4 \times 10^{-3}$
40%	$0.046 \pm 2.8 \times 10^{-3}$	$0.078 \pm 9.6 \times 10^{-3}$	$0.046 \pm 2.7 \times 10^{-3}$	$0.077 \pm 9.1 \times 10^{-3}$
50%	$0.065 \pm 5.8 \times 10^{-3}$	$0.102 \pm 1.0 \times 10^{-2}$	$0.064 \pm 2.9 \times 10^{-3}$	$0.111 \pm 9.2 \times 10^{-3}$
60%	$0.079 \pm 3.0 \times 10^{-3}$	$0.127 \pm 5.1 \times 10^{-3}$	$0.080 \pm 4.1 \times 10^{-3}$	$0.136 \pm 1.0 \times 10^{-2}$
	Service $s = 3$			
0%	$0.008 \pm 3.3 \times 10^{-3}$	$0.027 \pm 7.6 \times 10^{-3}$	$0.008 \pm 2.6 \times 10^{-3}$	$0.031 \pm 5.4 \times 10^{-3}$
10%	$0.024 \pm 5.9 \times 10^{-3}$	$0.061 \pm 1.7 \times 10^{-2}$	$0.025 \pm 5.1 \times 10^{-3}$	$0.063 \pm 7.0 \times 10^{-3}$
20%	$0.044 \pm 2.2 \times 10^{-3}$	$0.103 \pm 1.3 \times 10^{-2}$	$0.047 \pm 3.2 \times 10^{-3}$	$0.100 \pm 1.2 \times 10^{-2}$
30%	$0.077 \pm 8.8 \times 10^{-3}$	$0.150 \pm 3.4 \times 10^{-2}$	$0.077 \pm 8.2 \times 10^{-3}$	$0.161 \pm 1.1 \times 10^{-2}$
40%	$0.112 \pm 6.4 \times 10^{-3}$	$0.212 \pm 2.3 \times 10^{-2}$	$0.112 \pm 9.2 \times 10^{-3}$	$0.216 \pm 1.3 \times 10^{-2}$
50%	$0.151 \pm 9.2 \times 10^{-3}$	$0.240 \pm 2.7 \times 10^{-2}$	$0.151 \pm 4.2 \times 10^{-3}$	$0.256 \pm 1.5 \times 10^{-2}$
60%	$0.182 \pm 4.5 \times 10^{-3}$	$0.317 \pm 3.2 \times 10^{-2}$	$0.183 \pm 5.4 \times 10^{-3}$	$0.296 \pm 2.7 \times 10^{-2}$

Table A.19: Network A - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.7, and $b = 0.9$.

Overload Factor	SMODR (Network A) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0001 \pm 4.0 \times 10^{-5}$	$0.0007 \pm 1.9 \times 10^{-4}$	$0.0002 \pm 5.7 \times 10^{-5}$	$0.0006 \pm 2.4 \times 10^{-4}$
10%	$0.0004 \pm 8.2 \times 10^{-5}$	$0.0012 \pm 2.1 \times 10^{-4}$	$0.0004 \pm 1.0 \times 10^{-4}$	$0.0011 \pm 3.1 \times 10^{-4}$
20%	$0.0007 \pm 1.4 \times 10^{-4}$	$0.0018 \pm 3.9 \times 10^{-4}$	$0.0008 \pm 6.9 \times 10^{-5}$	$0.0019 \pm 1.8 \times 10^{-4}$
30%	$0.0013 \pm 4.0 \times 10^{-5}$	$0.0028 \pm 4.9 \times 10^{-4}$	$0.0013 \pm 1.4 \times 10^{-4}$	$0.0024 \pm 5.3 \times 10^{-4}$
40%	$0.0019 \pm 9.6 \times 10^{-5}$	$0.0033 \pm 2.7 \times 10^{-4}$	$0.0019 \pm 2.3 \times 10^{-4}$	$0.0032 \pm 5.7 \times 10^{-4}$
50%	$0.0027 \pm 2.3 \times 10^{-4}$	$0.0048 \pm 8.6 \times 10^{-4}$	$0.0027 \pm 3.0 \times 10^{-4}$	$0.0046 \pm 1.3 \times 10^{-3}$
60%	$0.0034 \pm 2.2 \times 10^{-4}$	$0.0054 \pm 6.5 \times 10^{-4}$	$0.0032 \pm 1.1 \times 10^{-4}$	$0.0055 \pm 6.9 \times 10^{-4}$
	Service $s = 2$			
0%	$0.003 \pm 1.1 \times 10^{-3}$	$0.012 \pm 4.6 \times 10^{-3}$	$0.003 \pm 1.3 \times 10^{-3}$	$0.010 \pm 2.2 \times 10^{-3}$
10%	$0.009 \pm 2.1 \times 10^{-3}$	$0.024 \pm 6.8 \times 10^{-3}$	$0.009 \pm 2.3 \times 10^{-3}$	$0.025 \pm 7.5 \times 10^{-3}$
20%	$0.016 \pm 1.1 \times 10^{-3}$	$0.040 \pm 3.6 \times 10^{-3}$	$0.017 \pm 1.0 \times 10^{-3}$	$0.037 \pm 4.4 \times 10^{-3}$
30%	$0.029 \pm 3.4 \times 10^{-3}$	$0.056 \pm 1.0 \times 10^{-2}$	$0.029 \pm 3.9 \times 10^{-3}$	$0.056 \pm 1.0 \times 10^{-2}$
40%	$0.044 \pm 2.7 \times 10^{-3}$	$0.082 \pm 9.6 \times 10^{-3}$	$0.043 \pm 4.6 \times 10^{-3}$	$0.076 \pm 8.5 \times 10^{-3}$
50%	$0.062 \pm 3.9 \times 10^{-3}$	$0.109 \pm 2.0 \times 10^{-2}$	$0.061 \pm 5.8 \times 10^{-3}$	$0.115 \pm 1.8 \times 10^{-2}$
60%	$0.078 \pm 3.3 \times 10^{-3}$	$0.134 \pm 1.1 \times 10^{-2}$	$0.076 \pm 2.9 \times 10^{-3}$	$0.132 \pm 1.3 \times 10^{-2}$
	Service $s = 3$			
0%	$0.009 \pm 3.5 \times 10^{-3}$	$0.032 \pm 1.2 \times 10^{-2}$	$0.009 \pm 3.6 \times 10^{-3}$	$0.031 \pm 6.2 \times 10^{-3}$
10%	$0.025 \pm 5.8 \times 10^{-3}$	$0.071 \pm 1.4 \times 10^{-2}$	$0.026 \pm 4.7 \times 10^{-3}$	$0.067 \pm 1.0 \times 10^{-2}$
20%	$0.043 \pm 2.2 \times 10^{-3}$	$0.101 \pm 1.2 \times 10^{-2}$	$0.047 \pm 1.9 \times 10^{-3}$	$0.114 \pm 9.0 \times 10^{-3}$
30%	$0.072 \pm 7.7 \times 10^{-3}$	$0.158 \pm 2.3 \times 10^{-2}$	$0.074 \pm 7.0 \times 10^{-3}$	$0.160 \pm 1.1 \times 10^{-2}$
40%	$0.105 \pm 5.6 \times 10^{-3}$	$0.219 \pm 2.6 \times 10^{-2}$	$0.107 \pm 8.5 \times 10^{-3}$	$0.213 \pm 2.2 \times 10^{-2}$
50%	$0.139 \pm 6.9 \times 10^{-3}$	$0.261 \pm 4.1 \times 10^{-2}$	$0.143 \pm 6.7 \times 10^{-3}$	$0.264 \pm 2.8 \times 10^{-2}$
60%	$0.168 \pm 7.0 \times 10^{-3}$	$0.291 \pm 9.1 \times 10^{-3}$	$0.173 \pm 3.0 \times 10^{-3}$	$0.316 \pm 2.4 \times 10^{-2}$

Table A.20: Network M - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.6, and $b = 0.9$.

Overload Factor	SMODR (Network M) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$< 10^{-4}$	$0.0008 \pm 1.4 \times 10^{-4}$	$< 10^{-4}$	$0.0010 \pm 4.6 \times 10^{-4}$
10%	$0.0001 \pm 3.3 \times 10^{-5}$	$0.0014 \pm 5.3 \times 10^{-4}$	$0.0001 \pm 3.6 \times 10^{-5}$	$0.0012 \pm 3.8 \times 10^{-4}$
20%	$0.0005 \pm 3.4 \times 10^{-5}$	$0.0024 \pm 6.8 \times 10^{-4}$	$0.0004 \pm 6.4 \times 10^{-5}$	$0.0019 \pm 5.6 \times 10^{-4}$
30%	$0.0011 \pm 1.5 \times 10^{-4}$	$0.0037 \pm 5.5 \times 10^{-4}$	$0.0010 \pm 7.0 \times 10^{-5}$	$0.0034 \pm 1.1 \times 10^{-3}$
40%	$0.0020 \pm 1.2 \times 10^{-4}$	$0.0055 \pm 4.6 \times 10^{-4}$	$0.0019 \pm 1.8 \times 10^{-4}$	$0.0052 \pm 6.7 \times 10^{-4}$
50%	$0.0030 \pm 2.5 \times 10^{-4}$	$0.0076 \pm 1.3 \times 10^{-3}$	$0.0026 \pm 2.3 \times 10^{-4}$	$0.0064 \pm 8.9 \times 10^{-4}$
60%	$0.0037 \pm 1.5 \times 10^{-4}$	$0.0089 \pm 1.6 \times 10^{-3}$	$0.0035 \pm 1.0 \times 10^{-4}$	$0.0079 \pm 7.7 \times 10^{-4}$
	Service $s = 2$			
0%	$0.001 \pm 2.6 \times 10^{-4}$	$0.014 \pm 3.4 \times 10^{-3}$	$0.001 \pm 2.0 \times 10^{-4}$	$0.013 \pm 6.0 \times 10^{-3}$
10%	$0.002 \pm 5.9 \times 10^{-4}$	$0.022 \pm 4.6 \times 10^{-3}$	$0.002 \pm 6.2 \times 10^{-4}$	$0.023 \pm 6.6 \times 10^{-3}$
20%	$0.008 \pm 5.1 \times 10^{-4}$	$0.036 \pm 7.4 \times 10^{-3}$	$0.009 \pm 1.1 \times 10^{-3}$	$0.041 \pm 7.8 \times 10^{-3}$
30%	$0.019 \pm 2.8 \times 10^{-3}$	$0.079 \pm 2.1 \times 10^{-2}$	$0.020 \pm 1.2 \times 10^{-3}$	$0.072 \pm 7.3 \times 10^{-3}$
40%	$0.036 \pm 2.1 \times 10^{-3}$	$0.105 \pm 1.8 \times 10^{-2}$	$0.037 \pm 2.7 \times 10^{-3}$	$0.111 \pm 1.5 \times 10^{-2}$
50%	$0.052 \pm 4.5 \times 10^{-3}$	$0.142 \pm 1.9 \times 10^{-2}$	$0.051 \pm 4.0 \times 10^{-3}$	$0.156 \pm 1.8 \times 10^{-2}$
60%	$0.067 \pm 2.1 \times 10^{-3}$	$0.181 \pm 1.1 \times 10^{-2}$	$0.068 \pm 2.1 \times 10^{-3}$	$0.180 \pm 5.8 \times 10^{-3}$
	Service $s = 3$			
0%	$0.002 \pm 7.6 \times 10^{-4}$	$0.035 \pm 1.3 \times 10^{-2}$	$0.002 \pm 6.4 \times 10^{-4}$	$0.044 \pm 3.0 \times 10^{-2}$
10%	$0.005 \pm 1.2 \times 10^{-3}$	$0.055 \pm 1.7 \times 10^{-2}$	$0.005 \pm 1.4 \times 10^{-3}$	$0.059 \pm 4.6 \times 10^{-3}$
20%	$0.021 \pm 1.5 \times 10^{-3}$	$0.115 \pm 9.9 \times 10^{-3}$	$0.021 \pm 3.1 \times 10^{-3}$	$0.124 \pm 2.9 \times 10^{-2}$
30%	$0.046 \pm 6.2 \times 10^{-3}$	$0.193 \pm 2.7 \times 10^{-2}$	$0.047 \pm 3.9 \times 10^{-3}$	$0.209 \pm 4.7 \times 10^{-2}$
40%	$0.083 \pm 3.8 \times 10^{-3}$	$0.267 \pm 4.1 \times 10^{-2}$	$0.084 \pm 2.4 \times 10^{-3}$	$0.270 \pm 5.4 \times 10^{-2}$
50%	$0.116 \pm 7.9 \times 10^{-3}$	$0.319 \pm 3.5 \times 10^{-2}$	$0.116 \pm 8.2 \times 10^{-3}$	$0.325 \pm 3.5 \times 10^{-2}$
60%	$0.147 \pm 1.1 \times 10^{-3}$	$0.378 \pm 4.2 \times 10^{-2}$	$0.150 \pm 2.4 \times 10^{-3}$	$0.385 \pm 4.9 \times 10^{-2}$

Table A.21: Network M - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.7, and $b = 0.9$.

Overload Factor	SMODR (Network M) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$< 10^{-4}$	$0.0008 \pm 5.4 \times 10^{-4}$	$< 10^{-4}$	$0.0007 \pm 2.8 \times 10^{-4}$
10%	$0.0001 \pm 4.7 \times 10^{-5}$	$0.0013 \pm 5.0 \times 10^{-4}$	$< 10^{-4}$	$0.0012 \pm 2.5 \times 10^{-4}$
20%	$0.0004 \pm 6.3 \times 10^{-5}$	$0.0017 \pm 6.2 \times 10^{-4}$	$0.0003 \pm 4.4 \times 10^{-5}$	$0.0017 \pm 5.4 \times 10^{-4}$
30%	$0.0008 \pm 1.1 \times 10^{-4}$	$0.0029 \pm 8.2 \times 10^{-4}$	$0.0008 \pm 1.2 \times 10^{-4}$	$0.0027 \pm 7.2 \times 10^{-4}$
40%	$0.0016 \pm 1.1 \times 10^{-4}$	$0.0042 \pm 2.6 \times 10^{-4}$	$0.0014 \pm 9.9 \times 10^{-5}$	$0.0040 \pm 5.4 \times 10^{-4}$
50%	$0.0023 \pm 1.6 \times 10^{-4}$	$0.0054 \pm 5.3 \times 10^{-4}$	$0.0021 \pm 1.2 \times 10^{-4}$	$0.0052 \pm 8.6 \times 10^{-4}$
60%	$0.0029 \pm 1.1 \times 10^{-4}$	$0.0066 \pm 9.6 \times 10^{-4}$	$0.0026 \pm 1.3 \times 10^{-4}$	$0.0062 \pm 9.9 \times 10^{-4}$
	Service $s = 2$			
0%	$0.001 \pm 2.4 \times 10^{-4}$	$0.014 \pm 5.3 \times 10^{-3}$	$0.001 \pm 2.5 \times 10^{-4}$	$0.014 \pm 3.6 \times 10^{-3}$
10%	$0.002 \pm 5.9 \times 10^{-4}$	$0.022 \pm 3.5 \times 10^{-3}$	$0.002 \pm 6.6 \times 10^{-4}$	$0.022 \pm 4.6 \times 10^{-3}$
20%	$0.008 \pm 8.3 \times 10^{-4}$	$0.043 \pm 4.3 \times 10^{-3}$	$0.008 \pm 7.4 \times 10^{-4}$	$0.042 \pm 3.8 \times 10^{-3}$
30%	$0.018 \pm 1.2 \times 10^{-3}$	$0.078 \pm 1.1 \times 10^{-2}$	$0.018 \pm 1.7 \times 10^{-3}$	$0.072 \pm 6.2 \times 10^{-3}$
40%	$0.033 \pm 2.2 \times 10^{-3}$	$0.109 \pm 1.8 \times 10^{-2}$	$0.034 \pm 2.0 \times 10^{-3}$	$0.117 \pm 1.7 \times 10^{-2}$
50%	$0.049 \pm 3.4 \times 10^{-3}$	$0.145 \pm 1.6 \times 10^{-2}$	$0.048 \pm 4.0 \times 10^{-3}$	$0.147 \pm 2.4 \times 10^{-2}$
60%	$0.063 \pm 1.8 \times 10^{-3}$	$0.175 \pm 8.4 \times 10^{-3}$	$0.064 \pm 1.0 \times 10^{-3}$	$0.183 \pm 1.2 \times 10^{-2}$
	Service $s = 3$			
0%	$0.002 \pm 8.1 \times 10^{-4}$	$0.035 \pm 1.1 \times 10^{-2}$	$0.002 \pm 6.3 \times 10^{-4}$	$0.042 \pm 2.6 \times 10^{-2}$
10%	$0.005 \pm 1.1 \times 10^{-3}$	$0.068 \pm 1.6 \times 10^{-2}$	$0.006 \pm 1.3 \times 10^{-3}$	$0.062 \pm 1.3 \times 10^{-2}$
20%	$0.020 \pm 2.1 \times 10^{-3}$	$0.119 \pm 1.4 \times 10^{-2}$	$0.020 \pm 2.5 \times 10^{-3}$	$0.122 \pm 1.8 \times 10^{-2}$
30%	$0.043 \pm 3.5 \times 10^{-3}$	$0.187 \pm 3.0 \times 10^{-2}$	$0.044 \pm 4.0 \times 10^{-3}$	$0.189 \pm 3.8 \times 10^{-2}$
40%	$0.076 \pm 4.2 \times 10^{-3}$	$0.243 \pm 2.5 \times 10^{-2}$	$0.077 \pm 3.1 \times 10^{-3}$	$0.247 \pm 2.8 \times 10^{-2}$
50%	$0.106 \pm 7.3 \times 10^{-3}$	$0.305 \pm 3.3 \times 10^{-2}$	$0.108 \pm 8.0 \times 10^{-3}$	$0.340 \pm 3.9 \times 10^{-2}$
60%	$0.134 \pm 2.8 \times 10^{-3}$	$0.361 \pm 2.7 \times 10^{-2}$	$0.136 \pm 2.8 \times 10^{-3}$	$0.383 \pm 1.9 \times 10^{-2}$

Table A.22: Network A - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.8, and $b = 0.9$.

Overload Factor	SMODR (Network A) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$0.0004 \pm 1.7 \times 10^{-4}$	$0.0016 \pm 7.2 \times 10^{-4}$	$0.0004 \pm 1.6 \times 10^{-4}$	$0.0018 \pm 5.3 \times 10^{-4}$
10%	$0.0014 \pm 2.6 \times 10^{-4}$	$0.0041 \pm 4.5 \times 10^{-4}$	$0.0014 \pm 3.2 \times 10^{-4}$	$0.0047 \pm 7.0 \times 10^{-4}$
20%	$0.0026 \pm 2.1 \times 10^{-4}$	$0.0062 \pm 9.9 \times 10^{-4}$	$0.0027 \pm 3.9 \times 10^{-4}$	$0.0084 \pm 2.1 \times 10^{-3}$
30%	$0.0049 \pm 5.4 \times 10^{-4}$	$0.0108 \pm 2.1 \times 10^{-3}$	$0.0051 \pm 7.8 \times 10^{-4}$	$0.0127 \pm 2.1 \times 10^{-3}$
40%	$0.0074 \pm 6.9 \times 10^{-4}$	$0.0151 \pm 1.8 \times 10^{-3}$	$0.0073 \pm 5.7 \times 10^{-4}$	$0.0154 \pm 2.3 \times 10^{-3}$
50%	$0.0105 \pm 7.7 \times 10^{-4}$	$0.0202 \pm 2.3 \times 10^{-3}$	$0.0109 \pm 6.9 \times 10^{-4}$	$0.0219 \pm 4.1 \times 10^{-3}$
60%	$0.0130 \pm 5.7 \times 10^{-4}$	$0.0256 \pm 3.8 \times 10^{-3}$	$0.0136 \pm 7.1 \times 10^{-4}$	$0.0258 \pm 2.5 \times 10^{-3}$
	Service $s = 2$			
0%	$0.004 \pm 1.7 \times 10^{-3}$	$0.015 \pm 5.9 \times 10^{-3}$	$0.004 \pm 1.2 \times 10^{-3}$	$0.013 \pm 3.0 \times 10^{-3}$
10%	$0.012 \pm 2.2 \times 10^{-3}$	$0.029 \pm 4.5 \times 10^{-3}$	$0.012 \pm 2.4 \times 10^{-3}$	$0.031 \pm 8.3 \times 10^{-3}$
20%	$0.021 \pm 2.5 \times 10^{-3}$	$0.042 \pm 4.6 \times 10^{-3}$	$0.021 \pm 1.9 \times 10^{-3}$	$0.051 \pm 5.5 \times 10^{-3}$
30%	$0.037 \pm 4.6 \times 10^{-3}$	$0.073 \pm 8.9 \times 10^{-3}$	$0.036 \pm 3.2 \times 10^{-3}$	$0.076 \pm 1.5 \times 10^{-2}$
40%	$0.053 \pm 4.9 \times 10^{-3}$	$0.098 \pm 1.2 \times 10^{-2}$	$0.051 \pm 2.0 \times 10^{-3}$	$0.097 \pm 1.0 \times 10^{-2}$
50%	$0.074 \pm 5.7 \times 10^{-3}$	$0.128 \pm 8.2 \times 10^{-3}$	$0.071 \pm 4.0 \times 10^{-3}$	$0.125 \pm 1.9 \times 10^{-2}$
60%	$0.088 \pm 3.1 \times 10^{-3}$	$0.151 \pm 1.7 \times 10^{-2}$	$0.088 \pm 4.9 \times 10^{-3}$	$0.156 \pm 9.5 \times 10^{-3}$
	Service $s = 3$			
0%	$0.007 \pm 3.1 \times 10^{-3}$	$0.031 \pm 1.2 \times 10^{-2}$	$0.008 \pm 2.0 \times 10^{-3}$	$0.030 \pm 5.7 \times 10^{-3}$
10%	$0.020 \pm 4.7 \times 10^{-3}$	$0.054 \pm 1.2 \times 10^{-2}$	$0.022 \pm 4.6 \times 10^{-3}$	$0.063 \pm 1.0 \times 10^{-2}$
20%	$0.037 \pm 2.9 \times 10^{-3}$	$0.086 \pm 1.1 \times 10^{-2}$	$0.040 \pm 1.6 \times 10^{-3}$	$0.090 \pm 1.2 \times 10^{-2}$
30%	$0.062 \pm 6.8 \times 10^{-3}$	$0.127 \pm 1.4 \times 10^{-2}$	$0.064 \pm 7.6 \times 10^{-3}$	$0.131 \pm 2.3 \times 10^{-2}$
40%	$0.092 \pm 4.4 \times 10^{-3}$	$0.187 \pm 2.8 \times 10^{-2}$	$0.092 \pm 3.4 \times 10^{-3}$	$0.195 \pm 2.7 \times 10^{-2}$
50%	$0.124 \pm 8.0 \times 10^{-3}$	$0.205 \pm 2.0 \times 10^{-2}$	$0.127 \pm 5.8 \times 10^{-3}$	$0.223 \pm 3.4 \times 10^{-2}$
60%	$0.150 \pm 5.7 \times 10^{-3}$	$0.259 \pm 2.1 \times 10^{-2}$	$0.152 \pm 5.0 \times 10^{-3}$	$0.274 \pm 3.2 \times 10^{-2}$

Table A.23: Network A - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.9, and $b = 0.9$.

Overload Factor	SMODR (Network A) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$0.0004 \pm 1.6 \times 10^{-4}$	$0.0016 \pm 1.2 \times 10^{-3}$	$0.0004 \pm 1.4 \times 10^{-4}$	$0.0017 \pm 4.1 \times 10^{-4}$
10%	$0.0011 \pm 1.9 \times 10^{-4}$	$0.0034 \pm 1.0 \times 10^{-3}$	$0.0011 \pm 2.9 \times 10^{-4}$	$0.0038 \pm 9.2 \times 10^{-4}$
20%	$0.0021 \pm 2.3 \times 10^{-4}$	$0.0065 \pm 2.4 \times 10^{-3}$	$0.0022 \pm 1.9 \times 10^{-4}$	$0.0061 \pm 1.5 \times 10^{-3}$
30%	$0.0038 \pm 4.0 \times 10^{-4}$	$0.0090 \pm 9.9 \times 10^{-4}$	$0.0041 \pm 6.2 \times 10^{-4}$	$0.0112 \pm 2.5 \times 10^{-3}$
40%	$0.0060 \pm 5.4 \times 10^{-4}$	$0.0128 \pm 2.1 \times 10^{-3}$	$0.0062 \pm 7.1 \times 10^{-4}$	$0.0144 \pm 4.1 \times 10^{-3}$
50%	$0.0089 \pm 7.3 \times 10^{-4}$	$0.0185 \pm 1.5 \times 10^{-3}$	$0.0094 \pm 5.9 \times 10^{-4}$	$0.0190 \pm 2.2 \times 10^{-3}$
60%	$0.0111 \pm 8.0 \times 10^{-4}$	$0.0222 \pm 1.9 \times 10^{-3}$	$0.0118 \pm 6.6 \times 10^{-4}$	$0.0241 \pm 3.0 \times 10^{-3}$
	Service $s = 2$			
0%	$0.004 \pm 1.6 \times 10^{-3}$	$0.016 \pm 5.2 \times 10^{-3}$	$0.0040 \pm 1.5 \times 10^{-3}$	$0.014 \pm 2.6 \times 10^{-3}$
10%	$0.011 \pm 1.5 \times 10^{-3}$	$0.034 \pm 3.1 \times 10^{-3}$	$0.0111 \pm 1.8 \times 10^{-3}$	$0.030 \pm 7.6 \times 10^{-3}$
20%	$0.020 \pm 1.4 \times 10^{-3}$	$0.050 \pm 6.9 \times 10^{-3}$	$0.0196 \pm 9.6 \times 10^{-4}$	$0.048 \pm 5.3 \times 10^{-3}$
30%	$0.033 \pm 3.7 \times 10^{-3}$	$0.068 \pm 5.5 \times 10^{-3}$	$0.0321 \pm 3.9 \times 10^{-3}$	$0.068 \pm 1.2 \times 10^{-2}$
40%	$0.049 \pm 2.7 \times 10^{-3}$	$0.095 \pm 1.0 \times 10^{-2}$	$0.0468 \pm 2.3 \times 10^{-3}$	$0.095 \pm 1.8 \times 10^{-2}$
50%	$0.069 \pm 4.8 \times 10^{-3}$	$0.125 \pm 9.7 \times 10^{-3}$	$0.0659 \pm 3.6 \times 10^{-3}$	$0.116 \pm 1.0 \times 10^{-2}$
60%	$0.083 \pm 4.6 \times 10^{-3}$	$0.153 \pm 1.2 \times 10^{-2}$	$0.0795 \pm 2.8 \times 10^{-3}$	$0.150 \pm 1.3 \times 10^{-2}$
	Service $s = 3$			
0%	$0.008 \pm 3.5 \times 10^{-3}$	$0.028 \pm 1.3 \times 10^{-2}$	$0.008 \pm 2.7 \times 10^{-3}$	$0.035 \pm 3.6 \times 10^{-3}$
10%	$0.022 \pm 5.5 \times 10^{-3}$	$0.055 \pm 1.6 \times 10^{-2}$	$0.023 \pm 5.1 \times 10^{-3}$	$0.063 \pm 7.3 \times 10^{-3}$
20%	$0.038 \pm 3.1 \times 10^{-3}$	$0.089 \pm 1.3 \times 10^{-2}$	$0.041 \pm 1.8 \times 10^{-3}$	$0.106 \pm 2.6 \times 10^{-2}$
30%	$0.061 \pm 8.0 \times 10^{-3}$	$0.124 \pm 2.2 \times 10^{-2}$	$0.065 \pm 6.7 \times 10^{-3}$	$0.134 \pm 1.5 \times 10^{-2}$
40%	$0.091 \pm 4.6 \times 10^{-3}$	$0.183 \pm 2.2 \times 10^{-2}$	$0.092 \pm 5.3 \times 10^{-3}$	$0.196 \pm 3.0 \times 10^{-2}$
50%	$0.122 \pm 6.6 \times 10^{-3}$	$0.216 \pm 1.7 \times 10^{-2}$	$0.127 \pm 7.8 \times 10^{-3}$	$0.233 \pm 3.8 \times 10^{-2}$
60%	$0.146 \pm 4.0 \times 10^{-3}$	$0.252 \pm 1.1 \times 10^{-2}$	$0.151 \pm 6.3 \times 10^{-3}$	$0.272 \pm 2.0 \times 10^{-2}$

Table A.24: Network M - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.8, and $b = 0.9$.

Overload Factor	SMODR (Network M) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$< 10^{-4}$	$0.0014 \pm 5.6 \times 10^{-4}$	$< 10^{-4}$	$0.0020 \pm 3.5 \times 10^{-4}$
10%	$0.0003 \pm 9.9 \times 10^{-5}$	$0.0040 \pm 1.4 \times 10^{-3}$	$0.0003 \pm 5.9 \times 10^{-5}$	$0.0040 \pm 7.2 \times 10^{-4}$
20%	$0.0015 \pm 2.3 \times 10^{-4}$	$0.0105 \pm 1.8 \times 10^{-3}$	$0.0016 \pm 2.0 \times 10^{-4}$	$0.0093 \pm 2.1 \times 10^{-3}$
30%	$0.0033 \pm 2.2 \times 10^{-4}$	$0.0157 \pm 2.8 \times 10^{-3}$	$0.0035 \pm 3.1 \times 10^{-4}$	$0.0169 \pm 2.6 \times 10^{-3}$
40%	$0.0059 \pm 3.0 \times 10^{-4}$	$0.0207 \pm 2.1 \times 10^{-3}$	$0.0063 \pm 3.3 \times 10^{-4}$	$0.0258 \pm 4.7 \times 10^{-3}$
50%	$0.0083 \pm 5.9 \times 10^{-4}$	$0.0300 \pm 4.0 \times 10^{-3}$	$0.0087 \pm 6.8 \times 10^{-4}$	$0.0310 \pm 3.8 \times 10^{-3}$
60%	$0.0110 \pm 3.9 \times 10^{-4}$	$0.0364 \pm 2.6 \times 10^{-3}$	$0.0115 \pm 3.3 \times 10^{-4}$	$0.0405 \pm 9.2 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 2.5 \times 10^{-4}$	$0.015 \pm 4.6 \times 10^{-3}$	$0.001 \pm 2.5 \times 10^{-4}$	$0.014 \pm 5.4 \times 10^{-3}$
10%	$0.003 \pm 5.7 \times 10^{-4}$	$0.031 \pm 7.6 \times 10^{-3}$	$0.003 \pm 7.6 \times 10^{-4}$	$0.031 \pm 6.5 \times 10^{-3}$
20%	$0.010 \pm 1.1 \times 10^{-3}$	$0.056 \pm 4.6 \times 10^{-3}$	$0.011 \pm 1.4 \times 10^{-3}$	$0.054 \pm 5.0 \times 10^{-3}$
30%	$0.023 \pm 2.4 \times 10^{-3}$	$0.097 \pm 1.4 \times 10^{-2}$	$0.023 \pm 1.7 \times 10^{-3}$	$0.097 \pm 9.6 \times 10^{-3}$
40%	$0.040 \pm 2.1 \times 10^{-3}$	$0.128 \pm 9.7 \times 10^{-3}$	$0.041 \pm 2.9 \times 10^{-3}$	$0.139 \pm 3.7 \times 10^{-2}$
50%	$0.057 \pm 3.9 \times 10^{-3}$	$0.158 \pm 7.9 \times 10^{-3}$	$0.056 \pm 3.9 \times 10^{-3}$	$0.167 \pm 1.8 \times 10^{-2}$
60%	$0.073 \pm 1.6 \times 10^{-3}$	$0.193 \pm 1.7 \times 10^{-2}$	$0.072 \pm 1.6 \times 10^{-3}$	$0.207 \pm 1.5 \times 10^{-2}$
	Service $s = 3$			
0%	$0.002 \pm 8.4 \times 10^{-4}$	$0.034 \pm 1.2 \times 10^{-2}$	$0.002 \pm 6.5 \times 10^{-4}$	$0.035 \pm 3.0 \times 10^{-2}$
10%	$0.004 \pm 1.2 \times 10^{-3}$	$0.049 \pm 5.6 \times 10^{-3}$	$0.005 \pm 1.0 \times 10^{-3}$	$0.056 \pm 1.5 \times 10^{-2}$
20%	$0.018 \pm 2.0 \times 10^{-3}$	$0.100 \pm 1.8 \times 10^{-2}$	$0.017 \pm 2.3 \times 10^{-3}$	$0.117 \pm 2.8 \times 10^{-2}$
30%	$0.038 \pm 4.1 \times 10^{-3}$	$0.163 \pm 3.2 \times 10^{-2}$	$0.040 \pm 2.5 \times 10^{-3}$	$0.181 \pm 2.3 \times 10^{-2}$
40%	$0.069 \pm 3.7 \times 10^{-3}$	$0.220 \pm 4.1 \times 10^{-2}$	$0.071 \pm 4.4 \times 10^{-3}$	$0.235 \pm 2.8 \times 10^{-2}$
50%	$0.097 \pm 6.7 \times 10^{-3}$	$0.268 \pm 2.4 \times 10^{-2}$	$0.098 \pm 5.8 \times 10^{-3}$	$0.297 \pm 4.5 \times 10^{-2}$
60%	$0.123 \pm 2.3 \times 10^{-3}$	$0.328 \pm 4.1 \times 10^{-2}$	$0.125 \pm 2.6 \times 10^{-3}$	$0.357 \pm 4.3 \times 10^{-2}$

Table A.25: Network M - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.9, and $b = 0.9$.

Overload Factor	SMODR (Network M) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$< 10^{-4}$	$0.0014 \pm 3.3 \times 10^{-4}$	$< 10^{-4}$	$0.0016 \pm 2.7 \times 10^{-4}$
10%	$0.0003 \pm 7.9 \times 10^{-5}$	$0.0041 \pm 1.1 \times 10^{-3}$	$0.0003 \pm 7.0 \times 10^{-5}$	$0.0040 \pm 1.0 \times 10^{-3}$
20%	$0.0013 \pm 1.6 \times 10^{-4}$	$0.0086 \pm 1.8 \times 10^{-3}$	$0.0014 \pm 2.4 \times 10^{-4}$	$0.0083 \pm 1.5 \times 10^{-3}$
30%	$0.0030 \pm 3.7 \times 10^{-4}$	$0.0160 \pm 3.0 \times 10^{-3}$	$0.0031 \pm 3.3 \times 10^{-4}$	$0.0174 \pm 3.9 \times 10^{-3}$
40%	$0.0053 \pm 3.0 \times 10^{-4}$	$0.0222 \pm 1.0 \times 10^{-3}$	$0.0057 \pm 4.0 \times 10^{-4}$	$0.0218 \pm 5.6 \times 10^{-3}$
50%	$0.0077 \pm 6.5 \times 10^{-4}$	$0.0262 \pm 1.3 \times 10^{-3}$	$0.0081 \pm 5.2 \times 10^{-4}$	$0.0280 \pm 3.0 \times 10^{-3}$
60%	$0.0101 \pm 1.4 \times 10^{-4}$	$0.0312 \pm 2.8 \times 10^{-3}$	$0.0105 \pm 6.7 \times 10^{-4}$	$0.0329 \pm 2.5 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 2.7 \times 10^{-4}$	$0.016 \pm 7.6 \times 10^{-3}$	$0.001 \pm 2.3 \times 10^{-4}$	$0.017 \pm 7.7 \times 10^{-3}$
10%	$0.003 \pm 6.0 \times 10^{-4}$	$0.028 \pm 6.2 \times 10^{-3}$	$0.003 \pm 8.1 \times 10^{-4}$	$0.033 \pm 8.6 \times 10^{-3}$
20%	$0.010 \pm 9.4 \times 10^{-4}$	$0.055 \pm 1.2 \times 10^{-2}$	$0.010 \pm 1.6 \times 10^{-3}$	$0.053 \pm 1.1 \times 10^{-2}$
30%	$0.021 \pm 1.9 \times 10^{-3}$	$0.096 \pm 1.1 \times 10^{-2}$	$0.020 \pm 2.1 \times 10^{-3}$	$0.099 \pm 1.9 \times 10^{-2}$
40%	$0.037 \pm 2.0 \times 10^{-3}$	$0.128 \pm 1.5 \times 10^{-2}$	$0.037 \pm 2.3 \times 10^{-3}$	$0.118 \pm 3.0 \times 10^{-2}$
50%	$0.053 \pm 3.6 \times 10^{-3}$	$0.161 \pm 1.2 \times 10^{-2}$	$0.051 \pm 4.2 \times 10^{-3}$	$0.156 \pm 1.0 \times 10^{-2}$
60%	$0.067 \pm 1.3 \times 10^{-3}$	$0.193 \pm 1.5 \times 10^{-2}$	$0.067 \pm 1.9 \times 10^{-3}$	$0.192 \pm 1.1 \times 10^{-2}$
	Service $s = 3$			
0%	$0.002 \pm 7.5 \times 10^{-4}$	$0.035 \pm 8.1 \times 10^{-3}$	$0.002 \pm 6.6 \times 10^{-4}$	$0.032 \pm 1.2 \times 10^{-2}$
10%	$0.005 \pm 1.1 \times 10^{-3}$	$0.052 \pm 4.7 \times 10^{-3}$	$0.005 \pm 1.1 \times 10^{-3}$	$0.061 \pm 1.6 \times 10^{-2}$
20%	$0.017 \pm 1.7 \times 10^{-3}$	$0.100 \pm 1.9 \times 10^{-2}$	$0.016 \pm 2.3 \times 10^{-3}$	$0.109 \pm 2.3 \times 10^{-2}$
30%	$0.035 \pm 3.5 \times 10^{-3}$	$0.171 \pm 2.6 \times 10^{-2}$	$0.036 \pm 3.2 \times 10^{-3}$	$0.179 \pm 1.9 \times 10^{-2}$
40%	$0.064 \pm 4.3 \times 10^{-3}$	$0.220 \pm 1.2 \times 10^{-2}$	$0.065 \pm 2.8 \times 10^{-3}$	$0.216 \pm 2.6 \times 10^{-2}$
50%	$0.090 \pm 5.3 \times 10^{-3}$	$0.266 \pm 2.4 \times 10^{-2}$	$0.092 \pm 5.6 \times 10^{-3}$	$0.299 \pm 1.4 \times 10^{-2}$
60%	$0.115 \pm 2.3 \times 10^{-3}$	$0.324 \pm 2.6 \times 10^{-2}$	$0.117 \pm 3.7 \times 10^{-3}$	$0.340 \pm 3.5 \times 10^{-2}$

Table A.26: Network A - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.10, and $b = 0.9$.

Overload Factor	SMODR (Network A) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$0.0008 \pm 2.6 \times 10^{-4}$	$0.0033 \pm 2.9 \times 10^{-4}$	$0.0008 \pm 1.2 \times 10^{-4}$	$0.0043 \pm 1.2 \times 10^{-3}$
10%	$0.0019 \pm 3.4 \times 10^{-4}$	$0.0056 \pm 6.9 \times 10^{-4}$	$0.0020 \pm 3.3 \times 10^{-4}$	$0.0071 \pm 1.4 \times 10^{-3}$
20%	$0.0030 \pm 2.1 \times 10^{-4}$	$0.0086 \pm 1.9 \times 10^{-3}$	$0.0032 \pm 3.2 \times 10^{-4}$	$0.0082 \pm 7.8 \times 10^{-4}$
30%	$0.0050 \pm 6.3 \times 10^{-4}$	$0.0125 \pm 2.3 \times 10^{-3}$	$0.0053 \pm 5.6 \times 10^{-4}$	$0.0133 \pm 2.0 \times 10^{-3}$
40%	$0.0072 \pm 5.7 \times 10^{-4}$	$0.0155 \pm 1.5 \times 10^{-3}$	$0.0074 \pm 7.0 \times 10^{-4}$	$0.0165 \pm 2.7 \times 10^{-3}$
50%	$0.0099 \pm 4.2 \times 10^{-4}$	$0.0207 \pm 1.8 \times 10^{-3}$	$0.0105 \pm 9.1 \times 10^{-4}$	$0.0200 \pm 1.3 \times 10^{-3}$
60%	$0.0122 \pm 5.2 \times 10^{-4}$	$0.0243 \pm 3.7 \times 10^{-3}$	$0.0126 \pm 3.8 \times 10^{-4}$	$0.0255 \pm 2.6 \times 10^{-3}$
	Service $s = 2$			
0%	$0.004 \pm 1.7 \times 10^{-3}$	$0.014 \pm 2.5 \times 10^{-3}$	$0.0043 \pm 1.3 \times 10^{-3}$	$0.015 \pm 2.5 \times 10^{-3}$
10%	$0.012 \pm 1.7 \times 10^{-3}$	$0.034 \pm 1.0 \times 10^{-2}$	$0.0119 \pm 2.6 \times 10^{-3}$	$0.034 \pm 8.0 \times 10^{-3}$
20%	$0.020 \pm 8.8 \times 10^{-4}$	$0.052 \pm 5.7 \times 10^{-3}$	$0.0202 \pm 1.3 \times 10^{-3}$	$0.049 \pm 8.6 \times 10^{-3}$
30%	$0.033 \pm 3.7 \times 10^{-3}$	$0.073 \pm 1.0 \times 10^{-2}$	$0.0329 \pm 4.2 \times 10^{-3}$	$0.073 \pm 1.5 \times 10^{-2}$
40%	$0.048 \pm 4.3 \times 10^{-3}$	$0.094 \pm 1.1 \times 10^{-2}$	$0.0464 \pm 3.2 \times 10^{-3}$	$0.093 \pm 4.9 \times 10^{-3}$
50%	$0.067 \pm 2.6 \times 10^{-3}$	$0.134 \pm 9.6 \times 10^{-3}$	$0.0653 \pm 4.0 \times 10^{-3}$	$0.129 \pm 1.4 \times 10^{-2}$
60%	$0.081 \pm 3.6 \times 10^{-3}$	$0.151 \pm 1.5 \times 10^{-2}$	$0.0800 \pm 1.5 \times 10^{-3}$	$0.150 \pm 2.1 \times 10^{-2}$
	Service $s = 3$			
0%	$0.008 \pm 3.5 \times 10^{-3}$	$0.028 \pm 1.0 \times 10^{-2}$	$0.008 \pm 2.5 \times 10^{-3}$	$0.034 \pm 8.9 \times 10^{-3}$
10%	$0.021 \pm 4.1 \times 10^{-3}$	$0.056 \pm 8.8 \times 10^{-3}$	$0.023 \pm 3.7 \times 10^{-3}$	$0.065 \pm 1.1 \times 10^{-2}$
20%	$0.037 \pm 2.5 \times 10^{-3}$	$0.090 \pm 1.2 \times 10^{-2}$	$0.039 \pm 1.2 \times 10^{-3}$	$0.108 \pm 2.9 \times 10^{-2}$
30%	$0.060 \pm 7.8 \times 10^{-3}$	$0.127 \pm 2.1 \times 10^{-2}$	$0.063 \pm 6.4 \times 10^{-3}$	$0.144 \pm 1.6 \times 10^{-2}$
40%	$0.088 \pm 4.0 \times 10^{-3}$	$0.196 \pm 4.1 \times 10^{-2}$	$0.089 \pm 5.7 \times 10^{-3}$	$0.179 \pm 1.6 \times 10^{-2}$
50%	$0.118 \pm 4.6 \times 10^{-3}$	$0.220 \pm 3.6 \times 10^{-2}$	$0.122 \pm 8.4 \times 10^{-3}$	$0.230 \pm 2.7 \times 10^{-2}$
60%	$0.142 \pm 5.0 \times 10^{-3}$	$0.258 \pm 2.4 \times 10^{-2}$	$0.146 \pm 3.2 \times 10^{-3}$	$0.255 \pm 1.8 \times 10^{-2}$

Table A.27: Network A - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.11, and $b = 0.9$.

Overload Factor	SMODR (Network A) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$0.0009 \pm 2.4 \times 10^{-4}$	$0.0041 \pm 1.6 \times 10^{-3}$	$0.0010 \pm 3.2 \times 10^{-4}$	$0.0046 \pm 1.3 \times 10^{-3}$
10%	$0.0021 \pm 2.0 \times 10^{-4}$	$0.0076 \pm 2.2 \times 10^{-3}$	$0.0022 \pm 3.6 \times 10^{-4}$	$0.0070 \pm 1.0 \times 10^{-3}$
20%	$0.0033 \pm 2.7 \times 10^{-4}$	$0.0088 \pm 2.1 \times 10^{-3}$	$0.0033 \pm 2.0 \times 10^{-4}$	$0.0093 \pm 1.1 \times 10^{-3}$
30%	$0.0052 \pm 6.1 \times 10^{-4}$	$0.0120 \pm 1.5 \times 10^{-3}$	$0.0055 \pm 4.6 \times 10^{-4}$	$0.0141 \pm 2.5 \times 10^{-3}$
40%	$0.0075 \pm 4.5 \times 10^{-4}$	$0.0160 \pm 2.3 \times 10^{-3}$	$0.0078 \pm 5.4 \times 10^{-4}$	$0.0180 \pm 3.3 \times 10^{-3}$
50%	$0.0105 \pm 8.1 \times 10^{-4}$	$0.0213 \pm 3.3 \times 10^{-3}$	$0.0109 \pm 1.0 \times 10^{-3}$	$0.0205 \pm 1.6 \times 10^{-3}$
60%	$0.0129 \pm 6.5 \times 10^{-4}$	$0.0258 \pm 3.2 \times 10^{-3}$	$0.0134 \pm 6.8 \times 10^{-4}$	$0.0269 \pm 3.2 \times 10^{-3}$
	Service $s = 2$			
0%	$0.005 \pm 1.7 \times 10^{-3}$	$0.021 \pm 3.5 \times 10^{-3}$	$0.005 \pm 1.5 \times 10^{-3}$	$0.019 \pm 6.7 \times 10^{-3}$
10%	$0.012 \pm 2.0 \times 10^{-3}$	$0.036 \pm 1.0 \times 10^{-3}$	$0.012 \pm 2.3 \times 10^{-3}$	$0.036 \pm 1.2 \times 10^{-2}$
20%	$0.021 \pm 1.1 \times 10^{-3}$	$0.052 \pm 8.8 \times 10^{-3}$	$0.021 \pm 5.6 \times 10^{-4}$	$0.050 \pm 5.9 \times 10^{-3}$
30%	$0.034 \pm 4.1 \times 10^{-3}$	$0.072 \pm 6.5 \times 10^{-3}$	$0.034 \pm 3.6 \times 10^{-3}$	$0.073 \pm 9.8 \times 10^{-3}$
40%	$0.048 \pm 3.4 \times 10^{-3}$	$0.097 \pm 1.2 \times 10^{-2}$	$0.047 \pm 2.6 \times 10^{-3}$	$0.095 \pm 1.6 \times 10^{-2}$
50%	$0.067 \pm 4.0 \times 10^{-3}$	$0.124 \pm 1.2 \times 10^{-2}$	$0.066 \pm 4.6 \times 10^{-3}$	$0.122 \pm 1.2 \times 10^{-2}$
60%	$0.081 \pm 3.5 \times 10^{-3}$	$0.145 \pm 1.3 \times 10^{-2}$	$0.080 \pm 3.1 \times 10^{-3}$	$0.149 \pm 1.8 \times 10^{-2}$
	Service $s = 3$			
0%	$0.008 \pm 2.7 \times 10^{-3}$	$0.034 \pm 9.8 \times 10^{-3}$	$0.008 \pm 2.3 \times 10^{-3}$	$0.032 \pm 1.3 \times 10^{-2}$
10%	$0.021 \pm 4.8 \times 10^{-3}$	$0.058 \pm 1.4 \times 10^{-2}$	$0.023 \pm 4.1 \times 10^{-3}$	$0.066 \pm 1.4 \times 10^{-2}$
20%	$0.036 \pm 2.6 \times 10^{-3}$	$0.090 \pm 6.4 \times 10^{-3}$	$0.038 \pm 1.7 \times 10^{-3}$	$0.098 \pm 3.7 \times 10^{-2}$
30%	$0.058 \pm 6.3 \times 10^{-3}$	$0.137 \pm 1.3 \times 10^{-2}$	$0.058 \pm 6.1 \times 10^{-3}$	$0.140 \pm 2.3 \times 10^{-2}$
40%	$0.084 \pm 4.7 \times 10^{-3}$	$0.174 \pm 2.0 \times 10^{-2}$	$0.086 \pm 6.6 \times 10^{-3}$	$0.174 \pm 3.2 \times 10^{-2}$
50%	$0.114 \pm 7.0 \times 10^{-3}$	$0.209 \pm 1.9 \times 10^{-2}$	$0.116 \pm 6.6 \times 10^{-3}$	$0.213 \pm 1.4 \times 10^{-2}$
60%	$0.139 \pm 5.3 \times 10^{-3}$	$0.254 \pm 1.9 \times 10^{-2}$	$0.139 \pm 5.7 \times 10^{-3}$	$0.252 \pm 1.4 \times 10^{-2}$

Table A.28: Network M - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.10, and $b = 0.9$.

Overload Factor	SMODR (Network M) - ΔT=1m Heuristic 1		Heuristic 2	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0001 \pm 2.9 \times 10^{-5}$	$0.0038 \pm 1.0 \times 10^{-3}$	$0.0002 \pm 4.4 \times 10^{-5}$	$0.0038 \pm 1.3 \times 10^{-3}$
10%	$0.0004 \pm 1.1 \times 10^{-4}$	$0.0075 \pm 2.4 \times 10^{-3}$	$0.0005 \pm 1.3 \times 10^{-4}$	$0.0059 \pm 1.7 \times 10^{-3}$
20%	$0.0013 \pm 1.2 \times 10^{-4}$	$0.0095 \pm 1.6 \times 10^{-3}$	$0.0014 \pm 2.0 \times 10^{-4}$	$0.0085 \pm 1.4 \times 10^{-3}$
30%	$0.0026 \pm 2.1 \times 10^{-4}$	$0.0154 \pm 4.0 \times 10^{-3}$	$0.0028 \pm 3.7 \times 10^{-4}$	$0.0189 \pm 4.0 \times 10^{-3}$
40%	$0.0046 \pm 3.7 \times 10^{-4}$	$0.0185 \pm 2.6 \times 10^{-3}$	$0.0050 \pm 2.2 \times 10^{-4}$	$0.0216 \pm 2.7 \times 10^{-3}$
50%	$0.0068 \pm 4.8 \times 10^{-4}$	$0.0246 \pm 4.6 \times 10^{-3}$	$0.0071 \pm 8.1 \times 10^{-4}$	$0.0262 \pm 3.7 \times 10^{-3}$
60%	$0.0091 \pm 2.6 \times 10^{-4}$	$0.0283 \pm 2.7 \times 10^{-3}$	$0.0096 \pm 5.6 \times 10^{-4}$	$0.0302 \pm 2.8 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 2.7 \times 10^{-4}$	$0.017 \pm 8.5 \times 10^{-3}$	$0.001 \pm 2.6 \times 10^{-4}$	$0.022 \pm 3.2 \times 10^{-3}$
10%	$0.003 \pm 6.5 \times 10^{-4}$	$0.033 \pm 7.0 \times 10^{-3}$	$0.003 \pm 7.6 \times 10^{-4}$	$0.036 \pm 1.5 \times 10^{-2}$
20%	$0.009 \pm 9.7 \times 10^{-4}$	$0.053 \pm 7.2 \times 10^{-3}$	$0.009 \pm 9.7 \times 10^{-4}$	$0.053 \pm 1.5 \times 10^{-2}$
30%	$0.019 \pm 1.4 \times 10^{-3}$	$0.087 \pm 1.0 \times 10^{-2}$	$0.018 \pm 1.9 \times 10^{-3}$	$0.089 \pm 2.4 \times 10^{-2}$
40%	$0.033 \pm 2.5 \times 10^{-3}$	$0.110 \pm 1.9 \times 10^{-2}$	$0.032 \pm 1.8 \times 10^{-3}$	$0.125 \pm 2.3 \times 10^{-2}$
50%	$0.048 \pm 3.8 \times 10^{-3}$	$0.138 \pm 8.5 \times 10^{-3}$	$0.045 \pm 3.6 \times 10^{-3}$	$0.143 \pm 1.6 \times 10^{-2}$
60%	$0.062 \pm 8.8 \times 10^{-4}$	$0.172 \pm 2.2 \times 10^{-2}$	$0.060 \pm 2.0 \times 10^{-3}$	$0.168 \pm 2.1 \times 10^{-2}$
	Service $s = 3$			
0%	$0.002 \pm 7.8 \times 10^{-4}$	$0.037 \pm 8.1 \times 10^{-3}$	$0.002 \pm 6.0 \times 10^{-4}$	$0.043 \pm 2.2 \times 10^{-2}$
10%	$0.005 \pm 1.3 \times 10^{-3}$	$0.050 \pm 5.7 \times 10^{-3}$	$0.005 \pm 1.3 \times 10^{-3}$	$0.067 \pm 1.8 \times 10^{-2}$
20%	$0.017 \pm 1.5 \times 10^{-3}$	$0.099 \pm 2.0 \times 10^{-2}$	$0.017 \pm 1.5 \times 10^{-3}$	$0.102 \pm 1.8 \times 10^{-2}$
30%	$0.034 \pm 2.7 \times 10^{-3}$	$0.152 \pm 1.9 \times 10^{-2}$	$0.035 \pm 3.1 \times 10^{-3}$	$0.160 \pm 3.7 \times 10^{-2}$
40%	$0.059 \pm 3.5 \times 10^{-3}$	$0.190 \pm 3.2 \times 10^{-2}$	$0.060 \pm 2.0 \times 10^{-3}$	$0.222 \pm 5.9 \times 10^{-2}$
50%	$0.084 \pm 5.1 \times 10^{-3}$	$0.251 \pm 1.5 \times 10^{-2}$	$0.085 \pm 5.9 \times 10^{-3}$	$0.268 \pm 1.6 \times 10^{-2}$
60%	$0.107 \pm 2.8 \times 10^{-3}$	$0.296 \pm 2.2 \times 10^{-2}$	$0.108 \pm 2.1 \times 10^{-3}$	$0.293 \pm 1.8 \times 10^{-2}$

Table A.29: Network M - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.11, and $b = 0.9$.

Overload Factor	SMODR (Network M) - ΔT=1m Heuristic 1		Heuristic 2	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0002 \pm 3.5 \times 10^{-5}$	$0.0039 \pm 8.0 \times 10^{-4}$	$0.0002 \pm 4.8 \times 10^{-5}$	$0.0061 \pm 3.0 \times 10^{-4}$
10%	$0.0005 \pm 8.7 \times 10^{-5}$	$0.0070 \pm 6.9 \times 10^{-4}$	$0.0005 \pm 1.3 \times 10^{-4}$	$0.0062 \pm 1.9 \times 10^{-3}$
20%	$0.0013 \pm 1.1 \times 10^{-4}$	$0.0124 \pm 3.4 \times 10^{-3}$	$0.0015 \pm 2.1 \times 10^{-4}$	$0.0105 \pm 1.3 \times 10^{-3}$
30%	$0.0027 \pm 1.8 \times 10^{-4}$	$0.0152 \pm 4.5 \times 10^{-3}$	$0.0029 \pm 3.2 \times 10^{-4}$	$0.0176 \pm 5.3 \times 10^{-3}$
40%	$0.0048 \pm 3.2 \times 10^{-4}$	$0.0186 \pm 2.8 \times 10^{-3}$	$0.0052 \pm 4.1 \times 10^{-4}$	$0.0194 \pm 2.8 \times 10^{-3}$
50%	$0.0070 \pm 4.6 \times 10^{-4}$	$0.0233 \pm 1.2 \times 10^{-3}$	$0.0073 \pm 5.3 \times 10^{-4}$	$0.0248 \pm 1.3 \times 10^{-3}$
60%	$0.0093 \pm 3.0 \times 10^{-4}$	$0.0284 \pm 3.2 \times 10^{-3}$	$0.0098 \pm 4.1 \times 10^{-4}$	$0.0317 \pm 5.3 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 2.9 \times 10^{-4}$	$0.020 \pm 6.8 \times 10^{-3}$	$0.001 \pm 2.5 \times 10^{-4}$	$0.023 \pm 4.7 \times 10^{-3}$
10%	$0.003 \pm 5.8 \times 10^{-4}$	$0.039 \pm 1.5 \times 10^{-2}$	$0.003 \pm 7.2 \times 10^{-4}$	$0.038 \pm 1.0 \times 10^{-2}$
20%	$0.009 \pm 6.2 \times 10^{-4}$	$0.058 \pm 1.9 \times 10^{-2}$	$0.009 \pm 8.9 \times 10^{-4}$	$0.057 \pm 1.2 \times 10^{-2}$
30%	$0.019 \pm 1.5 \times 10^{-3}$	$0.091 \pm 1.5 \times 10^{-2}$	$0.018 \pm 1.9 \times 10^{-3}$	$0.098 \pm 2.7 \times 10^{-2}$
40%	$0.033 \pm 1.7 \times 10^{-3}$	$0.106 \pm 1.6 \times 10^{-2}$	$0.032 \pm 2.5 \times 10^{-3}$	$0.118 \pm 1.6 \times 10^{-2}$
50%	$0.047 \pm 2.7 \times 10^{-3}$	$0.136 \pm 1.2 \times 10^{-2}$	$0.045 \pm 3.5 \times 10^{-3}$	$0.146 \pm 1.5 \times 10^{-2}$
60%	$0.061 \pm 1.5 \times 10^{-3}$	$0.161 \pm 1.3 \times 10^{-2}$	$0.059 \pm 2.1 \times 10^{-3}$	$0.174 \pm 2.0 \times 10^{-2}$
	Service $s = 3$			
0%	$0.002 \pm 7.8 \times 10^{-4}$	$0.036 \pm 1.4 \times 10^{-2}$	$0.002 \pm 6.8 \times 10^{-4}$	$0.045 \pm 1.7 \times 10^{-2}$
10%	$0.005 \pm 1.3 \times 10^{-3}$	$0.057 \pm 4.7 \times 10^{-3}$	$0.005 \pm 1.1 \times 10^{-3}$	$0.065 \pm 1.3 \times 10^{-2}$
20%	$0.016 \pm 1.3 \times 10^{-3}$	$0.107 \pm 2.5 \times 10^{-2}$	$0.016 \pm 2.3 \times 10^{-3}$	$0.111 \pm 2.1 \times 10^{-2}$
30%	$0.033 \pm 2.3 \times 10^{-3}$	$0.150 \pm 1.5 \times 10^{-2}$	$0.034 \pm 3.4 \times 10^{-3}$	$0.159 \pm 2.8 \times 10^{-2}$
40%	$0.058 \pm 3.2 \times 10^{-3}$	$0.198 \pm 4.8 \times 10^{-2}$	$0.060 \pm 2.2 \times 10^{-3}$	$0.220 \pm 4.9 \times 10^{-2}$
50%	$0.082 \pm 5.5 \times 10^{-3}$	$0.236 \pm 2.0 \times 10^{-2}$	$0.084 \pm 5.5 \times 10^{-3}$	$0.239 \pm 2.3 \times 10^{-2}$
60%	$0.105 \pm 3.2 \times 10^{-3}$	$0.295 \pm 1.9 \times 10^{-2}$	$0.107 \pm 2.5 \times 10^{-3}$	$0.282 \pm 2.4 \times 10^{-2}$

Table A.30: Network A - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.12, and $b = 0.9$.

Overload Factor	SMODR (Network A) - ΔT=1m Heuristic 1		Heuristic 2	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0011 \pm 3.6 \times 10^{-4}$	$0.0046 \pm 1.4 \times 10^{-3}$	$0.0011 \pm 1.7 \times 10^{-4}$	$0.0046 \pm 7.6 \times 10^{-4}$
10%	$0.0022 \pm 2.8 \times 10^{-4}$	$0.0074 \pm 2.3 \times 10^{-3}$	$0.0023 \pm 3.1 \times 10^{-4}$	$0.0076 \pm 9.3 \times 10^{-4}$
20%	$0.0033 \pm 2.9 \times 10^{-4}$	$0.0113 \pm 3.8 \times 10^{-3}$	$0.0034 \pm 3.7 \times 10^{-4}$	$0.0099 \pm 1.7 \times 10^{-3}$
30%	$0.0053 \pm 5.0 \times 10^{-4}$	$0.0130 \pm 1.4 \times 10^{-3}$	$0.0054 \pm 4.4 \times 10^{-4}$	$0.0147 \pm 2.8 \times 10^{-3}$
40%	$0.0073 \pm 6.9 \times 10^{-4}$	$0.0168 \pm 2.2 \times 10^{-3}$	$0.0074 \pm 5.8 \times 10^{-4}$	$0.0166 \pm 1.7 \times 10^{-3}$
50%	$0.0100 \pm 6.8 \times 10^{-4}$	$0.0184 \pm 1.7 \times 10^{-3}$	$0.0101 \pm 4.9 \times 10^{-4}$	$0.0185 \pm 2.1 \times 10^{-3}$
60%	$0.0122 \pm 7.9 \times 10^{-4}$	$0.0233 \pm 2.3 \times 10^{-3}$	$0.0124 \pm 6.5 \times 10^{-4}$	$0.0236 \pm 1.1 \times 10^{-3}$
	Service $s = 2$			
0%	$0.006 \pm 1.9 \times 10^{-3}$	$0.025 \pm 4.3 \times 10^{-3}$	$0.007 \pm 1.6 \times 10^{-3}$	$0.025 \pm 5.4 \times 10^{-3}$
10%	$0.014 \pm 1.8 \times 10^{-3}$	$0.044 \pm 9.4 \times 10^{-3}$	$0.014 \pm 2.1 \times 10^{-3}$	$0.042 \pm 1.2 \times 10^{-2}$
20%	$0.021 \pm 1.2 \times 10^{-3}$	$0.058 \pm 1.2 \times 10^{-2}$	$0.021 \pm 1.5 \times 10^{-3}$	$0.055 \pm 1.2 \times 10^{-2}$
30%	$0.033 \pm 3.6 \times 10^{-3}$	$0.078 \pm 1.2 \times 10^{-2}$	$0.032 \pm 3.8 \times 10^{-3}$	$0.076 \pm 8.7 \times 10^{-3}$
40%	$0.045 \pm 4.6 \times 10^{-3}$	$0.095 \pm 1.7 \times 10^{-2}$	$0.044 \pm 3.1 \times 10^{-3}$	$0.096 \pm 1.1 \times 10^{-2}$
50%	$0.062 \pm 3.3 \times 10^{-3}$	$0.115 \pm 6.9 \times 10^{-2}$	$0.061 \pm 5.0 \times 10^{-3}$	$0.119 \pm 7.9 \times 10^{-3}$
60%	$0.075 \pm 2.8 \times 10^{-3}$	$0.140 \pm 1.3 \times 10^{-2}$	$0.074 \pm 3.0 \times 10^{-3}$	$0.138 \pm 1.1 \times 10^{-2}$
	Service $s = 3$			
0%	$0.011 \pm 3.0 \times 10^{-3}$	$0.042 \pm 8.7 \times 10^{-3}$	$0.011 \pm 2.8 \times 10^{-3}$	$0.044 \pm 2.6 \times 10^{-3}$
10%	$0.022 \pm 3.8 \times 10^{-3}$	$0.068 \pm 2.0 \times 10^{-2}$	$0.024 \pm 3.6 \times 10^{-3}$	$0.073 \pm 1.5 \times 10^{-2}$
20%	$0.037 \pm 2.1 \times 10^{-3}$	$0.095 \pm 1.2 \times 10^{-2}$	$0.039 \pm 1.9 \times 10^{-3}$	$0.099 \pm 1.7 \times 10^{-2}$
30%	$0.055 \pm 5.5 \times 10^{-3}$	$0.136 \pm 2.9 \times 10^{-2}$	$0.057 \pm 6.8 \times 10^{-3}$	$0.128 \pm 2.4 \times 10^{-2}$
40%	$0.077 \pm 3.6 \times 10^{-3}$	$0.172 \pm 2.2 \times 10^{-2}$	$0.079 \pm 5.5 \times 10^{-3}$	$0.192 \pm 3.4 \times 10^{-2}$
50%	$0.104 \pm 4.6 \times 10^{-3}$	$0.196 \pm 2.0 \times 10^{-2}$	$0.107 \pm 4.1 \times 10^{-3}$	$0.201 \pm 1.7 \times 10^{-2}$
60%	$0.126 \pm 6.3 \times 10^{-3}$	$0.230 \pm 1.6 \times 10^{-2}$	$0.128 \pm 5.6 \times 10^{-3}$	$0.236 \pm 1.9 \times 10^{-2}$

Table A.31: Network M - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.12, and $b = 0.9$.

Overload Factor	SMODR (Network M) - ΔT=1m Heuristic 1		Heuristic 2	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0002 \pm 5.5 \times 10^{-5}$	$0.0050 \pm 1.7 \times 10^{-3}$	$0.0002 \pm 5.1 \times 10^{-5}$	$0.0048 \pm 8.3 \times 10^{-4}$
10%	$0.0005 \pm 9.6 \times 10^{-5}$	$0.0079 \pm 1.1 \times 10^{-3}$	$0.0005 \pm 9.1 \times 10^{-5}$	$0.0075 \pm 2.2 \times 10^{-3}$
20%	$0.0015 \pm 2.1 \times 10^{-4}$	$0.0102 \pm 2.7 \times 10^{-3}$	$0.0015 \pm 1.4 \times 10^{-4}$	$0.0115 \pm 2.8 \times 10^{-3}$
30%	$0.0029 \pm 2.7 \times 10^{-4}$	$0.0163 \pm 4.0 \times 10^{-3}$	$0.0030 \pm 3.6 \times 10^{-4}$	$0.0170 \pm 4.8 \times 10^{-3}$
40%	$0.0050 \pm 2.8 \times 10^{-4}$	$0.0183 \pm 1.1 \times 10^{-3}$	$0.0053 \pm 2.2 \times 10^{-4}$	$0.0198 \pm 3.9 \times 10^{-3}$
50%	$0.0074 \pm 4.4 \times 10^{-4}$	$0.0202 \pm 1.6 \times 10^{-3}$	$0.0073 \pm 4.6 \times 10^{-4}$	$0.0214 \pm 2.2 \times 10^{-3}$
60%	$0.0096 \pm 2.5 \times 10^{-4}$	$0.0263 \pm 2.0 \times 10^{-3}$	$0.0098 \pm 2.7 \times 10^{-4}$	$0.0252 \pm 3.0 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 3.9 \times 10^{-4}$	$0.024 \pm 6.1 \times 10^{-3}$	$0.001 \pm 3.2 \times 10^{-4}$	$0.030 \pm 6.9 \times 10^{-3}$
10%	$0.003 \pm 7.1 \times 10^{-4}$	$0.043 \pm 8.4 \times 10^{-3}$	$0.003 \pm 7.4 \times 10^{-4}$	$0.040 \pm 8.6 \times 10^{-3}$
20%	$0.010 \pm 8.8 \times 10^{-4}$	$0.061 \pm 1.3 \times 10^{-2}$	$0.009 \pm 5.5 \times 10^{-4}$	$0.065 \pm 1.6 \times 10^{-2}$
30%	$0.019 \pm 1.5 \times 10^{-3}$	$0.099 \pm 2.5 \times 10^{-2}$	$0.018 \pm 1.5 \times 10^{-3}$	$0.102 \pm 2.6 \times 10^{-2}$
40%	$0.032 \pm 1.7 \times 10^{-3}$	$0.108 \pm 9.0 \times 10^{-3}$	$0.032 \pm 1.7 \times 10^{-3}$	$0.108 \pm 6.9 \times 10^{-3}$
50%	$0.047 \pm 2.6 \times 10^{-3}$	$0.124 \pm 5.6 \times 10^{-3}$	$0.044 \pm 2.6 \times 10^{-3}$	$0.125 \pm 1.3 \times 10^{-2}$
60%	$0.060 \pm 1.8 \times 10^{-3}$	$0.147 \pm 1.2 \times 10^{-2}$	$0.058 \pm 1.3 \times 10^{-3}$	$0.145 \pm 8.8 \times 10^{-3}$
	Service $s = 3$			
0%	$0.002 \pm 8.0 \times 10^{-4}$	$0.044 \pm 1.4 \times 10^{-2}$	$0.002 \pm 8.7 \times 10^{-4}$	$0.048 \pm 1.5 \times 10^{-2}$
10%	$0.005 \pm 1.1 \times 10^{-3}$	$0.072 \pm 1.9 \times 10^{-2}$	$0.006 \pm 1.0 \times 10^{-3}$	$0.081 \pm 1.6 \times 10^{-2}$
20%	$0.016 \pm 1.8 \times 10^{-3}$	$0.111 \pm 2.2 \times 10^{-2}$	$0.016 \pm 1.9 \times 10^{-3}$	$0.125 \pm 1.9 \times 10^{-2}$
30%	$0.032 \pm 2.2 \times 10^{-3}$	$0.164 \pm 2.7 \times 10^{-2}$	$0.032 \pm 2.6 \times 10^{-3}$	$0.157 \pm 2.8 \times 10^{-2}$
40%	$0.055 \pm 2.4 \times 10^{-3}$	$0.190 \pm 2.6 \times 10^{-2}$	$0.056 \pm 3.0 \times 10^{-3}$	$0.189 \pm 3.2 \times 10^{-2}$
50%	$0.079 \pm 5.4 \times 10^{-3}$	$0.209 \pm 1.9 \times 10^{-2}$	$0.080 \pm 5.8 \times 10^{-3}$	$0.233 \pm 1.1 \times 10^{-2}$
60%	$0.102 \pm 2.7 \times 10^{-3}$	$0.249 \pm 2.7 \times 10^{-2}$	$0.102 \pm 2.2 \times 10^{-3}$	$0.248 \pm 2.5 \times 10^{-2}$

Table A.32: Service performance simulations results for direct routing.

Overload Factor	Network A		Network M	
	DIRECT ROUTING			
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$0.0025 \pm 3.8 \times 10^{-4}$	$0.0119 \pm 3.6 \times 10^{-3}$	$0.0007 \pm 1.5 \times 10^{-4}$	$0.0111 \pm 2.8 \times 10^{-3}$
10%	$0.0032 \pm 3.9 \times 10^{-4}$	$0.0133 \pm 3.2 \times 10^{-3}$	$0.0012 \pm 1.4 \times 10^{-4}$	$0.0129 \pm 2.5 \times 10^{-3}$
20%	$0.0041 \pm 2.9 \times 10^{-4}$	$0.0137 \pm 2.1 \times 10^{-3}$	$0.0022 \pm 2.0 \times 10^{-4}$	$0.0135 \pm 2.3 \times 10^{-3}$
30%	$0.0057 \pm 2.7 \times 10^{-4}$	$0.0181 \pm 2.4 \times 10^{-3}$	$0.0034 \pm 2.6 \times 10^{-4}$	$0.0157 \pm 4.8 \times 10^{-3}$
40%	$0.0075 \pm 4.7 \times 10^{-4}$	$0.0191 \pm 3.4 \times 10^{-3}$	$0.0052 \pm 1.6 \times 10^{-4}$	$0.0164 \pm 3.9 \times 10^{-3}$
50%	$0.0098 \pm 6.2 \times 10^{-4}$	$0.0216 \pm 7.2 \times 10^{-4}$	$0.0071 \pm 5.2 \times 10^{-4}$	$0.0193 \pm 2.9 \times 10^{-3}$
60%	$0.0119 \pm 5.5 \times 10^{-4}$	$0.0252 \pm 2.7 \times 10^{-3}$	$0.0093 \pm 2.9 \times 10^{-4}$	$0.0222 \pm 2.3 \times 10^{-3}$
	Service $s = 2$			
0%	$0.016 \pm 2.0 \times 10^{-3}$	$0.069 \pm 1.9 \times 10^{-2}$	$0.004 \pm 8.2 \times 10^{-4}$	$0.067 \pm 1.3 \times 10^{-2}$
10%	$0.021 \pm 2.6 \times 10^{-3}$	$0.085 \pm 1.7 \times 10^{-2}$	$0.008 \pm 1.0 \times 10^{-3}$	$0.080 \pm 1.9 \times 10^{-2}$
20%	$0.026 \pm 9.2 \times 10^{-4}$	$0.085 \pm 9.8 \times 10^{-3}$	$0.013 \pm 6.9 \times 10^{-4}$	$0.077 \pm 1.7 \times 10^{-2}$
30%	$0.036 \pm 2.6 \times 10^{-3}$	$0.101 \pm 1.7 \times 10^{-2}$	$0.020 \pm 1.3 \times 10^{-3}$	$0.103 \pm 2.3 \times 10^{-2}$
40%	$0.046 \pm 2.8 \times 10^{-3}$	$0.120 \pm 1.3 \times 10^{-2}$	$0.031 \pm 1.2 \times 10^{-3}$	$0.098 \pm 1.0 \times 10^{-2}$
50%	$0.060 \pm 3.7 \times 10^{-3}$	$0.125 \pm 1.4 \times 10^{-2}$	$0.043 \pm 3.3 \times 10^{-3}$	$0.121 \pm 1.6 \times 10^{-2}$
60%	$0.071 \pm 1.6 \times 10^{-3}$	$0.153 \pm 1.3 \times 10^{-2}$	$0.055 \pm 1.4 \times 10^{-3}$	$0.132 \pm 2.1 \times 10^{-2}$
	Service $s = 3$			
0%	$0.027 \pm 3.4 \times 10^{-3}$	$0.133 \pm 2.5 \times 10^{-2}$	$0.008 \pm 1.4 \times 10^{-3}$	$0.124 \pm 1.1 \times 10^{-2}$
10%	$0.036 \pm 3.7 \times 10^{-3}$	$0.144 \pm 2.0 \times 10^{-2}$	$0.013 \pm 1.5 \times 10^{-3}$	$0.142 \pm 3.6 \times 10^{-2}$
20%	$0.046 \pm 1.9 \times 10^{-3}$	$0.155 \pm 1.3 \times 10^{-2}$	$0.022 \pm 1.5 \times 10^{-3}$	$0.149 \pm 1.6 \times 10^{-2}$
30%	$0.060 \pm 5.3 \times 10^{-3}$	$0.182 \pm 3.7 \times 10^{-2}$	$0.034 \pm 2.1 \times 10^{-3}$	$0.169 \pm 3.2 \times 10^{-2}$
40%	$0.078 \pm 3.1 \times 10^{-3}$	$0.208 \pm 3.0 \times 10^{-2}$	$0.052 \pm 2.2 \times 10^{-3}$	$0.171 \pm 1.8 \times 10^{-2}$
50%	$0.100 \pm 4.8 \times 10^{-3}$	$0.222 \pm 1.8 \times 10^{-2}$	$0.071 \pm 4.7 \times 10^{-3}$	$0.187 \pm 9.6 \times 10^{-3}$
60%	$0.120 \pm 4.9 \times 10^{-3}$	$0.244 \pm 2.7 \times 10^{-2}$	$0.090 \pm 2.3 \times 10^{-3}$	$0.234 \pm 2.1 \times 10^{-2}$

Table A.33: Network A - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.13, and $b = 0.9$.

Overload Factor	SMODR (Network A) - ΔT=1m			
	Heuristic 1		Heuristic 2	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$0.0003 \pm 1.5 \times 10^{-4}$	$0.0014 \pm 6.4 \times 10^{-4}$	$0.0016 \pm 3.2 \times 10^{-4}$	$0.0187 \pm 5.3 \times 10^{-3}$
10%	$0.0011 \pm 1.8 \times 10^{-4}$	$0.0040 \pm 7.1 \times 10^{-4}$	$0.0024 \pm 2.5 \times 10^{-4}$	$0.0225 \pm 4.4 \times 10^{-3}$
20%	$0.0019 \pm 8.5 \times 10^{-5}$	$0.0056 \pm 1.1 \times 10^{-3}$	$0.0035 \pm 4.2 \times 10^{-4}$	$0.0253 \pm 3.7 \times 10^{-3}$
30%	$0.0036 \pm 3.7 \times 10^{-4}$	$0.0085 \pm 1.0 \times 10^{-3}$	$0.0054 \pm 2.4 \times 10^{-4}$	$0.0344 \pm 3.2 \times 10^{-3}$
40%	$0.0057 \pm 7.1 \times 10^{-4}$	$0.0126 \pm 1.3 \times 10^{-3}$	$0.0074 \pm 4.6 \times 10^{-4}$	$0.0390 \pm 5.5 \times 10^{-3}$
50%	$0.0083 \pm 5.8 \times 10^{-4}$	$0.0173 \pm 1.7 \times 10^{-3}$	$0.0103 \pm 8.5 \times 10^{-4}$	$0.0453 \pm 2.1 \times 10^{-3}$
60%	$0.0106 \pm 5.1 \times 10^{-4}$	$0.0223 \pm 3.5 \times 10^{-3}$	$0.0127 \pm 6.4 \times 10^{-4}$	$0.0554 \pm 4.0 \times 10^{-3}$
	Service $s = 2$			
0%	$0.004 \pm 1.6 \times 10^{-3}$	$0.015 \pm 4.7 \times 10^{-3}$	$0.010 \pm 1.7 \times 10^{-3}$	$0.109 \pm 2.7 \times 10^{-2}$
10%	$0.011 \pm 1.6 \times 10^{-3}$	$0.032 \pm 4.7 \times 10^{-3}$	$0.015 \pm 2.7 \times 10^{-3}$	$0.143 \pm 2.1 \times 10^{-2}$
20%	$0.019 \pm 1.2 \times 10^{-3}$	$0.050 \pm 6.4 \times 10^{-3}$	$0.023 \pm 1.5 \times 10^{-3}$	$0.150 \pm 8.2 \times 10^{-3}$
30%	$0.032 \pm 2.4 \times 10^{-3}$	$0.067 \pm 7.7 \times 10^{-3}$	$0.034 \pm 3.0 \times 10^{-3}$	$0.182 \pm 1.2 \times 10^{-2}$
40%	$0.048 \pm 5.2 \times 10^{-3}$	$0.099 \pm 1.3 \times 10^{-2}$	$0.047 \pm 2.8 \times 10^{-3}$	$0.211 \pm 3.6 \times 10^{-2}$
50%	$0.066 \pm 4.6 \times 10^{-3}$	$0.128 \pm 8.7 \times 10^{-3}$	$0.066 \pm 4.2 \times 10^{-3}$	$0.241 \pm 2.6 \times 10^{-2}$
60%	$0.081 \pm 2.3 \times 10^{-3}$	$0.156 \pm 1.8 \times 10^{-2}$	$0.080 \pm 2.3 \times 10^{-3}$	$0.274 \pm 1.8 \times 10^{-2}$
	Service $s = 3$			
0%	$0.008 \pm 3.1 \times 10^{-3}$	$0.036 \pm 1.7 \times 10^{-2}$	$0.016 \pm 2.4 \times 10^{-3}$	$0.176 \pm 4.5 \times 10^{-2}$
10%	$0.023 \pm 3.9 \times 10^{-3}$	$0.057 \pm 1.7 \times 10^{-2}$	$0.027 \pm 3.5 \times 10^{-3}$	$0.228 \pm 3.8 \times 10^{-2}$
20%	$0.039 \pm 8.7 \times 10^{-4}$	$0.096 \pm 1.3 \times 10^{-2}$	$0.039 \pm 2.4 \times 10^{-3}$	$0.246 \pm 2.7 \times 10^{-2}$
30%	$0.063 \pm 4.5 \times 10^{-3}$	$0.138 \pm 1.2 \times 10^{-2}$	$0.058 \pm 5.3 \times 10^{-3}$	$0.286 \pm 2.3 \times 10^{-2}$
40%	$0.091 \pm 6.4 \times 10^{-3}$	$0.211 \pm 3.9 \times 10^{-2}$	$0.083 \pm 4.1 \times 10^{-3}$	$0.351 \pm 6.7 \times 10^{-2}$
50%	$0.122 \pm 7.7 \times 10^{-3}$	$0.235 \pm 4.6 \times 10^{-2}$	$0.111 \pm 5.6 \times 10^{-3}$	$0.333 \pm 5.6 \times 10^{-2}$
60%	$0.147 \pm 5.2 \times 10^{-3}$	$0.258 \pm 1.2 \times 10^{-2}$	$0.136 \pm 5.8 \times 10^{-3}$	$0.408 \pm 3.9 \times 10^{-2}$

Table A.34: Network M - Service performance simulations results for SMODR (Heuristics 1 and 2) using path elimination criterion in eq. 4.13, and $b = 0.9$.

Overload Factor	SMODR (Network M) - ΔT=1m Heuristic 1		Heuristic 2	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$< 10^{-4}$	$0.0014 \pm 6.0 \times 10^{-4}$	$< 10^{-4}$	$0.0015 \pm 2.9 \times 10^{-4}$
10%	$0.0003 \pm 8.9 \times 10^{-5}$	$0.0038 \pm 1.3 \times 10^{-3}$	$0.0002 \pm 8.9 \times 10^{-5}$	$0.0033 \pm 1.2 \times 10^{-3}$
20%	$0.0010 \pm 1.5 \times 10^{-4}$	$0.0075 \pm 2.4 \times 10^{-3}$	$0.0011 \pm 1.5 \times 10^{-4}$	$0.0076 \pm 2.3 \times 10^{-3}$
30%	$0.0023 \pm 2.3 \times 10^{-4}$	$0.0127 \pm 2.1 \times 10^{-3}$	$0.0026 \pm 3.8 \times 10^{-4}$	$0.0161 \pm 6.9 \times 10^{-3}$
40%	$0.0043 \pm 3.8 \times 10^{-4}$	$0.0173 \pm 4.1 \times 10^{-3}$	$0.0047 \pm 2.2 \times 10^{-4}$	$0.0195 \pm 3.0 \times 10^{-3}$
50%	$0.0065 \pm 4.4 \times 10^{-4}$	$0.0223 \pm 2.7 \times 10^{-3}$	$0.0068 \pm 9.9 \times 10^{-4}$	$0.0262 \pm 3.9 \times 10^{-3}$
60%	$0.0087 \pm 3.5 \times 10^{-4}$	$0.0278 \pm 2.1 \times 10^{-3}$	$0.0093 \pm 3.9 \times 10^{-4}$	$0.0313 \pm 3.7 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 3.0 \times 10^{-4}$	$0.016 \pm 7.3 \times 10^{-3}$	$0.001 \pm 1.7 \times 10^{-4}$	$0.016 \pm 6.8 \times 10^{-3}$
10%	$0.003 \pm 5.7 \times 10^{-4}$	$0.030 \pm 8.3 \times 10^{-3}$	$0.003 \pm 7.7 \times 10^{-4}$	$0.025 \pm 5.7 \times 10^{-3}$
20%	$0.009 \pm 8.0 \times 10^{-4}$	$0.051 \pm 1.3 \times 10^{-2}$	$0.009 \pm 6.4 \times 10^{-4}$	$0.051 \pm 1.4 \times 10^{-2}$
30%	$0.018 \pm 1.5 \times 10^{-3}$	$0.089 \pm 2.8 \times 10^{-2}$	$0.018 \pm 2.0 \times 10^{-3}$	$0.088 \pm 3.0 \times 10^{-2}$
40%	$0.032 \pm 2.3 \times 10^{-3}$	$0.110 \pm 1.2 \times 10^{-2}$	$0.031 \pm 2.3 \times 10^{-3}$	$0.103 \pm 7.3 \times 10^{-3}$
50%	$0.048 \pm 3.3 \times 10^{-3}$	$0.144 \pm 1.8 \times 10^{-2}$	$0.045 \pm 3.3 \times 10^{-3}$	$0.148 \pm 2.1 \times 10^{-2}$
60%	$0.062 \pm 1.7 \times 10^{-3}$	$0.172 \pm 7.9 \times 10^{-3}$	$0.059 \pm 1.2 \times 10^{-3}$	$0.168 \pm 6.4 \times 10^{-3}$
	Service $s = 3$			
0%	$0.002 \pm 1.0 \times 10^{-3}$	$0.038 \pm 9.6 \times 10^{-3}$	$0.002 \pm 7.6 \times 10^{-4}$	$0.037 \pm 1.5 \times 10^{-2}$
10%	$0.005 \pm 1.3 \times 10^{-3}$	$0.057 \pm 9.3 \times 10^{-3}$	$0.005 \pm 1.2 \times 10^{-3}$	$0.067 \pm 1.5 \times 10^{-2}$
20%	$0.017 \pm 2.0 \times 10^{-3}$	$0.110 \pm 1.9 \times 10^{-2}$	$0.017 \pm 2.3 \times 10^{-3}$	$0.109 \pm 2.5 \times 10^{-2}$
30%	$0.034 \pm 2.6 \times 10^{-3}$	$0.169 \pm 4.0 \times 10^{-2}$	$0.036 \pm 3.7 \times 10^{-3}$	$0.173 \pm 2.0 \times 10^{-2}$
40%	$0.058 \pm 4.0 \times 10^{-3}$	$0.206 \pm 2.0 \times 10^{-2}$	$0.061 \pm 1.8 \times 10^{-3}$	$0.222 \pm 3.4 \times 10^{-2}$
50%	$0.084 \pm 5.5 \times 10^{-3}$	$0.256 \pm 4.1 \times 10^{-2}$	$0.085 \pm 5.2 \times 10^{-3}$	$0.279 \pm 3.4 \times 10^{-2}$
60%	$0.108 \pm 2.5 \times 10^{-3}$	$0.299 \pm 3.2 \times 10^{-2}$	$0.108 \pm 2.3 \times 10^{-3}$	$0.306 \pm 2.9 \times 10^{-2}$

Table A.35: Network A - Service performance simulations results for SMODR (Heuristic 1) using path elimination criterion in eq. 4.12, with $b = 0.1$ and $b = 0.5$.

Overload Factor	SMODR (Network A) - Eq. 4.12 - ΔT=1m $b = 0.1$		$b = 0.5$	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0009 \pm 2.9 \times 10^{-4}$	$0.0034 \pm 1.3 \times 10^{-3}$	$0.0010 \pm 2.9 \times 10^{-4}$	$0.0041 \pm 1.7 \times 10^{-3}$
10%	$0.0021 \pm 3.9 \times 10^{-4}$	$0.0068 \pm 1.9 \times 10^{-3}$	$0.0021 \pm 3.0 \times 10^{-4}$	$0.0063 \pm 9.9 \times 10^{-4}$
20%	$0.0033 \pm 3.1 \times 10^{-4}$	$0.0085 \pm 2.2 \times 10^{-3}$	$0.0033 \pm 2.3 \times 10^{-4}$	$0.0094 \pm 2.1 \times 10^{-3}$
30%	$0.0052 \pm 3.8 \times 10^{-4}$	$0.0136 \pm 3.2 \times 10^{-3}$	$0.0053 \pm 3.8 \times 10^{-4}$	$0.0129 \pm 1.6 \times 10^{-3}$
40%	$0.0071 \pm 5.7 \times 10^{-4}$	$0.0159 \pm 3.8 \times 10^{-3}$	$0.0073 \pm 6.6 \times 10^{-4}$	$0.0167 \pm 1.9 \times 10^{-3}$
50%	$0.0099 \pm 6.1 \times 10^{-4}$	$0.0184 \pm 1.0 \times 10^{-3}$	$0.0101 \pm 4.9 \times 10^{-4}$	$0.0195 \pm 8.8 \times 10^{-4}$
60%	$0.0119 \pm 6.1 \times 10^{-4}$	$0.0241 \pm 2.3 \times 10^{-3}$	$0.0119 \pm 4.9 \times 10^{-4}$	$0.0233 \pm 1.2 \times 10^{-3}$
	Service $s = 2$			
0%	$0.006 \pm 2.0 \times 10^{-3}$	$0.020 \pm 4.6 \times 10^{-3}$	$0.006 \pm 1.6 \times 10^{-3}$	$0.026 \pm 2.6 \times 10^{-3}$
10%	$0.014 \pm 2.3 \times 10^{-3}$	$0.038 \pm 1.0 \times 10^{-2}$	$0.013 \pm 2.3 \times 10^{-3}$	$0.042 \pm 8.1 \times 10^{-3}$
20%	$0.022 \pm 1.1 \times 10^{-3}$	$0.053 \pm 8.0 \times 10^{-3}$	$0.021 \pm 1.3 \times 10^{-3}$	$0.060 \pm 6.2 \times 10^{-3}$
30%	$0.033 \pm 3.5 \times 10^{-3}$	$0.076 \pm 1.0 \times 10^{-2}$	$0.032 \pm 3.2 \times 10^{-3}$	$0.075 \pm 1.2 \times 10^{-2}$
40%	$0.044 \pm 3.5 \times 10^{-3}$	$0.100 \pm 1.8 \times 10^{-2}$	$0.045 \pm 4.2 \times 10^{-3}$	$0.100 \pm 1.7 \times 10^{-2}$
50%	$0.060 \pm 4.1 \times 10^{-3}$	$0.116 \pm 9.7 \times 10^{-3}$	$0.061 \pm 3.4 \times 10^{-3}$	$0.120 \pm 1.6 \times 10^{-2}$
60%	$0.072 \pm 1.9 \times 10^{-3}$	$0.148 \pm 1.1 \times 10^{-2}$	$0.073 \pm 1.8 \times 10^{-3}$	$0.138 \pm 7.5 \times 10^{-3}$
	Service $s = 3$			
0%	$0.010 \pm 2.9 \times 10^{-3}$	$0.038 \pm 1.1 \times 10^{-2}$	$0.010 \pm 2.6 \times 10^{-3}$	$0.041 \pm 8.8 \times 10^{-3}$
10%	$0.024 \pm 4.4 \times 10^{-3}$	$0.065 \pm 1.1 \times 10^{-2}$	$0.023 \pm 3.4 \times 10^{-3}$	$0.064 \pm 5.4 \times 10^{-3}$
20%	$0.038 \pm 2.2 \times 10^{-3}$	$0.098 \pm 1.5 \times 10^{-2}$	$0.036 \pm 2.1 \times 10^{-3}$	$0.092 \pm 1.5 \times 10^{-2}$
30%	$0.056 \pm 5.3 \times 10^{-3}$	$0.124 \pm 3.1 \times 10^{-2}$	$0.054 \pm 4.0 \times 10^{-3}$	$0.131 \pm 1.7 \times 10^{-2}$
40%	$0.077 \pm 2.9 \times 10^{-3}$	$0.182 \pm 2.3 \times 10^{-2}$	$0.077 \pm 3.2 \times 10^{-3}$	$0.172 \pm 2.1 \times 10^{-2}$
50%	$0.101 \pm 5.8 \times 10^{-3}$	$0.196 \pm 1.8 \times 10^{-2}$	$0.104 \pm 3.2 \times 10^{-3}$	$0.193 \pm 2.8 \times 10^{-2}$
60%	$0.120 \pm 5.4 \times 10^{-3}$	$0.241 \pm 2.3 \times 10^{-2}$	$0.124 \pm 5.5 \times 10^{-3}$	$0.235 \pm 2.1 \times 10^{-2}$

Table A.36: Network M - Service performance simulations results for SMODR (Heuristic 1) using path elimination criterion in eq. 4.12, with $b = 0.1$ and $b = 0.5$.

Overload Factor	SMODR (Network M) - Eq. 4.12 - ΔT=1m, $b = 0.1$		$b = 0.5$	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0002 \pm 6.2 \times 10^{-5}$	$0.0034 \pm 1.0 \times 10^{-3}$	$0.0002 \pm 4.4 \times 10^{-5}$	$0.0046 \pm 1.8 \times 10^{-3}$
10%	$0.0004 \pm 9.8 \times 10^{-5}$	$0.0072 \pm 1.4 \times 10^{-3}$	$0.0005 \pm 7.4 \times 10^{-5}$	$0.0082 \pm 2.2 \times 10^{-3}$
20%	$0.0014 \pm 1.9 \times 10^{-4}$	$0.0100 \pm 2.2 \times 10^{-3}$	$0.0015 \pm 2.1 \times 10^{-4}$	$0.0104 \pm 1.7 \times 10^{-3}$
30%	$0.0029 \pm 1.9 \times 10^{-4}$	$0.0140 \pm 4.4 \times 10^{-3}$	$0.0029 \pm 1.6 \times 10^{-4}$	$0.0151 \pm 3.5 \times 10^{-3}$
40%	$0.0048 \pm 2.3 \times 10^{-4}$	$0.0149 \pm 4.1 \times 10^{-3}$	$0.0050 \pm 2.2 \times 10^{-4}$	$0.0177 \pm 4.2 \times 10^{-3}$
50%	$0.0069 \pm 4.7 \times 10^{-4}$	$0.0180 \pm 2.7 \times 10^{-3}$	$0.0071 \pm 5.4 \times 10^{-4}$	$0.0203 \pm 7.9 \times 10^{-4}$
60%	$0.0091 \pm 2.2 \times 10^{-4}$	$0.0210 \pm 2.1 \times 10^{-3}$	$0.0094 \pm 2.5 \times 10^{-4}$	$0.0233 \pm 2.7 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 3.8 \times 10^{-4}$	$0.025 \pm 7.8 \times 10^{-3}$	$0.001 \pm 3.5 \times 10^{-4}$	$0.026 \pm 4.0 \times 10^{-3}$
10%	$0.003 \pm 6.4 \times 10^{-4}$	$0.041 \pm 7.0 \times 10^{-3}$	$0.003 \pm 6.7 \times 10^{-4}$	$0.042 \pm 7.3 \times 10^{-3}$
20%	$0.010 \pm 9.7 \times 10^{-4}$	$0.052 \pm 8.5 \times 10^{-3}$	$0.010 \pm 1.1 \times 10^{-3}$	$0.058 \pm 1.3 \times 10^{-2}$
30%	$0.019 \pm 9.6 \times 10^{-4}$	$0.087 \pm 2.6 \times 10^{-2}$	$0.019 \pm 1.0 \times 10^{-3}$	$0.082 \pm 1.4 \times 10^{-2}$
40%	$0.031 \pm 1.5 \times 10^{-3}$	$0.090 \pm 1.4 \times 10^{-2}$	$0.032 \pm 1.9 \times 10^{-3}$	$0.096 \pm 1.4 \times 10^{-2}$
50%	$0.043 \pm 2.9 \times 10^{-3}$	$0.117 \pm 1.3 \times 10^{-2}$	$0.045 \pm 3.1 \times 10^{-3}$	$0.123 \pm 9.4 \times 10^{-3}$
60%	$0.055 \pm 1.1 \times 10^{-3}$	$0.129 \pm 2.0 \times 10^{-2}$	$0.058 \pm 1.4 \times 10^{-3}$	$0.133 \pm 1.6 \times 10^{-2}$
	Service $s = 3$			
0%	$0.002 \pm 7.1 \times 10^{-4}$	$0.048 \pm 1.3 \times 10^{-2}$	$0.002 \pm 7.7 \times 10^{-4}$	$0.051 \pm 3.7 \times 10^{-3}$
10%	$0.005 \pm 1.1 \times 10^{-3}$	$0.059 \pm 1.1 \times 10^{-3}$	$0.005 \pm 1.0 \times 10^{-3}$	$0.073 \pm 2.0 \times 10^{-2}$
20%	$0.016 \pm 1.7 \times 10^{-3}$	$0.105 \pm 1.5 \times 10^{-2}$	$0.016 \pm 1.7 \times 10^{-3}$	$0.109 \pm 1.2 \times 10^{-2}$
30%	$0.031 \pm 1.9 \times 10^{-3}$	$0.135 \pm 2.5 \times 10^{-2}$	$0.031 \pm 1.9 \times 10^{-3}$	$0.151 \pm 3.0 \times 10^{-2}$
40%	$0.052 \pm 2.7 \times 10^{-3}$	$0.154 \pm 1.1 \times 10^{-2}$	$0.054 \pm 2.3 \times 10^{-3}$	$0.171 \pm 4.2 \times 10^{-2}$
50%	$0.072 \pm 4.5 \times 10^{-3}$	$0.178 \pm 1.0 \times 10^{-2}$	$0.077 \pm 5.2 \times 10^{-3}$	$0.216 \pm 1.6 \times 10^{-2}$
60%	$0.092 \pm 1.7 \times 10^{-3}$	$0.229 \pm 2.7 \times 10^{-2}$	$0.098 \pm 2.2 \times 10^{-3}$	$0.243 \pm 3.8 \times 10^{-2}$

Table A.37: Network A and M: Service performance for SMODR (Heuristic 1) using path elimination criterion in eq. 4.12, $b = 0.1$ and ΔT=10s.

Overload Factor	SMODR (Heuristic 1) - Eq. 4.12 - $b = 0.1$ - ΔT=10s, Network A		Network M	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B_{Ms} \pm \Delta$
	Service $s = 1$			
0%	$0.001 \pm 2.5 \times 10^{-4}$	$0.004 \pm 1.0 \times 10^{-3}$	$< 10^{-3}$	$0.004 \pm 1.3 \times 10^{-3}$
10%	$0.002 \pm 3.1 \times 10^{-4}$	$0.006 \pm 1.8 \times 10^{-3}$	$< 10^{-3}$	$0.007 \pm 4.9 \times 10^{-4}$
20%	$0.003 \pm 1.9 \times 10^{-4}$	$0.009 \pm 1.8 \times 10^{-3}$	$0.001 \pm 1.8 \times 10^{-4}$	$0.011 \pm 2.9 \times 10^{-3}$
30%	$0.005 \pm 4.5 \times 10^{-4}$	$0.013 \pm 8.5 \times 10^{-4}$	$0.003 \pm 2.6 \times 10^{-4}$	$0.013 \pm 2.7 \times 10^{-3}$
40%	$0.007 \pm 6.0 \times 10^{-4}$	$0.015 \pm 3.1 \times 10^{-3}$	$0.005 \pm 2.6 \times 10^{-4}$	$0.016 \pm 2.2 \times 10^{-3}$
50%	$0.010 \pm 6.6 \times 10^{-4}$	$0.018 \pm 2.1 \times 10^{-3}$	$0.007 \pm 4.5 \times 10^{-4}$	$0.018 \pm 1.4 \times 10^{-3}$
60%	$0.012 \pm 6.0 \times 10^{-4}$	$0.023 \pm 1.6 \times 10^{-3}$	$0.009 \pm 2.9 \times 10^{-4}$	$0.023 \pm 3.2 \times 10^{-3}$
	Service $s = 2$			
0%	$0.005 \pm 1.9 \times 10^{-3}$	$0.022 \pm 2.5 \times 10^{-3}$	$0.001 \pm 2.6 \times 10^{-4}$	$0.023 \pm 1.0 \times 10^{-2}$
10%	$0.013 \pm 2.0 \times 10^{-3}$	$0.039 \pm 1.0 \times 10^{-2}$	$0.003 \pm 6.0 \times 10^{-4}$	$0.038 \pm 4.1 \times 10^{-3}$
20%	$0.020 \pm 1.3 \times 10^{-3}$	$0.053 \pm 6.3 \times 10^{-3}$	$0.008 \pm 8.1 \times 10^{-4}$	$0.051 \pm 7.3 \times 10^{-3}$
30%	$0.031 \pm 3.2 \times 10^{-3}$	$0.073 \pm 1.6 \times 10^{-2}$	$0.017 \pm 1.5 \times 10^{-3}$	$0.076 \pm 1.5 \times 10^{-2}$
40%	$0.042 \pm 3.0 \times 10^{-3}$	$0.092 \pm 1.5 \times 10^{-2}$	$0.030 \pm 1.2 \times 10^{-3}$	$0.093 \pm 1.1 \times 10^{-2}$
50%	$0.058 \pm 4.3 \times 10^{-3}$	$0.108 \pm 1.1 \times 10^{-2}$	$0.043 \pm 3.0 \times 10^{-3}$	$0.116 \pm 9.1 \times 10^{-3}$
60%	$0.072 \pm 1.8 \times 10^{-3}$	$0.138 \pm 4.1 \times 10^{-3}$	$0.056 \pm 9.9 \times 10^{-4}$	$0.134 \pm 8.4 \times 10^{-3}$
	Service $s = 3$			
0%	$0.008 \pm 2.4 \times 10^{-3}$	$0.034 \pm 6.4 \times 10^{-3}$	$0.002 \pm 6.9 \times 10^{-4}$	$0.045 \pm 1.6 \times 10^{-2}$
10%	$0.020 \pm 3.2 \times 10^{-3}$	$0.061 \pm 8.5 \times 10^{-3}$	$0.004 \pm 7.0 \times 10^{-4}$	$0.064 \pm 1.4 \times 10^{-2}$
20%	$0.034 \pm 2.2 \times 10^{-3}$	$0.090 \pm 1.2 \times 10^{-2}$	$0.014 \pm 1.5 \times 10^{-3}$	$0.108 \pm 1.2 \times 10^{-2}$
30%	$0.052 \pm 6.3 \times 10^{-3}$	$0.124 \pm 2.3 \times 10^{-2}$	$0.029 \pm 2.1 \times 10^{-3}$	$0.143 \pm 2.7 \times 10^{-2}$
40%	$0.073 \pm 2.6 \times 10^{-3}$	$0.169 \pm 2.4 \times 10^{-2}$	$0.051 \pm 2.1 \times 10^{-3}$	$0.172 \pm 1.6 \times 10^{-2}$
50%	$0.098 \pm 4.3 \times 10^{-3}$	$0.183 \pm 8.0 \times 10^{-3}$	$0.072 \pm 4.4 \times 10^{-3}$	$0.197 \pm 1.4 \times 10^{-2}$
60%	$0.120 \pm 5.7 \times 10^{-3}$	$0.227 \pm 1.9 \times 10^{-2}$	$0.093 \pm 1.5 \times 10^{-3}$	$0.235 \pm 9.9 \times 10^{-3}$

A.3.3 SMODR, using Howard Costs in MMRA

Table A.38: Network A - Service performance for SMODR (Heuristic 1), $b = 0.1$ and ΔT=1m.

Overload Factor	SMODR - Heuristic 1 - ΔT=1m			
	Eq. 4.16		Eq. 4.17	
	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$	$B_m^s \pm \Delta$	$B_M^s \pm \Delta$
	Service $s = 1$			
0%	$0.001 \pm 3.1 \times 10^{-4}$	$0.007 \pm 3.4 \times 10^{-3}$	$0.0008 \pm 2.8 \times 10^{-4}$	$0.005 \pm 2.0 \times 10^{-3}$
10%	$0.002 \pm 1.1 \times 10^{-4}$	$0.009 \pm 1.4 \times 10^{-3}$	$0.0016 \pm 2.9 \times 10^{-4}$	$0.009 \pm 1.3 \times 10^{-3}$
20%	$0.003 \pm 1.6 \times 10^{-4}$	$0.012 \pm 2.2 \times 10^{-3}$	$0.0023 \pm 2.8 \times 10^{-4}$	$0.013 \pm 2.4 \times 10^{-3}$
30%	$0.004 \pm 2.1 \times 10^{-4}$	$0.017 \pm 3.1 \times 10^{-3}$	$0.0036 \pm 2.5 \times 10^{-4}$	$0.017 \pm 1.5 \times 10^{-3}$
40%	$0.006 \pm 4.3 \times 10^{-4}$	$0.021 \pm 1.7 \times 10^{-3}$	$0.0048 \pm 3.7 \times 10^{-4}$	$0.021 \pm 1.7 \times 10^{-3}$
50%	$0.008 \pm 3.9 \times 10^{-4}$	$0.025 \pm 1.4 \times 10^{-3}$	$0.0069 \pm 3.2 \times 10^{-4}$	$0.028 \pm 1.2 \times 10^{-3}$
60%	$0.009 \pm 6.0 \times 10^{-4}$	$0.031 \pm 4.4 \times 10^{-3}$	$0.0085 \pm 3.0 \times 10^{-4}$	$0.033 \pm 3.4 \times 10^{-3}$
	Service $s = 2$			
0%	$0.012 \pm 3.1 \times 10^{-3}$	$0.055 \pm 1.7 \times 10^{-2}$	$0.010 \pm 3.3 \times 10^{-3}$	$0.056 \pm 1.7 \times 10^{-2}$
10%	$0.020 \pm 1.9 \times 10^{-3}$	$0.095 \pm 1.3 \times 10^{-2}$	$0.020 \pm 2.2 \times 10^{-3}$	$0.104 \pm 1.5 \times 10^{-2}$
20%	$0.028 \pm 2.1 \times 10^{-3}$	$0.122 \pm 2.2 \times 10^{-2}$	$0.028 \pm 1.9 \times 10^{-3}$	$0.130 \pm 1.3 \times 10^{-2}$
30%	$0.041 \pm 3.9 \times 10^{-3}$	$0.156 \pm 1.6 \times 10^{-2}$	$0.042 \pm 3.4 \times 10^{-3}$	$0.173 \pm 1.2 \times 10^{-2}$
40%	$0.054 \pm 3.0 \times 10^{-3}$	$0.193 \pm 6.6 \times 10^{-3}$	$0.056 \pm 4.1 \times 10^{-3}$	$0.207 \pm 1.3 \times 10^{-2}$
50%	$0.072 \pm 4.6 \times 10^{-3}$	$0.235 \pm 2.3 \times 10^{-2}$	$0.076 \pm 3.6 \times 10^{-3}$	$0.260 \pm 1.3 \times 10^{-2}$
60%	$0.088 \pm 3.3 \times 10^{-3}$	$0.276 \pm 1.6 \times 10^{-2}$	$0.093 \pm 1.9 \times 10^{-3}$	$0.298 \pm 1.5 \times 10^{-2}$
	Service $s = 3$			
0%	$0.023 \pm 5.4 \times 10^{-3}$	$0.110 \pm 3.4 \times 10^{-2}$	$0.021 \pm 6.1 \times 10^{-3}$	$0.121 \pm 4.3 \times 10^{-2}$
10%	$0.039 \pm 3.0 \times 10^{-3}$	$0.183 \pm 2.6 \times 10^{-2}$	$0.039 \pm 4.0 \times 10^{-3}$	$0.194 \pm 2.7 \times 10^{-2}$
20%	$0.054 \pm 3.6 \times 10^{-3}$	$0.213 \pm 3.1 \times 10^{-2}$	$0.054 \pm 4.3 \times 10^{-3}$	$0.224 \pm 3.5 \times 10^{-2}$
30%	$0.075 \pm 7.8 \times 10^{-3}$	$0.279 \pm 4.1 \times 10^{-2}$	$0.080 \pm 7.2 \times 10^{-3}$	$0.305 \pm 1.3 \times 10^{-2}$
40%	$0.100 \pm 5.1 \times 10^{-3}$	$0.331 \pm 3.4 \times 10^{-2}$	$0.106 \pm 6.2 \times 10^{-3}$	$0.355 \pm 1.1 \times 10^{-2}$
50%	$0.132 \pm 6.2 \times 10^{-3}$	$0.380 \pm 4.3 \times 10^{-2}$	$0.141 \pm 4.9 \times 10^{-3}$	$0.413 \pm 1.3 \times 10^{-2}$
60%	$0.153 \pm 4.7 \times 10^{-3}$	$0.455 \pm 3.0 \times 10^{-2}$	$0.168 \pm 4.8 \times 10^{-3}$	$0.479 \pm 2.3 \times 10^{-2}$

Table A.39: Network A - Service performance for SMODR (Heuristic 1), $b = 0.1$ and ΔT=10s.

Overload Factor	SMODR - Heuristic 1 - ΔT=10s			
	Eq. 4.16		Eq. 4.17	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0011 \pm 2.7 \times 10^{-4}$	$0.006 \pm 2.2 \times 10^{-3}$	$0.0008 \pm 2.6 \times 10^{-4}$	$0.005 \pm 2.0 \times 10^{-3}$
10%	$0.0019 \pm 2.8 \times 10^{-4}$	$0.008 \pm 1.2 \times 10^{-3}$	$0.0015 \pm 2.5 \times 10^{-4}$	$0.009 \pm 2.3 \times 10^{-3}$
20%	$0.0027 \pm 1.0 \times 10^{-4}$	$0.012 \pm 1.5 \times 10^{-3}$	$0.0023 \pm 2.0 \times 10^{-4}$	$0.012 \pm 1.8 \times 10^{-3}$
30%	$0.0041 \pm 2.8 \times 10^{-4}$	$0.016 \pm 1.3 \times 10^{-3}$	$0.0035 \pm 2.1 \times 10^{-4}$	$0.017 \pm 1.3 \times 10^{-3}$
40%	$0.0055 \pm 5.0 \times 10^{-4}$	$0.019 \pm 1.4 \times 10^{-3}$	$0.0048 \pm 2.6 \times 10^{-4}$	$0.022 \pm 1.4 \times 10^{-3}$
50%	$0.0077 \pm 3.1 \times 10^{-4}$	$0.025 \pm 1.9 \times 10^{-3}$	$0.0068 \pm 3.6 \times 10^{-4}$	$0.029 \pm 1.2 \times 10^{-3}$
60%	$0.0094 \pm 3.6 \times 10^{-4}$	$0.030 \pm 2.8 \times 10^{-3}$	$0.0085 \pm 4.9 \times 10^{-4}$	$0.034 \pm 4.5 \times 10^{-3}$
	Service $s = 2$			
0%	$0.011 \pm 2.8 \times 10^{-3}$	$0.053 \pm 1.6 \times 10^{-2}$	$0.010 \pm 2.8 \times 10^{-3}$	$0.057 \pm 2.0 \times 10^{-2}$
10%	$0.020 \pm 2.0 \times 10^{-3}$	$0.093 \pm 1.1 \times 10^{-2}$	$0.019 \pm 1.9 \times 10^{-3}$	$0.102 \pm 3.2 \times 10^{-3}$
20%	$0.028 \pm 1.5 \times 10^{-3}$	$0.117 \pm 1.8 \times 10^{-2}$	$0.027 \pm 1.9 \times 10^{-3}$	$0.132 \pm 1.2 \times 10^{-2}$
30%	$0.040 \pm 3.6 \times 10^{-3}$	$0.150 \pm 7.9 \times 10^{-2}$	$0.041 \pm 4.2 \times 10^{-3}$	$0.168 \pm 1.0 \times 10^{-2}$
40%	$0.053 \pm 4.0 \times 10^{-3}$	$0.191 \pm 6.8 \times 10^{-2}$	$0.055 \pm 4.2 \times 10^{-3}$	$0.202 \pm 3.4 \times 10^{-3}$
50%	$0.072 \pm 3.8 \times 10^{-3}$	$0.230 \pm 7.8 \times 10^{-3}$	$0.076 \pm 4.8 \times 10^{-3}$	$0.255 \pm 9.7 \times 10^{-3}$
60%	$0.087 \pm 2.8 \times 10^{-3}$	$0.270 \pm 1.4 \times 10^{-2}$	$0.093 \pm 4.2 \times 10^{-3}$	$0.297 \pm 1.4 \times 10^{-2}$
	Service $s = 3$			
0%	$0.022 \pm 5.0 \times 10^{-3}$	$0.110 \pm 1.4 \times 10^{-2}$	$0.021 \pm 5.4 \times 10^{-3}$	$0.114 \pm 2.2 \times 10^{-2}$
10%	$0.038 \pm 2.9 \times 10^{-3}$	$0.174 \pm 2.8 \times 10^{-2}$	$0.039 \pm 4.4 \times 10^{-3}$	$0.193 \pm 2.5 \times 10^{-2}$
20%	$0.053 \pm 3.2 \times 10^{-3}$	$0.216 \pm 1.8 \times 10^{-2}$	$0.054 \pm 4.2 \times 10^{-3}$	$0.230 \pm 1.7 \times 10^{-2}$
30%	$0.075 \pm 7.0 \times 10^{-3}$	$0.283 \pm 2.2 \times 10^{-2}$	$0.079 \pm 6.7 \times 10^{-3}$	$0.309 \pm 3.2 \times 10^{-2}$
40%	$0.100 \pm 4.3 \times 10^{-3}$	$0.327 \pm 2.0 \times 10^{-2}$	$0.106 \pm 5.6 \times 10^{-3}$	$0.355 \pm 2.9 \times 10^{-2}$
50%	$0.132 \pm 5.3 \times 10^{-3}$	$0.391 \pm 2.6 \times 10^{-2}$	$0.142 \pm 5.8 \times 10^{-3}$	$0.430 \pm 2.4 \times 10^{-2}$
60%	$0.156 \pm 4.8 \times 10^{-3}$	$0.466 \pm 2.6 \times 10^{-2}$	$0.169 \pm 6.6 \times 10^{-3}$	$0.479 \pm 4.0 \times 10^{-2}$

Table A.40: Network M - Service performance for SMODR (Heuristic 1), $b = 0.1$ and ΔT=1m.

Overload Factor	SMODR - Heuristic 1 - ΔT=1m			
	Eq. 4.16		Eq. 4.17	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$< 10^{-3}$	$0.006 \pm 3.4 \times 10^{-3}$	$< 10^{-4}$	$0.0009 \pm 5.3 \times 10^{-4}$
10%	$< 10^{-3}$	$0.006 \pm 8.1 \times 10^{-4}$	$0.0001 \pm 5.6 \times 10^{-5}$	$0.0013 \pm 5.1 \times 10^{-4}$
20%	$0.001 \pm 1.9 \times 10^{-4}$	$0.009 \pm 8.7 \times 10^{-4}$	$0.0007 \pm 6.3 \times 10^{-5}$	$0.002 \pm 3.3 \times 10^{-4}$
30%	$0.003 \pm 2.8 \times 10^{-4}$	$0.014 \pm 4.5 \times 10^{-3}$	$0.0017 \pm 2.3 \times 10^{-4}$	$0.005 \pm 1.1 \times 10^{-3}$
40%	$0.005 \pm 2.3 \times 10^{-4}$	$0.015 \pm 2.2 \times 10^{-3}$	$0.0033 \pm 1.6 \times 10^{-4}$	$0.007 \pm 8.3 \times 10^{-4}$
50%	$0.007 \pm 4.8 \times 10^{-4}$	$0.018 \pm 2.3 \times 10^{-3}$	$0.0048 \pm 3.8 \times 10^{-4}$	$0.010 \pm 1.4 \times 10^{-3}$
60%	$0.009 \pm 2.9 \times 10^{-4}$	$0.021 \pm 2.2 \times 10^{-3}$	$0.0065 \pm 2.1 \times 10^{-4}$	$0.013 \pm 1.3 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 3.4 \times 10^{-4}$	$0.027 \pm 8.4 \times 10^{-3}$	$0.0007 \pm 3.0 \times 10^{-4}$	$0.015 \pm 5.1 \times 10^{-3}$
10%	$0.003 \pm 5.9 \times 10^{-4}$	$0.042 \pm 7.1 \times 10^{-3}$	$0.0022 \pm 7.2 \times 10^{-4}$	$0.019 \pm 5.0 \times 10^{-3}$
20%	$0.010 \pm 1.2 \times 10^{-3}$	$0.051 \pm 8.7 \times 10^{-3}$	$0.0105 \pm 8.1 \times 10^{-4}$	$0.038 \pm 6.7 \times 10^{-3}$
30%	$0.019 \pm 1.3 \times 10^{-3}$	$0.087 \pm 1.9 \times 10^{-2}$	$0.026 \pm 3.0 \times 10^{-3}$	$0.077 \pm 1.5 \times 10^{-2}$
40%	$0.032 \pm 1.7 \times 10^{-3}$	$0.094 \pm 9.6 \times 10^{-3}$	$0.050 \pm 2.7 \times 10^{-3}$	$0.114 \pm 1.5 \times 10^{-2}$
50%	$0.043 \pm 3.2 \times 10^{-3}$	$0.112 \pm 1.0 \times 10^{-2}$	$0.069 \pm 4.2 \times 10^{-3}$	$0.141 \pm 9.6 \times 10^{-3}$
60%	$0.056 \pm 1.3 \times 10^{-3}$	$0.128 \pm 1.8 \times 10^{-2}$	$0.091 \pm 1.9 \times 10^{-3}$	$0.172 \pm 1.5 \times 10^{-2}$
	Service $s = 3$			
0%	$0.002 \pm 7.6 \times 10^{-4}$	$0.041 \pm 1.2 \times 10^{-2}$	$0.0017 \pm 5.8 \times 10^{-4}$	$0.036 \pm 7.4 \times 10^{-2}$
10%	$0.005 \pm 1.1 \times 10^{-3}$	$0.062 \pm 6.7 \times 10^{-3}$	$0.005 \pm 1.2 \times 10^{-3}$	$0.048 \pm 1.3 \times 10^{-2}$
20%	$0.017 \pm 1.7 \times 10^{-3}$	$0.108 \pm 2.1 \times 10^{-2}$	$0.022 \pm 1.9 \times 10^{-3}$	$0.094 \pm 1.5 \times 10^{-2}$
30%	$0.031 \pm 2.4 \times 10^{-3}$	$0.137 \pm 2.6 \times 10^{-2}$	$0.054 \pm 5.1 \times 10^{-3}$	$0.163 \pm 2.4 \times 10^{-2}$
40%	$0.053 \pm 2.4 \times 10^{-3}$	$0.177 \pm 1.5 \times 10^{-2}$	$0.099 \pm 5.5 \times 10^{-3}$	$0.243 \pm 2.1 \times 10^{-2}$
50%	$0.072 \pm 4.6 \times 10^{-3}$	$0.180 \pm 1.8 \times 10^{-2}$	$0.135 \pm 7.5 \times 10^{-3}$	$0.310 \pm 2.0 \times 10^{-2}$
60%	$0.093 \pm 2.0 \times 10^{-3}$	$0.227 \pm 2.9 \times 10^{-2}$	$0.173 \pm 2.9 \times 10^{-3}$	$0.364 \pm 4.1 \times 10^{-2}$

Table A.41: Network M - Service performance for SMODR (Heuristic 1), $b = 0.1$ and ΔT=10s.

Overload Factor	SMODR - Heuristic 1 - ΔT=10s			
	Eq. 4.16		Eq. 4.17	
	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$	$B^s_m \pm \Delta$	$B^s_M \pm \Delta$
	Service $s = 1$			
0%	$0.0002 \pm 6.4 \times 10^{-5}$	$0.005 \pm 6.0 \times 10^{-4}$	$< 10^{-4}$	$0.0008 \pm 3.2 \times 10^{-4}$
10%	$0.0004 \pm 6.2 \times 10^{-5}$	$0.006 \pm 2.0 \times 10^{-3}$	$< 10^{-4}$	$0.0013 \pm 2.1 \times 10^{-4}$
20%	$0.0014 \pm 1.6 \times 10^{-4}$	$0.009 \pm 1.8 \times 10^{-3}$	$0.0006 \pm 7.1 \times 10^{-5}$	$0.0023 \pm 5.0 \times 10^{-4}$
30%	$0.0028 \pm 1.8 \times 10^{-4}$	$0.014 \pm 4.8 \times 10^{-3}$	$0.0017 \pm 2.0 \times 10^{-4}$	$0.0048 \pm 6.4 \times 10^{-4}$
40%	$0.0050 \pm 3.5 \times 10^{-4}$	$0.016 \pm 3.2 \times 10^{-3}$	$0.0034 \pm 1.5 \times 10^{-4}$	$0.0078 \pm 1.0 \times 10^{-3}$
50%	$0.0070 \pm 4.3 \times 10^{-4}$	$0.020 \pm 2.4 \times 10^{-3}$	$0.0049 \pm 4.7 \times 10^{-4}$	$0.011 \pm 2.0 \times 10^{-3}$
60%	$0.0093 \pm 2.5 \times 10^{-4}$	$0.021 \pm 2.0 \times 10^{-3}$	$0.0066 \pm 2.7 \times 10^{-4}$	$0.013 \pm 1.6 \times 10^{-3}$
	Service $s = 2$			
0%	$0.001 \pm 4.1 \times 10^{-4}$	$0.024 \pm 9.2 \times 10^{-3}$	$0.0004 \pm 2.2 \times 10^{-4}$	$0.008 \pm 3.2 \times 10^{-3}$
10%	$0.003 \pm 6.0 \times 10^{-4}$	$0.041 \pm 1.4 \times 10^{-2}$	$0.0018 \pm 5.8 \times 10^{-4}$	$0.021 \pm 5.1 \times 10^{-3}$
20%	$0.009 \pm 9.8 \times 10^{-4}$	$0.055 \pm 9.8 \times 10^{-3}$	$0.010 \pm 1.5 \times 10^{-3}$	$0.039 \pm 4.1 \times 10^{-3}$
30%	$0.018 \pm 1.3 \times 10^{-3}$	$0.081 \pm 9.7 \times 10^{-3}$	$0.028 \pm 3.7 \times 10^{-3}$	$0.081 \pm 1.3 \times 10^{-2}$
40%	$0.030 \pm 1.5 \times 10^{-3}$	$0.095 \pm 6.0 \times 10^{-3}$	$0.050 \pm 2.1 \times 10^{-3}$	$0.123 \pm 8.3 \times 10^{-3}$
50%	$0.043 \pm 2.9 \times 10^{-3}$	$0.119 \pm 1.4 \times 10^{-2}$	$0.071 \pm 5.1 \times 10^{-3}$	$0.148 \pm 1.5 \times 10^{-2}$
60%	$0.057 \pm 9.5 \times 10^{-4}$	$0.132 \pm 1.3 \times 10^{-2}$	$0.092 \pm 1.7 \times 10^{-3}$	$0.186 \pm 1.3 \times 10^{-2}$
	Service $s = 3$			
0%	$0.002 \pm 6.7 \times 10^{-4}$	$0.048 \pm 1.7 \times 10^{-2}$	$0.0011 \pm 4.4 \times 10^{-4}$	$0.025 \pm 8.6 \times 10^{-3}$
10%	$0.004 \pm 7.8 \times 10^{-4}$	$0.068 \pm 1.4 \times 10^{-2}$	$0.0039 \pm 9.0 \times 10^{-4}$	$0.051 \pm 1.9 \times 10^{-2}$
20%	$0.014 \pm 1.8 \times 10^{-3}$	$0.101 \pm 9.1 \times 10^{-3}$	$0.021 \pm 3.1 \times 10^{-3}$	$0.095 \pm 1.5 \times 10^{-2}$
30%	$0.029 \pm 2.3 \times 10^{-3}$	$0.148 \pm 2.1 \times 10^{-2}$	$0.056 \pm 6.9 \times 10^{-3}$	$0.185 \pm 2.9 \times 10^{-2}$
40%	$0.051 \pm 2.4 \times 10^{-3}$	$0.166 \pm 2.0 \times 10^{-2}$	$0.101 \pm 4.5 \times 10^{-3}$	$0.244 \pm 2.6 \times 10^{-2}$
50%	$0.072 \pm 4.7 \times 10^{-3}$	$0.188 \pm 1.6 \times 10^{-2}$	$0.138 \pm 9.2 \times 10^{-3}$	$0.301 \pm 3.3 \times 10^{-2}$
60%	$0.094 \pm 2.1 \times 10^{-3}$	$0.227 \pm 2.1 \times 10^{-2}$	$0.176 \pm 2.7 \times 10^{-3}$	$0.350 \pm 8.8 \times 10^{-3}$

Appendix B

DMAR

Appendix B presents supplementary material to the validation work of the DMAR method in the simulation study presented in Chapter 5.

B.1 Traffic Matrices

The traffic scenarios are based on the traffic matrices made available by Sprint for a 24-hours period of voice service [56]. Single service and multiservice networks are used for testing the routing methods in diversified traffic environments including stationary and dynamic traffic patterns.

B.1.1 Stationary Traffic

The stationary traffic in the single service network model is inspired by the traffic matrix of the voice service in a ten-nodes network in one of the busiest hours, available from Sprint. This traffic matrix is called "BH" from this moment forward and detailed information of it is shown in Table B.1.

The multiservice traffic considers three services and it is inspired by the work in [69] whose load distribution is based on an actual service provider, leading to the following load distribution $5(s_1)$: $20(s_2)$: $75(s_3)$. The following required bandwidth d = [1, 6, 10] for services s_1, s_2 and s_3, respectively, is assumed, and

Table B.1: Stationary traffic in the single service network model - "BH".

O-D	Load	O-D	Load	O-D	Load	O-D	Load	O-D	Load
1-2	358	2-3	766	3-5	1466	4-8	323	6-8	3375
1-3	1137	2-4	520	3-6	2215	4-9	361	6-9	1210
1-4	299	2-5	378	3-7	1375	4-10	372	6-10	1679
1-5	338	2-6	902	3-8	835	5-6	713	7-8	661
1-6	990	2-7	399	3-9	745	5-7	557	7-9	2360
1-7	456	2-8	320	3-10	750	5-8	244	7-10	620
1-8	416	2-9	227	4-5	1218	5-9	302	8-9	467
1-9	238	2-10	513	4-6	921	5-10	359	8-10	621
1-10	529	3-4	1054	4-7	670	6-7	2417	9-10	407

services s_2 and s_3 use a bandwidth value that is a multiple of the bandwidth in use by service s_1. The single service traffic defined in Table B.1 serves as the basis for the service s_1 traffic, and the traffic that is offered to each of the services s_2 and s_3 is such that it maintains the relative load distribution before mentioned. To reduce the simulation time, the average traffic value that is offered to each service is affected by the multiplicative factor f = [1/3, 2/9, 1/2] for services s_1, s_2 and s_3, respectively.

B.1.2 Dynamic Traffic

The dynamic traffic matrices associated with each of the node pairs in the network are represented in this context by the time dependent (t) sinusoidal waves of the type Traf(t) = Avg + $A \sin(2\pi f t + \varphi)$, where Avg is the average value, A the peak amplitude, f the ordinary frequency and φ the phase. Table B.2 defines the sine waves inspired by the "7 BH" period ([10,17[h) of the voice service in the Sprint network.

The offered traffic corresponding to the first simulated dynamic traffic scenarios in section 5.3.1.2 is depicted in Table B.3, according to which the traffic that is offered to each pair of nodes is modulated by a curve with Avg="BH" traffic in Table B.1, A=5% or A=10% and T(minutes)=117, 101 or 128, sequentially assigned according to the ordered list of the node pairs. The choice of these values (117, 101, 128 minutes) for the curves period, close together but with a high

Table B.2: Dynamic traffic in the single service network model - “7 BH”.

O-D	Avg	A(%)	T(h)	$\varphi(^\circ)$	O-D	Avg	A(%)	T(h)	$\varphi(^\circ)$
1-2	289	30	5	0	3-10	649	21	4	-112.5
1-3	978	22	5	0	4-5	981	35	4	-112.5
1-4	255	23	5	0	4-6	775	25	4	-112.5
1-5	284	25	5	0	4-7	700	36	2	-135
1-6	823	27	5	0	4-8	282	22	4.5	-50
1-7	490	26	2.5	-234	4-9	404	34	2	-135
1-8	332	32	5	0	4-10	315	24	4	-112.5
1-9	254	32	2.5	-234	5-6	597	26	4	-112.5
1-10	434	28	5	0	5-7	680	14	2	-135
2-3	649	24	5	0	5-8	205	25	4	-112.5
2-4	441	30	4	-112.5	5-9	374	15	2	-135
2-5	311	28	5	0	5-10	302	25	4	-112.5
2-6	751	26	5	0	6-7	2819	10	3	-300
2-7	413	33	2.5	-234	6-8	2911	25	5	0
2-8	258	31	5	0	6-9	1439	11	2	-135
2-9	233	35	2.5	-234	6-10	1451	22	4	-112.5
2-10	421	29	4	-22.5	7-8	677	34	2.5	-234
3-4	853	30	4	-112.5	7-9	3714	33	4	-292.5
3-5	1174	32	4	-112.5	7-10	606	38	2.5	-234
3-6	1926	23	4	-112.5	8-9	576	15	2.5	-234
3-7	1403	37	2	-135	8-10	516	27	5	0
3-8	728	21	4	-112.5	9-10	497	14	2.5	-234
3-9	770	35	2	-135					

value for the least common multiple, promotes the desired diversity in the curves of the traffic that is offered to the several pairs of nodes of the network.

B.2 Test Networks

This section includes the definition of the test networks used in the DMAR simulation study.

Table B.3: Dynamic traffic in the single service network model - A=5%,10%.

O-D	Avg	A(%)	T(h)	$\varphi(^\circ)$	O-D	Avg	A(%)	T(h)	$\varphi(^\circ)$
1-2	358	5,10	117	0	3-10	750	5,10	128	0
1-3	1137	5,10	101	0	4-5	1218	5,10	117	0
1-4	299	5,10	128	0	4-6	921	5,10	101	0
1-5	338	5,10	117	0	4-7	670	5,10	128	0
1-6	990	5,10	101	0	4-8	323	5,10	117	0
1-7	456	5,10	128	0	4-9	361	5,10	101	0
1-8	416	5,10	117	0	4-10	372	5,10	128	0
1-9	238	5,10	101	0	5-6	713	5,10	117	0
1-10	529	5,10	128	0	5-7	557	5,10	101	0
2-3	766	5,10	117	0	5-8	244	5,10	128	0
2-4	520	5,10	101	0	5-9	302	5,10	117	0
2-5	378	5,10	128	0	5-10	359	5,10	101	0
2-6	902	5,10	117	0	6-7	2417	5,10	128	0
2-7	399	5,10	101	0	6-8	3375	5,10	117	0
2-8	320	5,10	128	0	6-9	1210	5,10	101	0
2-9	227	5,10	117	0	6-10	1679	5,10	128	0
2-10	513	5,10	101	0	7-8	661	5,10	117	0
3-4	1054	5,10	128	0	7-9	2360	5,10	101	0
3-5	1466	5,10	117	0	7-10	620	5,10	128	0
3-6	2215	5,10	101	0	8-9	467	5,10	117	0
3-7	1375	5,10	128	0	8-10	621	5,10	101	0
3-8	835	5,10	117	0	9-10	407	5,10	128	0
3-9	745	5,10	101	0					

B.2.1 Single Service Networks

Single service networks were simplistically dimensioned based on the traffic matrices corresponding to the seven busy hours traffic of the voice service in the Sprint network [56]. The first step of it assumes the use of direct routing and the calculation of the capacity of each link using the inverse of Erlang B formula for a reference blocking probability value.

Alternative routing is often studied and applied to fully meshed networks. Network A in Table B.4 is a ten-nodes fully meshed network whose dimensioning was adjusted by simulation to the traffic matrix of one of the busiest hours of the Sprint voice network (see Table B.1) and to a mean network blocking probability of approximately 1% for DAR.

Network B in Table B.5 is a sparser network and it results from the removal of approximately 10% (5 links) of the links from Network A. The first-choice path is

Table B.4: Network A - links capacities.

O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap
1-2	363	2-3	754	3-5	1313	4-8	354	6-8	3121
1-3	1105	2-4	530	3-6	2099	4-9	490	6-9	1591
1-4	325	2-5	388	3-7	1553	4-10	392	6-10	1604
1-5	356	2-6	863	3-8	839	5-6	699	7-8	784
1-6	940	2-7	499	3-9	884	5-7	788	7-9	3948
1-7	583	2-8	328	3-10	754	5-8	268	7-10	708
1-8	411	2-9	300	4-5	1108	5-9	456	8-9	676
1-9	324	2-10	507	4-6	890	5-10	376	8-10	612
1-10	523	3-4	973	4-7	809	6-7	3025	9-10	591

fixed, being the same for all methods and in each of the various traffic scenarios. The selected first-choice paths with two-arcs are the paths with more available capacity in a fixed routing strategy. The capacities of the links in these paths were increased by an amount equivalent to the capacity of the direct link that was removed from the corresponding fully meshed network in Table B.4.

Table B.5: Network B - links capacities.

O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap
1-2	363	2-3	754	3-5	1313	4-8	354	6-8	3820
1-3	1105	2-4	-	3-6	2099	4-9	1020	6-9	1591
1-4	1215	2-5	388	3-7	1553	4-10	392	6-10	1604
1-5	812	2-6	863	3-8	839	5-6	-	7-8	1572
1-6	1830	2-7	499	3-9	884	5-7	-	7-9	3948
1-7	583	2-8	328	3-10	754	5-8	1755	7-10	708
1-8	411	2-9	830	4-5	1108	5-9	-	8-9	676
1-9	780	2-10	507	4-6	-	5-10	376	8-10	612
1-10	523	3-4	973	4-7	809	6-7	3025	9-10	591

The dimensioning of the Network C in Table B.6 was done based on fixed-point iterators, considering the three traffic peaks evidenced in the Figure 5.9 in section 5.3.1.2, which approximately represent the traffic in the hours 10h, 14h and 16h.

Table B.6: Network C - links capacities.

O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap
1-2	140	2-3	284	3-5	461	4-8	129	6-8	1222
1-3	415	2-4	181	3-6	720	4-9	184	6-9	538
1-4	119	2-5	147	3-7	609	4-10	131	6-10	545
1-5	133	2-6	332	3-8	281	5-6	237	7-8	304
1-6	364	2-7	190	3-9	339	5-7	267	7-9	1095
1-7	214	2-8	127	3-10	253	5-8	89	7-10	281
1-8	161	2-9	114	4-5	391	5-9	154	8-9	232
1-9	121	2-10	195	4-6	302	5-10	126	8-10	233
1-10	201	3-4	337	4-7	311	6-7	961	9-10	201

B.2.2 Multiservice Networks

Two multiservice fully meshed networks, networks D and E (in tables B.7 and B.8, respectively) were considered in the study. These multiservice networks D and E were dimensioned in a similar manner to the corresponding single service networks A and C, respectively, assuming that all offered traffic was single service.

Table B.7: Network D - links capacities.

O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap
1-2	2405	2-3	5123	3-5	9861	4-8	2196	6-8	23161
1-3	7600	2-4	3641	3-6	15048	4-9	3457	6-9	10178
1-4	2012	2-5	2538	3-7	12223	4-10	2500	6-10	11210
1-5	2272	2-6	6035	3-8	5585	5-6	4775	7-8	5756
1-6	6643	2-7	3489	3-9	6624	5-7	4927	7-9	31338
1-7	3919	2-8	2164	3-10	5015	5-8	1645	7-10	5332
1-8	2792	2-9	2019	4-5	8410	5-9	2741	8-9	4198
1-9	2145	2-10	3457	4-6	6156	5-10	2411	8-10	4160
1-10	3546	3-4	7049	4-7	6061	6-7	19614	9-10	3609

Table B.8: Network E - links capacities.

O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap	O-D	Cap
1-2	2211	2-3	4790	3-5	8318	4-8	2107	6-8	21190
1-3	7131	2-4	3168	3-6	13417	4-9	3020	6-9	10017
1-4	1918	2-5	2358	3-7	10332	4-10	2267	6-10	10120
1-5	2141	2-6	5564	3-8	5118	5-6	4241	7-8	5044
1-6	6099	2-7	3098	3-9	5695	5-7	4813	7-9	23915
1-7	3602	2-8	1983	3-10	4579	5-8	1498	7-10	4576
1-8	2541	2-9	1789	4-5	6988	5-9	2684	8-9	3906
1-9	1930	2-10	3167	4-6	5475	5-10	2176	8-10	3853
1-10	3267	3-4	6055	4-7	5192	6-7	18465	9-10	3554

Appendix C

DARMP

Appendix C describes the test networks that are used in the validation work of the DARMP strategy in the simulation study presented in Chapter 6.

C.1 Test Networks

C.1.1 Network A

Network A is based on the multiservice Network I in [69]. Network I is constituted by 15 nodes, connected by 58 links (see Table C.1), with a traffic profile consisting of 37 source-destination pairs, all of which have direct links between them. DARMP in Chapter 6 is tested in single service networks therefore some adjustments were made considering a single video service with an effective bandwidth of 5.2 Mbps (calculated based on the fluid-flow model given in [34] and considering an Active Burst Length of 1 second, a Cell Loss Ratio of 0.01% and a Peak Flow Rate of approx. 6 Mbps). Table C.2 shows the corresponding network, each circuit with a 5.2 Mbps rate.

Table C.1 shows 4 different link capacities: 933, 1866, 2799 and 3732 Mbps. 933.12 Mbps is the data rate on OC-18 in optical carriers. This work does not apply to optical networks and, consequently, the link capacity values were rounded

Table C.1: Test Network I, in terms of Mbps.

O-D Pair	Link Cap. (Mbps)	O-D Pair	Link Cap. (Mbps)	O-D Pair	Link Cap. (Mbps)	O-D Pair	Link Cap. (Mbps)
1-2	933	1-3	933	1-5	1866	1-7	1866
1-8	1866	1-9	933	1-10	933	1-11	1866
1-13	1866	1-15	1866	2-3	1866	2-6	1866
2-7	933	2-8	1866	2-9	1866	2-12	933
3-5	933	3-6	933	3-7	2799	3-9	3732
3-10	1866	3-11	933	3-13	933	3-14	2799
3-15	933	4-5	933	4-8	1866	4-9	933
4-10	933	4-13	933	5-7	2799	5-9	2799
5-11	1866	5-14	2799	6-7	933	6-8	1866
6-10	933	7-8	933	7-11	933	7-13	2799
7-14	933	8-9	1866	8-10	933	8-11	933
8-12	1866	9-11	1866	9-13	3732	9-14	933
10-11	933	10-12	1866	10-15	933	11-13	933
11-14	2799	12-13	1866	12-15	1866	13-14	3732
13-15	933	14-15	1866				

Table C.2: Test Network I, in terms of circuits.

O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap.
1-2	180	1-3	180	1-5	360	1-7	360
1-8	360	1-9	180	1-10	180	1-11	360
1-13	360	1-15	360	2-3	360	2-6	360
2-7	180	2-8	360	2-9	360	2-12	180
3-5	180	3-6	180	3-7	540	3-9	720
3-10	360	3-11	180	3-13	180	3-14	540
3-15	180	4-5	180	4-8	360	4-9	180
4-10	180	4-13	180	5-7	540	5-9	540
5-11	360	5-14	540	6-7	180	6-8	360
6-10	180	7-8	180	7-11	180	7-13	540
7-14	180	8-9	360	8-10	180	8-11	180
8-12	360	9-11	360	9-13	720	9-14	180
10-11	180	10-12	360	10-15	180	11-13	180
11-14	540	12-13	360	12-15	360	13-14	720
13-15	180	14-15	360				

(Table C.3). The resulting network in terms of number of circuits, herein designated as Network A, is shown in Table C.4. Network A presents a 5.6% blocking probability with the DAR routing scheme. This traffic scenario is designated as HIGH_LOAD in the simulation study.

Table C.3: Network A, in terms of Mbps.

O-D Pair	Link Cap. (Mbps)	O-D Pair	Link Cap. (Mbps)	O-D Pair	Link Cap. (Mbps)	O-D Pair	Link Cap. (Mbps)
1-2	1000	1-3	1000	1-5	2000	1-7	2000
1-8	2000	1-9	1000	1-10	1000	1-11	2000
1-13	2000	1-15	2000	2-3	2000	2-6	2000
2-7	1000	2-8	2000	2-9	2000	2-12	1000
3-5	1000	3-6	1000	3-7	3000	3-9	4000
3-10	2000	3-11	1000	3-13	1000	3-14	3000
3-15	1000	4-5	1000	4-8	2000	4-9	1000
4-10	1000	4-13	1000	5-7	3000	5-9	3000
5-11	2000	5-14	3000	6-7	1000	6-8	2000
6-10	1000	7-8	1000	7-11	1000	7-13	3000
7-14	1000	8-9	2000	8-10	1000	8-11	1000
8-12	2000	9-11	2000	9-13	4000	9-14	1000
10-11	1000	10-12	2000	10-15	1000	11-13	1000
11-14	3000	12-13	2000	12-15	2000	13-14	4000
13-15	1000	14-15	2000				

C.1.2 Network B

Network B in Table C.5 is a 10-nodes fully meshed network with 45 links, and the same average traffic load (45 Erlang) is offered to the network by each pair of nodes. Link capacities were adjusted by simulation to obtain a 1% mean blocking probability with the DAR routing scheme.

Table C.4: Network A, in terms of circuits.

O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap.
1-2	193	1-3	193	1-5	386	1-7	386
1-8	386	1-9	193	1-10	193	1-11	386
1-13	386	1-15	386	2-3	386	2-6	386
2-7	193	2-8	386	2-9	386	2-12	193
3-5	193	3-6	193	3-7	579	3-9	772
3-10	386	3-11	193	3-13	193	3-14	579
3-15	193	4-5	193	4-8	386	4-9	193
4-10	193	4-13	193	5-7	579	5-9	579
5-11	386	5-14	579	6-7	193	6-8	386
6-10	193	7-8	193	7-11	193	7-13	579
7-14	193	8-9	386	8-10	193	8-11	193
8-12	386	9-11	386	9-13	772	9-14	193
10-11	193	10-12	386	10-15	193	11-13	193
11-14	579	12-13	386	12-15	386	13-14	772
13-15	193	14-15	386				

Table C.5: Network B, in terms of circuits.

O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap. (circ.)	O-D Pair	Link Cap. (circ.)
1-2	104	2-3	104	3-5	102	4-8	103	6-8	104
1-3	106	2-4	105	3-6	104	4-9	102	6-9	105
1-4	103	2-5	103	3-7	101	4-10	102	6-10	101
1-5	105	2-6	105	3-8	102	5-6	101	7-8	102
1-6	102	2-7	103	3-9	103	5-7	102	7-9	102
1-7	102	2-8	100	3-10	105	5-8	102	7-10	99
1-8	100	2-9	101	4-5	100	5-9	103	8-9	101
1-9	100	2-10	103	4-6	100	5-10	103	8-10	102
1-10	100	3-4	106	4-7	100	6-7	103	9-10	102

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