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MULTICRITERIA ROUTING FOR GUARANTEED PERFORMANCE COMMUNICATIONS

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MULTICRITERIA ROUTING FOR GUARANTEED PERFORMANCE COMMUNICATIONS

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To my wife, babies, and parents

for their unlimited support, encouragement, and love

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ABSTRACT

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In this thesis, we investigate two routing problems. The first, which is known as the multiconstraint QoS (quality of service) routing problem, is to find a single path that satisfies multiple QoS constraints. For this problem, we consider two routing environments: (a) a given source node has detailed routing information provided by a link-state protocol, and (b) the source node has relatively simple routing information provided by a distance-vector protocol. First, we develop a greedy scheme, called MPLMR (multi-postpath-based lookahead multiconstraint routing), for case (a). MPLMR has an efficient "look-ahead" feature that uses the detailed information provided by link-state protocols. MPLMR has significantly better performance than competing schemes in the literature. We then develop a sequential path-search scheme, called SPMP (single-prepath multi-postpaths), for case (b). SPMP performs routing with simple routing information provided by distance-vector protocols, and maintains a small number of nodes involved in routing process. Hence, SPMP is suitable for multiconstraint QoS routing in the situations where reduction in computational/signaling overhead is a concern.

The second problem that we deal with in this thesis is to find a minimum number of paths that can collectively satisfy constraints on channel demand, capacity, and survivability between a given pair of source and destination nodes in a WDM (wavelength division multiplexing) network. Different from previous survivable routing schemes for WDM networks, we introduce link failure probabilities to the problem. Because this routing problem is NP-hard, we develop heuristic multipath routing schemes: CPMR (conditional-penalization multipath routing) and SPMR (successive-

penalization multipath routing). These schemes allow each link to be used for several channels. To deal with the difficulty that this link-sharing causes, we develop "link penalization" methods to control link-sharing. CPMR takes a long run-time to find a near-optimal solution, while SPMR uses a simple penalization method to reduce the run-time at the slight expense of the routing success rate. Via simulation, we show that our schemes achieve near-optimal routing success rates.

1. INTRODUCTION

1.1 Multicriteria routing

The goal of routing in computer/communication networks is to set up a routing path or paths between source and destination (terminal) nodes to forward user traffic in accordance with user requirements and network restrictions. Multicriteria routing refers to the process of finding a path or paths satisfying multiple criteria (e.g., objectives and constraints), which are set by such requirements and restrictions. Although routing for various requirements and restrictions has been studied for a long time, it is still an active area of research and development. User requirements for high-quality services and the evolution of networking technologies constantly reveal opportunities for the research and development of new routing schemes.

In this thesis, we deal with two routing problems. The first problem is to find a single path that satisfies multiple QoS (quality of service) constraints. This problem is known as the *multiconstraint QoS routing problem*, and has been receiving significant attention. The second problem is to find a minimum number of paths that can collectively satisfy constraints between a given pair of source and destination nodes in a WDM (wavelength division multiplexing) network. For this problem, we consider the constraints on channel demand, capacity, and survivability. Note that the first and second problems focus on multiconstraint routing and multipath routing, respectively. Both problems are NP-hard, and thus we develop heuristic schemes to solve these problems in efficient manners.

Typically, routing schemes consist of two components: information advertisement and path search. Information advertisement represents the periodical or event-triggering dissemination of routing information to be used for path search. Path

search represents the computation or examination to find a path or paths to achieve a given objective, while satisfying given constraints.

For information advertisement, there are two kinds of protocols: link-state protocols [Moy95] and distance-vector protocols [MaS95]. If a link-state protocol is used for information advertisement, each node u distributes to all other nodes the detailed information on the links between u and its neighboring nodes. Thus, the control message overhead for information advertisement is large in routing schemes based on link-state protocols. However, information advertisement using a link-state protocol is advantageous for path search, in the sense that routing paths can be computed using detailed link-state information.

In contrast, if a distance-vector protocol is used, each node u is provided the following information from each neighboring node v: the estimated value of the "best" (with respect to each of the attributes considered) path between v and every possible destination node. Node u estimates and updates the value of the best path to every possible destination node with respect to each attribute, using the estimates obtained from its neighboring nodes and the corresponding values of the links between u and the neighboring nodes. Because each node exchanges estimated values only with its neighboring nodes, distance-vector protocols have smaller signaling overhead than that of link-state protocols for the distribution of routing information.

Depending not only on given constraints but also on the protocol used for information advertisement, path search in multiconstraint routing may cause heavy signaling overhead or require intensive computation. In this thesis, we focus on path search, with the assumption that a protocol for information advertisement is given. For the first problem, we develop two routing schemes based on link-state and distance-vector protocols, respectively. For the second problem, we assume that a link-state protocol is used, and develop two routing schemes with characteristics different from each other.

1.2 Multiconstraint QoS routing

The notion of QoS has been proposed for the qualitatively or quantitatively defined performance contract between a service provider and a user. The QoS requirements of a user for a connection impose a set of constraints for routing. Multiconstraint QoS routing is to find a path satisfying the QoS constraints between given source and destination nodes, called a *feasible* path. The optimization of resource utilization is often considered additionally (e.g., [ChN98b, FeM02, KoK01, LiR01]).

Multiconstraint QoS routing is an essential mechanism to support future high-quality multimedia services. A great number of multiconstraint QoS routing schemes have been proposed for specific routing problems (e.g., the scheme in [WaC96] for routing problems with limitations on bandwidth and delay). However, in this thesis, we deal with "general" multiconstraint QoS routing schemes, which can be applied to routing problems with any QoS constraints.

We can classify multiconstraint QoS routing schemes into unicast routing schemes and multicast routing schemes, according to the number of destination nodes involved. *Unicast routing schemes* search for a feasible path between a single pair of source and destination nodes (e.g., [CuX03, GhS01, MaS97, KoK01, NeM00]). In contrast, *multicast routing schemes* search for a feasible tree covering a single source node and a set of destination nodes (e.g., [RoB02, RoB97, WuH00]). In this thesis, we limit ourselves to unicast routing schemes.

We can also classify multiconstraint QoS routing schemes into source routing schemes and distributed routing schemes, according to how many nodes in a given network participate in path search. In *source routing schemes* (e.g., [ChN98a, Jaf84, KoK01, NeM00, Yua02]), the source node computes a routing path using global state information (i.e., the routing information of all the nodes and links in the network), which is typically provided by a link-state protocol. Because of the local computation by the source node, source routing schemes are conceptually simple and easy to implement, maintain, and upgrade. In contrast, in *distributed routing schemes* (e.g.,

[GhS01, ShC95, SoP00, WaC96]), the path-search process is distributed among the nodes between source and destination nodes. Hence, the computational overhead at each node is relatively low, and thus distributed routing schemes are more scalable than source routing schemes.

We can further classify distributed routing schemes into two groups, according to how the routing information of a given network is maintained: distributed routing schemes using global state information and distributed routing schemes using local state information only. The global state information is provided by link-state or distance-vector routing protocols used for information advertisement. Distributed routing schemes using global state information have several features similar to those of source routing schemes because of the same information-advertisement process. In contrast, distributed routing schemes using local state information do not need information advertisement. However, these schemes have the drawback of heavy message overhead during the path-search procedure, because a large number of copies of a given connection request must be forwarded to find a feasible path. We limit our interest to routing schemes that can be implemented as source routing schemes or distributed routing schemes using global state information.

1.3 Survivable multipath routing for WDM networks

By aggregating wavelength channels onto a fiber, wavelength division multiplexing (WDM) makes it possible to use the large bandwidth of a fiber for a number of connections without the need for high-speed optoelectronic devices. It is clear that WDM networks will play an important role in the high-capacity telecommunication world. Kotelly [Kot96] pointed out that all major long-distance carriers in the United States have already used point-to-point WDM transmission technologies, and that wavelength routing will be introduced in most carrier networks in the world soon.

As the number of channels accommodated on a fiber increases, the following problem becomes more critical: even a single link failure may lead to the loss of many

end-to-end connections. Hence, survivability is indispensable in WDM networks. Moreover, as WDM transmission technologies are used more widely in current point-to-point networks, the dynamic establishment of channel demands becomes more important. In this thesis, we deal with the routing problem of finding a set of paths between a pair of source and destination nodes on a given physical network topology such that the paths accommodate the requested channels without violating given constraints, including the constraint on survivability. To develop routing schemes for this problem, we assume that the routing information associated with each link in the network is provided to the source node by a link-state protocol.

Survivable routing schemes can be categorized into two groups: restoration schemes (also known as dynamic or reactive schemes) and protection schemes (also known as preplanned or proactive schemes) [Ban99, HwA01, Kya98, RaM99, ZaO03]. Restoration schemes do not reserve redundant resources for backup channels. Instead, when failures occur, they search for available channels to reroute the connections of affected channels. In contrast, protection schemes reserve backup channels in advance so that in the event of failure the backup channels replace the affected channels. Protection schemes not only guarantee communication restoration, but also minimize the duration and range of failure impact. These features of protection schemes are highly desirable for networks that require high reliability. We limit our interest to protection schemes in this thesis.

1.4 Organization and contributions

The organization and contributions of this thesis are as follows.

Chapter 2: In this chapter, we develop a multiconstraint QoS routing scheme, called MPLMR (multi-postpath-based lookahead multiconstraint routing), with the assumption that a link-state protocol is used for information advertisement. MPLMR uses an extended version of a standard (single-constraint) shortest-path algorithm with the notion of the nonlinear path length. Like previous schemes using extended

shortest-path algorithms for polynomial complexity, MPLMR stores a limited number of subpaths between the source node and each intermediate node, and extends these subpaths toward the destination node. However, MPLMR uses an improved "look-ahead" method to predict the path length of the full path to which each subpath is extended. MPLMR then selects and stores the subpaths that have higher likelihood than other subpaths to be extended to feasible paths. We show via simulation that MPLMR has a significantly smaller probability of missing a feasible path than competing schemes in the literature.

Chapter 3: In this chapter, we propose another multiconstraint QoS routing scheme, called SPMP (single-prepath multi-postpaths). Different from most previous multiconstraint QoS routing schemes and MPLMR, SPMP assumes that a distance-vector protocol is used for information advertisement. Moreover, SPMP minimizes the number of nodes involved in the routing process by taking a sequential path-search approach. Hence, SPMP is a multiconstraint QoS routing scheme that is appropriate for a routing environment where the signaling overhead must be reduced. Via simulation, we show that SPMP has low average-case time complexity.

Chapter 4: Most previous protection schemes for WDM networks assume that the maximum number of simultaneous link failures is known (e.g., at most a single link failure), and search for link-disjoint paths based on this assumption. However, we take an alternative approach by introducing link failure probabilities to the routing problem, to develop routing schemes based on more general assumptions. In this chapter, we propose two survivable multipath routing schemes for WDM networks: CPMR (conditional-penalization multipath routing) and SPMR (successive-penalization multipath routing). These schemes allow each link to be used for several channels. To deal with the difficulty that this link-sharing causes, we develop "link penalization" methods to control link-sharing. CPMR takes a long run-time to find a near-optimal solution, while SPMR uses a simple penalization method to reduce the run-time at the slight expense of the routing success rate. We show via simulation

that our schemes have significantly higher routing success rates than a routing scheme that searches for disjoint paths.

Chapter 5: We summarize the important results of this thesis, and discuss some directions for future research.

2. MULTICONSTRAINT QOS ROUTING USING AN EFFICIENT LOOKAHEAD METHOD BASED ON LINK-STATE PROTOCOLS

2.1 Introduction

In this chapter, we deal with the multiconstraint QoS routing problem that searches for a feasible path between a single pair of source and destination nodes. We assume that a link-state protocol is used for the advertisement of routing information. Hence, detailed routing information (i.e., the topology of a given network and QoS attribute values of every link) is assumed to be avaliable for path search. However, this multiconstraint QoS routing problem is NP-complete [Wan99], and thus we need heuristic schemes to solve this problem within a limited time. Because heuristic schemes may fail to find an existing solution, typical performance measures for multiconstraint QoS routing schemes are time/memory complexity and erroneous decision rate (EDR). The *EDR* is defined as the fraction of instances that a routing scheme either fails to find a feasible path that exists, or finds a path that turns out to be infeasible. Low complexity and low EDR are the main goals of multiconstraint QoS routing schemes.

Every QoS attribute to be considered in multiconstraint QoS routing is either a min/max attribute or a cumulative attribute (i.e., an additive attribute and a multiplicative attribute in [Wan99]). A *min/max attribute* is a QoS attribute whose value for a path is the minimum/maximum value of that QoS attribute for any link on the path. In contrast, a *cumulative attribute* is a QoS attribute whose value for a path is the sum or product of that QoS attribute for all the links on the path. Because QoS attribute values of every link are known, min/max attributes (e.g., bandwidth) can be dealt with easily by pruning all links (and possibly their incident nodes) that

do not satisfy the constraints on the attributes before starting to search for a feasible path [WaC96]. Multiplicative QoS attributes can be regarded as additive by taking logarithms. Therefore, it suffices to consider only additive QoS attributes for the multiconstraint QoS routing problem. Hence, the constraint values are the maximum values that the QoS attributes of a routing path must not exceed.

Because of the additivity of QoS attributes considered, the value of a path with respect to a QoS attribute can be regarded as the "length" of the path with respect to the QoS attribute. If a QoS routing problem has only one QoS attribute considered, then the single-constraint QoS routing problem can be solved using a standard shortest-path algorithm (e.g., Dijkstra's algorithm or the Bellman-Ford algorithm). It is easy to see that the single-constraint QoS routing problem has a feasible solution if and only if the shortest path between the source and destination nodes is feasible.

To solve the multiconstraint QoS routing problem in the same way, several schemes take the approach that uses extended versions of a standard shortest-path algorithm, which we call *extended shortest path algorithms* in this chapter. However, these schemes must use a modified definition of length, because the "length" in the multiconstraint QoS routing problem cannot be defined as in the single-constraint QoS routing problem. Unfortunately, for the modified definitions of length, the multiconstraint QoS routing problem has the following property: *The shortest path between the source node and an arbitrary node u may not be a subpath of the shortest path between the source and destination nodes through u.* Hence, to find the shortest path between the source and destination nodes, we may have to store all the subpaths between the source node and each intermediate node during the routing procedure, extend them to the destination node, and compare all the paths between the source and destination nodes at the end. Unfortunately, this path search has exponential complexity.

Before we describe our approach to solving the multiconstraint QoS routing problem, we introduce the following terms: prepath, postpath, and full path. For an arbitrary node u, we call any path p from source node s to u a *prepath* of u, and any

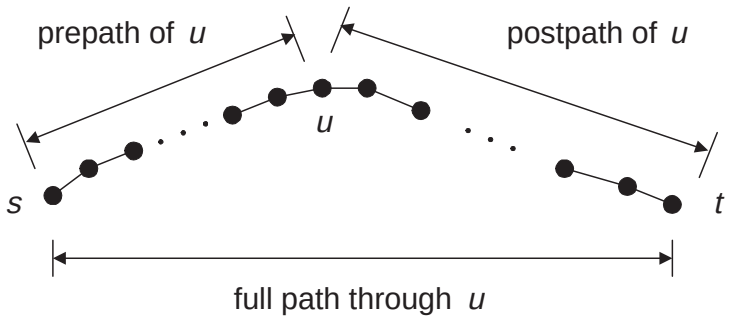


Fig. 2.1. A prepath and a postpath of node u, and a full path through node u when s and t are source and destination (terminal) nodes, respectively.

path π from u to destination node t a *postpath* of u. We call u the *endpoint node*[1] of p or π. In addition, we call any path between a given pair of source and destination nodes a *full path*, as illustrated in Figure 2.1.

To achieve polynomial complexity, heuristic multiconstraint QoS routing schemes using extended shortest-path algorithms limit the number of the prepaths to be stored for each node. Thus, these schemes should select the prepaths that have higher likelihood than other prepaths to be extended to the shortest full path. Typically, heuristic measures are used for the selection of prepaths, due to the NP-completeness of the multiconstraint QoS routing problem. These measures determine the performance of the schemes, and thus are the heart of the multiconstraint QoS routing schemes using extended shortest-path algorithms.

In this chapter, we propose a multiconstraint QoS routing scheme, called MPLMR (multi-postpath-based lookahead multiconstraint routing). Like previous schemes, e.g., TAMCRA [NeM00], MPLMR uses an extended shortest-path algorithm with the notion of the nonlinear path length, which will be explained in the following section. MPLMR also uses a "lookahead" method, exploited in previous schemes,

[1]Strictly speaking, every prepath p or postpath π has two endpoint nodes: source node s and destination node t are also endpoint nodes of p and π, respectively. However, in this chapter, we use the term "endpoint node" only for u (i.e., not s or t).

e.g., H_MCOP[2] [KoK01]. That is, MPLMR considers postpaths associated with prepaths for the selection of a limited number of prepaths to be stored during the routing procedure. However, MPLMR uses a more effective lookahead method than H_MCOP. In contrast to H_MCOP, which precomputes a single postpath for each node, MPLMR precomputes multiple postpaths for each node. During the routing procedure, MPLMR uses these postpaths to estimate the nonlinear path length of the shortest full path to which each prepath is extended. Using this lookahead method, MPLMR selects prepaths with higher likelihood than other prepaths to be extended to the shortest full path. We show via simulation that MPLMR performs much better than TAMCRA and H_MCOP without sacrificing execution time.

The rest of this chapter is organized as follows. In Section 2.2, we introduce our assumptions and notation, state the multiconstraint QoS routing problem, and discuss the notions of nonlinear path length and lookahead methods. We summarize related work on multiconstraint QoS routing in Section 2.3. In Section 2.4, we discuss the approach of MPLMR to multiconstraint QoS routing. We describe the algorithm and complexity of MPLMR in Section 2.5. In Section 2.6, we use simulation to evaluate and compare MPLMR with competing schemes in the literature. We conclude in Section 2.7.

2.2 Assumptions and definitions

2.2.1 Multiconstraint QoS routing problem

We assume that the following are given: a connected network topology, a source node, a destination node, a set of QoS attribute values associated with each link, and the QoS constraints that the routing path must satisfy. We assume that the network topology is represented by an undirected graph, although we can treat network

[2]H_MCOP searches for the path that not only is feasible but also minimizes the value of a primary QoS attribute. However, if there is no primary QoS attribute designated, we can use H_MCOP just for finding a feasible path, as pointed out in [FeM02, KoK01, KuM02]. Throughout this chapter, we assume that H_MCOP does not have a primary QoS attribute designated.

topologies represented by directed graphs without additional difficulty. We also assume that there is at most one link between any two nodes, that the network topology does not change throughout the routing procedure, and that every QoS attribute is additive, nonnegative, and fixed.

Because there is at most one link between any two nodes, we can represent any link by its two endpoint nodes. We denote the link between arbitrary nodes u and v by uv. To represent a path between two arbitrary nodes, we list all the nodes on the path between '$\langle$' and '$\rangle$'. For example, we denote the path consisting of nodes u, v, and w (in order) by $\langle u, v, w\rangle$. With this notation and all of the above assumptions, we state the multiconstraint QoS routing problem as follows.

Definition 2.2.1 (Multiconstraint QoS Routing Problem) *Suppose we are given a connected graph representing a network topology, $G = (V, E)$, where V and E represent sets of n nodes and m links, respectively. Suppose also that each link uv is characterized by nonnegative values with respect to q additive QoS attributes, $d_i(uv) \geq 0, i = 1, \ldots, q$. Given a source node s, a destination node t, and a constraint value C_i with respect to the ith QoS attribute for $i = 1, \ldots, q$, find a path $p = \langle s, w_1, \ldots, w_b, t\rangle$, where $w_j, j = 1, \ldots, b$, is an intermediate node on path p, such that the value of path p with respect to the ith QoS attribute, i.e., $L_i(p) = d_i(sw_1) + d_i(w_1w_2) + \ldots + d_i(w_bt)$, is less than or equal to the corresponding constraint value C_i for every $i = 1, \ldots, q$.*

2.2.2 Nonlinear path length

One approach to solving the multiconstraint QoS routing problem is to use an extended shortest-path algorithm. However, the "length" of a path in the multiconstraint QoS routing problem cannot be defined as in the single-constraint shortest-path problem. To resolve this difficulty, Neve and Mieghem [NeM00] propose the notion of nonlinear path length, described as follows. Let C_i and $L_i(p)$ for $i = 1, \ldots, q$

be as defined in Definition 2.2.1. Also define the *normalized length* of path p with respect to the ith QoS attribute, denoted by $NL_i(p)$, as follows:

$$NL_i(p) = \frac{L_i(p)}{C_i} \ . \tag{2.1}$$

The *nonlinear path length* of p, denoted by $\Lambda(p)$, is defined to be the maximum of the normalized lengths of p with respect to each QoS attribute, as follows:[3]

$$\Lambda(p) = \max\left[NL_1(p), NL_2(p), \ldots, NL_q(p)\right] \ . \tag{2.2}$$

It is straightforward to see that path p is feasible if and only if $\Lambda(p) \leq 1$. For the single-constraint QoS routing problem, this reduces to that p is feasible if and only if $L_I(p)/C_1 \leq 1$. Therefore, the nonlinear path length provides a basis for using a standard (single-constraint) shortest-path algorithm for the multiconstraint QoS routing problem. However, standard shortest-path algorithms rely on the property that the length of a path is the sum of quantities associated only with individual links on the path, a property that fails to hold for the nonlinear path length. For this reason, multiconstraint QoS routing schemes using the nonlinear path length as the measure for the "length" of a path entails a modification of the standard approach (the modification will be described in the following sections).

2.2.3 Eligibility test and lookahead method

An arbitrary prepath p of a node u is *dominated* [Hen85] if there is another prepath of u that has no larger value than p with respect to every QoS attribute, and has strictly smaller values than p with respect to some QoS attributes. If p is dominated by another prepath p' of node u, and if p' cannot be extended to a feasible path, then p also cannot. Hence, a brute-force approach is to maintain a set for each node that contains all nondominated prepaths found during the routing procedure, and extend the prepaths to the destination node [WaV00]. When the algorithm terminates, we

[3]The definition here is a special case of the definition in [NeM00].

get all nondominated full paths, and thus we can check their feasibility. However, this brute-force algorithm has exponential complexity.

To achieve polynomial complexity, extended shortest-path algorithms for multi-constraint QoS routing limit the number of prepaths to be stored for each node. Ideally, these schemes select prepaths that have higher likelihood than other prepaths to be extended to the shortest full path (in terms of the modified "length," the nonlinear path length). Eligibility tests and lookahead methods can be used for this purpose.

Eligibility tests check if each prepath has the possibility to be extended to a feasible path. We call a prepath *eligible* if it has any possibility to be extended to a feasible path (eligibility depends on the specific test being used). By eliminating ineligible prepaths from consideration, we can reduce the "search space" in which we search for a feasible path.

The idea of *lookahead* methods is that the consideration of postpaths associated with prepaths is helpful for selecting prepaths with higher likelihood than other prepaths to be extended to the shortest full path. Using lookahead methods, we estimate the nonlinear path length of the shortest full path to which each prepath is extended. Due to the NP-completeness of the multiconstraint QoS routing problem, we cannot consider all the postpaths associated with a given set of prepaths. Hence, we first select some specific subset of the postpaths for applying a lookahead method, as described later.

2.3 Related work

Neve and Mieghem propose a modification to the brute-force algorithm, called TAMCRA [NeM00], by limiting the number of prepaths to be stored for each node. TAMCRA includes an extended version of Dijkstra's algorithm using the nonlinear path length as the metric. During the course of the routing procedure, TAMCRA stores for each node at most k shortest (in terms of nonlinear path length) prepaths

that have been found so far, hoping that these prepaths would have higher likelihood than other prepaths to be extended to the shortest full path. However, TAMCRA uses no lookahead method. That is, when TAMCRA selects the prepaths to be stored for each node, the scheme considers the nonlinear path lengths of the prepaths only. Hence, if an arbitrary node u finds a new prepath p_n that has nonlinear path length smaller than its kth shortest prepath p_k, then p_n replaces p_k, even though prepath p_n may be connected to a much longer postpath than that of p_k. Neve and Mieghem also propose an alternative scheme, called SAMCRA [MiN01]. SAMCRA is almost the same as TAMCRA, but SAMCRA does not limit the number of prepaths to be stored for each node to guarantee finding an existing feasible path. Yuan proposes a scheme called the limited path heuristic [Yua02], which is similar to TAMCRA. However, for each node, the limited path heuristic stores the k prepaths that are not necessarily the shortest. Yuan proves that low EDR can be achieved by maintaining $O(n^2 \log n)$ prepaths for each node, where n is the number of nodes.

To overcome the drawback of TAMCRA mentioned above, Korkmaz and Krunz propose an enhanced scheme, called H_MCOP [KoK01]. Different from TAMCRA, H_MCOP uses a lookahead method as follows. H_MCOP precomputes a single postpath for each node at the first step of the routing procedure, with the hope that this single postpath would be the subpath of a feasible path through the node. Then, H_MCOP uses the postpath to update the set of at most k prepaths for each node, with the goal that combining these prepaths with the postpath results in near-minimum nonlinear path lengths. However, if the precomputed postpath is not the subpath of a feasible path, then the postpath may misguide the selection of prepaths. A* Prune [LiR01], proposed by Liu and Ramakrishnan for the problem of finding multiple feasible paths, uses a lookahead method similar to the one in H_MCOP. As in SAMCRA, A* Prune does not limit the maximum number of prepaths to be stored for each node.

There are several other approaches for solving the multiconstraint QoS routing problem. Some multiconstraint QoS routing schemes partition the QoS attribute val-

ues into a finite number of intervals and apply dynamic programming techniques or distributed routing techniques [Has92, Jaf84]. Some others prioritize QoS attributes to search for the path that optimizes the value of the top-priority QoS attribute under constraints on other QoS attributes [ChN99, ReS00, WaC96]. To reduce the NP-complete multiconstraint QoS routing problem to one that is solvable in polynomial time, some schemes approximate the given QoS attribute values [ChN98a, Yua02] or network topologies via topology aggregation [ChH01]. Similarly, the dependencies between QoS attributes are also exploited for the simplification of a given multiconstraint QoS routing problem [MaS97, PoC97]. There are also schemes that precompute the solutions to the expected routing problems to reduce the path-search time [CuX03].

In our study, we do not compare our scheme with all of the above schemes, limiting our comparison only to TAMCRA and H_MCOP. The performance of the schemes in [MiN01] and in [LiR01] corresponds to that of TAMCRA and H_MCOP respectively, when an infinite number of prepaths can be stored for each node to find a single feasible path. Korkmaz and Krunz [KoK01] maintain that H_MCOP is significantly superior to the schemes in [ChN98a, Has92, Jaf84, Yua02]. The number of additive QoS attributes to be considered in [ChN99, MaS97, PoC97, ReS00, WaC96] is limited to only two or less. As topology aggregation is used in [ChH01], the imprecision in estimating aggregated values of QoS attributes also accumulates, and this has a significant negative impact on QoS routing [GuO97]. The precomputation scheme in [CuX03] cannot solve routing problems if connection requests have QoS constraint values for which solutions are not prepared in advanced.

2.4 Elements of our approach

2.4.1 Multiple postpaths

Our approach to multiconstraint QoS routing, called MPLMR (described in detail in Section 2.5), uses an extended shortest-path routing algorithm based on the notion

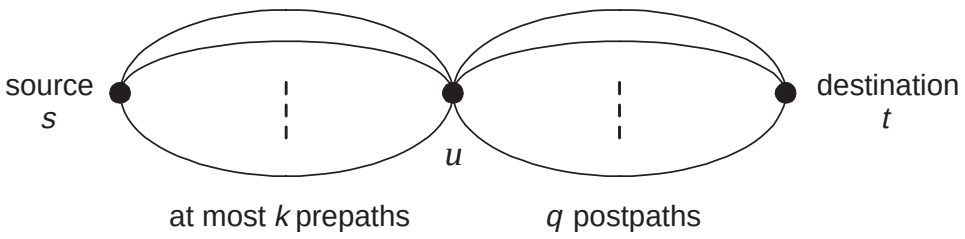


Fig. 2.2. Prepaths and postpaths for each node u.

of the nonlinear path length. Like previous schemes (e.g., TAMCRA and H_MCOP), MPLMR stores at most k prepaths for each node and updates them during the routing procedure, with the intent that these prepaths have higher likelihood than other prepaths to be extended to the shortest (in terms of nonlinear path length) full path. In addition, MPLMR incorporates a lookahead method by selecting and storing q postpaths for each node u at the beginning of the routing procedure (recall that q is the number of QoS attributes), as is shown in Figure 2.2. Each of these postpaths is the shortest path between u and destination node t with respect to the corresponding QoS attribute, i.e., the ith postpath has the smallest value for the ith QoS attribute among all possible postpaths. MPLMR uses these postpaths for the eligibility test and the lookahead method, as described in the following sections.

2.4.2 Eligibility test of MPLMR

Let p be a prepath of an intermediate node u, $\pi_j(u)$ the shortest postpath of u with respect to the jth QoS attribute for $j = 1, \ldots, q$, and $p + \pi_j(u)$ the full path combining p with $\pi_j(u)$. For each prepath p, MPLMR performs the following three steps. (1) MPLMR checks if p is dominated by any other prepath stored for node u, as TAMCRA does. If p is dominated by another prepath p', MPLMR eliminates p from consideration (because if p' cannot be extended to a feasible path, then p also cannot). (ii) If p is not dominated, MPLMR checks if the combined path $p + \pi_j(u)$ is

feasible for $j = 1, \ldots, q$. If any of these combined paths is feasible, then the routing procedure terminates—this combined path solves the routing problem. (iii) If none of the combined paths is feasible, MPLMR investigates the eligibility of p by checking if $NL_j(p + \pi_j(u)) > 1$ for any $j = 1, \ldots q$, following the method introduced in [KoK99]. If $NL_j(p + \pi_j(u)) > 1$, then p is declared ineligible because every full path extended from p violates the jth QoS constraint (recall that $\pi_j(u)$ is the shortest postpath of u with respect to the jth QoS attribute)—in this case, MPLMR eliminates p from consideration. Otherwise, p is declared eligible.

2.4.3 Lookahead method of MPLMR

Let node u, prepath p, and postpaths $\pi_j(u)$ be as given in Section 2.4.2. If the combined path $p + \pi_j(u)$ is infeasible for $j = 1, \ldots, q$, but if p is still eligible, then MPLMR uses its lookahead method to estimate the nonlinear path length of the shortest full path extended from p. To explain the lookahead method, let $p_s(p)$ be the shortest (in terms of nonlinear path length) full path extended from p, and π^* be the corresponding postpath of u (i.e., $p_s(p) = p + \pi^*$). The basic idea in the lookahead method of MPLMR is to estimate $NL_i(p_s(p))$ (i.e., the normalized length of $p_s(p)$ with respect to the ith QoS attribute) as the weighted sum of $NL_i(p + \pi_j(u))$ (i.e., the normalized length of $p + \pi_j(u)$ with respect to the ith QoS attribute) for $j = 1, \ldots, q$. Let w_{ij} be the weight of $NL_i(p + \pi_j(u))$ used to estimate the value of $NL_i(p_s(p))$. The estimated normalized length of $p_s(p)$ with respect to the ith QoS attribute, denoted by $\widetilde{NL}_i(p_s(p))$, is represented as follows:

$$\widetilde{NL}_i(p_s(p)) = \sum_{j=1}^{q} w_{ij} NL_i(p + \pi_j(u)), \tag{2.3}$$

where

$$\sum_{j=1}^{q} w_{ij} = 1. \tag{2.4}$$

As in (2.2), the estimated nonlinear path length of $p_s(p)$, denoted by $\widetilde{\Lambda}(p_s(p))$, is defined as follows:

$$\widetilde{\Lambda}(p_s(p)) = \max_{i=1,\ldots,q} \widetilde{NL}_i(p_s(p)). \tag{2.5}$$

MPLMR uses $\widetilde{\Lambda}(p_s(p))$ as the basis to determine if p should be stored for node u.

As shown in (2.3) and (2.5), the estimated nonlinear path length of $p_s(p)$ is determined by the estimated normalized lengths of $p_s(p)$, which depend on the weight values w_{ij} for $i = 1, \ldots, q$ and $j = 1, \ldots, q$. Hence, the selection of appropriate weight values is important. To select the weight values, we take into account the following two observations. First, $p_s(p)$ is likely to have a smaller normalized length with respect to every QoS attribute than most of the full paths extended from p. Based on this observation, our selection of the weights has the following property:

Property 1 *For each i and j, the smaller the value of $NL_i(p+\pi_j(u))$, the larger the value of w_{ij} in (2.3).*

The second observation is the following. Because $\pi_j(u)$ is the shortest postpath of node u with respect to the jth QoS attribute, $NL_j(p_s(p)) \geq NL_j(p + \pi_j(u))$. Thus, as the value of $NL_j(p + \pi_j(u))$ becomes larger, it becomes more probable that $NL_j(p_s(p)) > 1$, which is a violation of the jth QoS constraint. Hence, if the value of $NL_j(p + \pi_j(u))$ is larger than the value of $NL_i(p + \pi_i(u))$ (recall that if p is an eligible prepath, $NL_i(p+\pi_i(u)) \leq 1$ is nonnegative for $i = 1, \ldots, q$), then the jth QoS constraint is more stringent than the ith QoS constraint. In this case, the satisfaction of the jth QoS constraint must be given a higher priority than the ith QoS constraint if we are to find a feasible path by extending prepath p toward the destination node. For satisfying the jth QoS constraint, it is advantageous to take $\pi_j(u)$ as the postpath to be connected to p. Hence, as the value of $NL_j(p + \pi_j(u))$ becomes larger, π^* will likely be "closer" to $\pi_j(u)$ (i.e., π^* will likely share more links with $\pi_j(u)$). Based on this observation, our weight selection has the following property:

Property 2 *For each j, the larger the value of $NL_j(p + \pi_j(u))$, the larger the value of w_{ij} for all i in (2.3).*

Let r be a nonnegative real constant. Based on Properties 1 and 2, MPLMR uses the following weight w_{ij} for (2.3):

$$w_{ij} = \frac{a_i}{[NL_i(p + \pi_j(u))]^r [1 - NL_j(p + \pi_j(u))]}, \tag{2.6}$$

where

$$a_i = \Big(\sum_{j=1}^{q} \frac{1}{[NL_i(p + \pi_j(u))]^r [1 - NL_j(p + \pi_j(u))]} \Big)^{-1}. \tag{2.7}$$

In (2.6) and (2.7), a_i is the value needed to satisfy the condition of (2.4) for $i = 1, \ldots, q$, and r is a variable to control the relative contributions of $NL_i(p+\pi_j(u))$ and $1 - NL_j(p + \pi_j(u))$ to w_{ij}. (The effect of r to the performance of MPLMR will be described in Section 2.5.2.)

If $NL_i(p + \pi_j(u)) = 0$ or $NL_j(p + \pi_j(u)) = 1$, we cannot compute the value of $\widetilde{NL}_i(p_s(p))$ in (2.3) because the weight expression in (2.6) is not defined. To deal with this difficulty, MPLMR sets $\widetilde{NL}_i(p_s(p)) = 0$ if $NL_i(p + \pi_j(u)) = 0$, and simply eliminates p from consideration if $NL_j(p + \pi_j(u)) = 1$ and $u \neq t$ (recall that if $NL_j(p+\pi_j(u)) = 1$ and $u = t$, then the routing procedure terminates because $p+\pi_j(u)$ is a feasible path).

2.5 MPLMR: multi-postpath-based lookahead multiconstraint routing

2.5.1 MPLMR algorithm

The basic principle of MPLMR is to select and update at most k prepaths for each node u during the routing procedure, as in previous schemes (e.g., TAMCRA and H_MCOP). However, in contrast to previous schemes, MPLMR selects the prepaths of u to minimize the estimated nonlinear path lengths of the full paths containing these prepaths (i.e., the values of (2.5).) To compute the estimated nonlinear path lengths of (2.5), MPLMR uses (2.1), (2.3), (2.6), and (2.7). The pseudocode of MPLMR is shown in Figure 2.3.

When a connection request occurs, MPLMR starts the routing procedure. Lines 01–06 represent the initialization procedure of the modified Dijkstra's algo-

```
MPLMR(G = (V, E), s, t, q, k, C_1, ..., C_q)

01 for every v ∈ V, do
02     find the shortest postpath π_i(v) for i = 1, ..., q    /* using C_1, ..., C_q */
03     P(v) ← { }    /* P(v): set of prepaths to be stored for v */
04 if NL_i(π_i(s)) > 1 for any i = 1, ..., q, then
05     stop    /* routing failure: no feasible path */
06 Q ← {⟨s⟩}    /* Q: set of prepaths to be extended toward t */
07 while Q is not empty, do
08     x ← a path in Q such that Λ̃(p_s(x)) ≤ Λ̃(p_s(p)) for any path p ∈ Q
09     w ← endpoint node of x
10     Q ← Q − {x}
11     for each outgoing node u of w that is not on x, do
12         y ← x + wu    /* x extended to u */
13         if y is not dominated by another prepath of u in P(u), then
14             for each j = 1, ..., q, do
15                 if NL_i(y + π_j(u)) ≤ 1 for all i = 1, ..., q, then
16                     stop    /* routing success: y + π_j(u) is feasible */
17             if NL_i(y + π_i(u)) ≤ 1 for i = 1, ..., q and |P(u)| < k, then
               /* |P(u)|: number of paths in P(u) */
18                 Q ← Q ∪ {y} and P(u) ← P(u) ∪ {y}
19             if NL_i(y + π_i(u)) ≤ 1 for i = 1, ..., q and |P(u)| = k, then
20                 z ← a path in P(u) such that Λ̃(p_s(z)) ≥ Λ̃(p_s(p)) for any p in P(u)
21                 if Λ̃(p_s(z)) > Λ̃(p_s(y)), then
22                     Q ← Q ∪ {y} and P(u) ← P(u) − {z} ∪ {y}
23                     if z ∈ Q, then
24                         Q ← Q − {z}
25 stop    /* routing failure: no feasible path found */
```

Fig. 2.3. The pseudocode of MPLMR.

rithm, described on lines 07–25. We can use any standard shortest-path algorithm to find the q postpaths for every node on line 02. On lines 04–05, if the normalized length of the ith postpath of source node s with respect to the ith QoS attribute exceeds one, the routing procedure stops because no full path can satisfy the ith QoS constraint. MPLMR maintains a set $P(v)$ for each node v, and another set Q. $P(v)$ contains at most k prepaths of v, and Q contains prepaths (of any node) to be extended toward t. On line 06, Q initially contains only a zero-length path from s to itself.

While Q is not empty, MPLMR extracts from Q a prepath, denoted by x, such that the estimated nonlinear path length of the shortest full path including x is the smallest (lines 08–10). If the endpoint node of prepath x (denoted by w) has outgoing nodes, then MPLMR extends x to an outgoing node u that is not on x (the extended prepath is denoted by y on line 12). If y is not dominated by any other prepaths of u that are stored in $P(u)$, MPLMR performs the following tasks. (i) MPLMR checks the feasibility of the full paths that consist of y and each of the postpaths of u. If any of these full paths turns out to be feasible, then MPLMR outputs the path as a solution to the multiconstraint QoS routing problem, and terminates the routing procedure (lines 14–16). (ii) If none of the full paths is feasible, but if y is eligible (i.e., $NL_i(y + \pi_i(u)) \leq 1$ for $i = 1, \ldots, q$), then MPLMR inserts y into Q and $P(u)$. However, in this case, if the number of the prepaths that are stored for u (in $P(u)$) exceeds k (by one), then MPLMR removes a prepath from Q and $P(u)$, such that the shortest full path extended from this prepath has a larger estimated nonlinear path length than the shortest full paths extended from any other prepaths of u in $P(u)$. If there is no prepath in Q, then the routing procedure terminates on line 25 with no feasible path found.

2.5.2 Control variable r

MPLMR uses the estimated nonlinear path length in (2.5) as the basis for selecting the prepaths to be stored for each node. Because MPLMR computes the estimated nonlinear path length using the weight values given in (2.6), the value of control variable r of the weight affects the selection of prepaths. In (2.6), we can see that the value of the weight becomes more dependent on Property 1 (Property 2) as the value of r increases (decreases). Property 1 makes $\widetilde{NL}_i(p_s(p))$ close to $NL_i(p+\pi_i(u))$ for $i = 1, \ldots, q$, which is the minimum value that $NL_i(p_s(p))$ could take from the viewpoint of the endpoint node of p. Hence, the following proposition holds:

Proposition 2.5.1 *Let p be a prepath of node u, $p_s(p)$ the shortest (in terms of nonlinear path length) full path extended from p, and $\pi_j(u)$ the shortest postpath of u with respect to the j*th *QoS attribute for $j = 1, \ldots, q$. If $NL_i(p + \pi_j(u)) \neq 0$ and $NL_j(p + \pi_j(u)) \neq 1$ for $i = 1, \ldots, q$ and $j = 1, \ldots, q$, then, $\lim_{r\to\infty} \widetilde{\Lambda}(p_s(p)) \leq \Lambda(p_s(p))$.*

Proof Because $\pi_i(u)$ is the shortest postpath of u with respect to the ith QoS attribute, $NL_i(p + \pi_i(u)) \leq NL_i(p + \pi_j(u))$. If $NL_i(p + \pi_i(u)) < NL_i(p + \pi_j(u))$, then $w_{ij} \to 0$ as $r \to \infty$ (see (2.6) and (2.7)). Hence, if $w_{ij} \nrightarrow 0$ as $r \to \infty$, then $NL_i(p + \pi_i(u)) = NL_i(p + \pi_j(u))$. Thus, $\widetilde{NL}_i(p_s(p)) \to NL_i(p + \pi_i(u))$ as $r \to \infty$ for $i = 1, \ldots, q$ by (2.3) and (2.4). Because of the same reason (i.e., $\pi_i(u)$ is the shortest postpath of u with respect to the ith QoS attribute), $NL_i(p + \pi_i(u)) \leq NL_i(p_s(p))$ for $i = 1, \ldots, q$. Hence, $\widetilde{NL}_i(p_s(p)) \leq NL_i(p_s(p))$ for $i = 1, \ldots, q$, and therefore $\widetilde{\Lambda}(p_s(p)) \leq \Lambda(p_s(p))$ by (2.2) and (2.5). ■

In contrast, Property 2 makes $\widetilde{NL}_i(p_s(p))$ close to $NL_i(p+\pi_j(u))$ for $i = 1, \ldots, q$ if the jth QoS constraint is the most stringent for finding a feasible path by extending prepath p toward the destination node. Thus, in this case, $\widetilde{\Lambda}(p_s(p))$ becomes closer to $\Lambda(p + \pi_j(u))$ as the value of r decreases. Note that $\Lambda(p + \pi_j(u))$ must be larger than or equal to $\Lambda(p_s(p))$, and that $\widetilde{\Lambda}(p_s(p))$ does not necessarily converge to $\Lambda(p + \pi_j(u))$ as $r \to 0$.

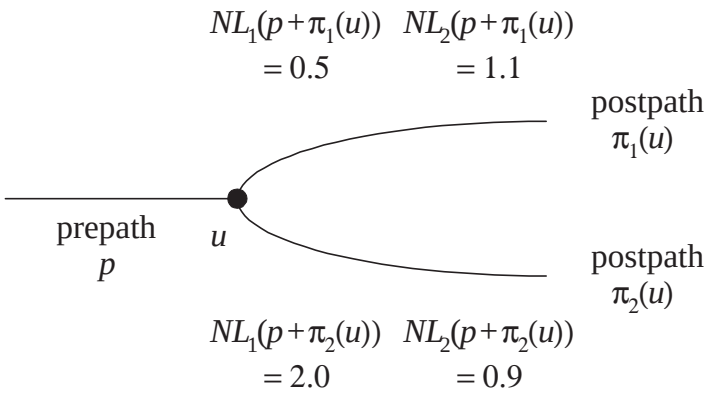


Fig. 2.4. An example to explain the effect of Properties 1 and 2.

Consider the example shown in Figure 2.4. Let the number of QoS attributes be two (i.e., $q = 2$). As illustrated, for prepath p and postpaths $\pi_j(u)$, $j = 1, 2$, of node u, suppose $NL_1(p + \pi_1(u)) = 0.5$, $NL_2(p + \pi_1(u)) = 1.1$, $NL_1(p + \pi_2(u)) = 2.0$, and $NL_2(p + \pi_2(u)) = 0.9$. Because $NL_1(p + \pi_1(u)) \leq 1$ and $NL_2(p + \pi_2(u)) \leq 1$, p is eligible. As the value of r increases, Property 1 makes the values of $\widetilde{NL}_1(p_s(u))$ and $\widetilde{NL}_2(p_s(u))$ become closer to $NL_1(p + \pi_1(u))$ (i.e., 0.5) and $NL_2(p + \pi_2(u))$ (i.e., 0.9), respectively. However, $NL_2(p + \pi_2(u)) = 0.9 > 0.5 = NL_1(p + \pi_1(u))$, and thus the second QoS constraint is more stringent than the first QoS constraint. Hence, Property 2 makes the values of $\widetilde{NL}_1(p_s(u))$ and $\widetilde{NL}_2(p_s(u))$ close to $NL_1(p + \pi_2(u))$ $(= 2.0)$ and $NL_2(p + \pi_2(u))$ $(= 0.9)$, respectively. As the value of r decreases, these estimated normalized lengths become closer to 2.0 and 0.9, respectively.

The best value of r (e.g., to minimize the EDR of MPLMR) depends on the given routing problem. Our simulation in Section 2.6 shows that the value of r to minimize EDR is typically between 3 and 10. If the value of r is much larger than the typical values, Property 1 dominates Property 2. In this case, $\widetilde{\Lambda}(p_s(p))$ is likely to be smaller than $\Lambda(p_s(p))$ (by Proposition 2.5.1), degrading the performance of MPLMR. In particular, the EDR may increase considerably for link values that are negatively correlated between QoS attributes, as will be shown in Section 2.6. This is because the shortest path with respect to a QoS attribute is likely to be long with respect to

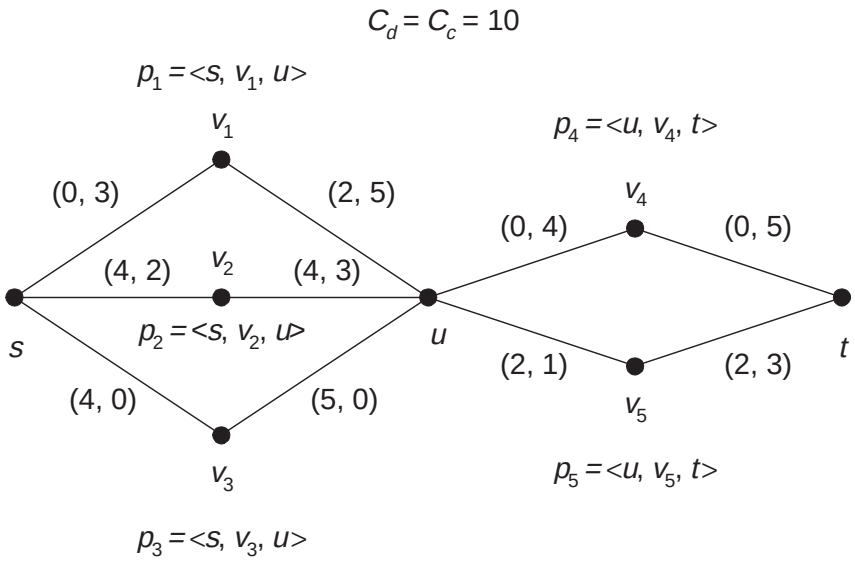


Fig. 2.5. An example to show how TAMCRA, H_MCOP, and MPLMR work.

another QoS attribute that is negatively correlated with the first QoS attribute. On the contrary, if the value of r is much smaller than the typical values, then Property 2 dominates Property 1. In this case, each estimated length may be larger than the actual length, and thus the EDR may also increase.

2.5.3 Comparison with competing schemes using an example

Figure 2.5 shows an example to compare how TAMCRA, H_MCOP, and MPMP work. Let the pair of values on each link represent two QoS attribute values associated with the link. Suppose that the constraint values with respect to the QoS attributes are given as $C_1 = C_2 = 10$, and that nodes s and t are the source and destination nodes, respectively. Suppose also that we are in the middle of the routing procedure to determine the prepaths of node u to be stored among three prepaths, p_1, p_2, and p_3. By an exhaustive search, we can see that path $p_3 + p_4 = \langle s, v_3, u, v_4, t \rangle$ is the only feasible path.

When TAMCRA selects the prepaths to be stored for u, the scheme considers the nonlinear path lengths of the prepaths only. The nonlinear path length of p_1 (i.e.,

$\Lambda(p_1))$ is 0.8 (i.e., $\min[(0+2)/10, (3+5)/10]$). Similarly, $\Lambda(p_2)$ and $\Lambda(p_3)$ are 0.8 and 0.9, respectively. Because $\Lambda(p_3) > \Lambda(p_1) = \Lambda(p_2)$, TAMCRA selects p_3 to store for u only if the maximum number of prepaths to be stored for each node (i.e., k) is at least three. Thus, TAMCRA finds a feasible path only if $k \geq 3$.

Recall that H_MCOP selects a single postpath for each node. Among all possible postpaths for each node, the selected postpath should have the minimum value of the sum of normalized lengths. Hence, H_MCOP selects path p_5 as this single postpath of node u, because the corresponding value for path p_5 (i.e., $NL_1(p_5)+NL_2(p_5) = 0.8$) is smaller than that for path p_4 (i.e., $NL_1(p_4) + NL_2(p_4) = 0.9$). When path p_5 is connected with the prepaths of u, $p_1 + p_5$, $p_2 + p_5$, and $p_3 + p_5$ have nonlinear path lengths of 1.2, 1.2, and 1.3, respectively. Because $\Lambda(p_3+p_5) > \Lambda(p_1+p_5) = \Lambda(p_2+p_5)$, H_MCOP stores p_3 for u only if $k \geq 3$. Thus, H_MCOP also finds a feasible path only if $k \geq 3$.

p_4 and p_5 are the shortest paths between u and t with respect to the first and the second QoS attributes, respectively. Hence, MPLMR selects paths p_4 and p_5 as the postpaths of node u with respect to the first and the second QoS attributes, respectively (i.e., $\pi_1(u) = p_4$ and $\pi_2(u) = p_5$). Suppose that $r = 5$. Using (2.1), MPLMR computes the normalized lengths of all the full paths in Figure 2.5, as shown in Table 2.1. Because $NL_2(p_1 + \pi_2(u)) = 1.2 > 1.0$, p_1 is ineligible. Hence, MPLMR eliminates p_1 from consideration. Using (2.6), (2.7), and the values in Table 2.1, MPLMR also computes the weight values in Table 2.2. From (2.3) and the values in Tables 2.1 and 2.2, $\widetilde{NL}_1(p_s(p_2)) = w_{11}NL_1(p_2 + \pi_1(u)) + w_{12}NL_1(p_2 + \pi_2(u)) = 0.884$. Similarly, $\widetilde{NL}_2(p_s(p_2)) = 0.926$, $\widetilde{NL}_1(p_s(p_3)) = 0.910$, and $\widetilde{NL}_2(p_s(p_3)) = 0.447$. Hence, the estimated nonlinear path lengths of the shortest full paths extended from p_2 and p_3 (i.e., $\widetilde{\Lambda}(p_s(p_2))$ and $\widetilde{\Lambda}(p_s(p_3))$) are 0.926 and 0.910, respectively. Because $\widetilde{\Lambda}(p_s(p_3)) < \widetilde{\Lambda}(p_s(p_2))$, MPLMR selects p_3 first. Therefore, MPLMR finds a feasible path even for $k = 1$.

Table 2.1

The normalized lengths of all the full paths in Figure 2.5.

$NL_1(p_1 + \pi_1(u)) = 0.2$	$NL_2(p_1 + \pi_1(u)) = 1.7$
$NL_1(p_1 + \pi_2(u)) = 0.6$	$NL_2(p_1 + \pi_2(u)) = 1.2$
$NL_1(p_2 + \pi_1(u)) = 0.8$	$NL_2(p_2 + \pi_1(u)) = 1.4$
$NL_1(p_2 + \pi_2(u)) = 1.2$	$NL_2(p_2 + \pi_2(u)) = 0.9$
$NL_1(p_3 + \pi_1(u)) = 0.9$	$NL_2(p_3 + \pi_1(u)) = 0.9$
$NL_1(p_3 + \pi_2(u)) = 1.3$	$NL_2(p_3 + \pi_2(u)) = 0.4$

Table 2.2

The values used to compute the estimated nonlinear path lengths of the shortest full paths extended from p_2 and p_3.

For p_2,
$w_{11} = 0.792$, $w_{12} = 0.208$, $w_{21} = 0.052$, and $w_{22} = 0.948$.
($a_1 = 0.0519$ and $a_2 = 0.0560$)
For p_3,
$w_{11} = 0.974$, $w_{12} = 0.026$, $w_{21} = 0.094$, and $w_{22} = 0.906$.
($a_1 = 0.0575$ and $a_2 = 0.0056$).

2.5.4 Complexity of MPLMR

Recall that n, m, and q are the numbers of nodes, links, and QoS attributes, respectively, and that k is the maximum number of prepaths to be stored for each node. Assume that we use a heap [CoL90] for the data structure to store paths. Lines 01–02 in the pseudocode of MPLMR (Figure 2.3) require q executions of a standard shortest-path algorithm to find the shortest postpaths of every node. If we use Dijkstra's algorithm, then the run-time of lines 01–02 is $O(mq+nq\log n)$ [CoL90]. Because each node has at most k prepaths, the set Q contains at most kn prepaths. The computation of the estimated nonlinear path length in (2.5) takes $O(nq^2)$ time for each prepath. Hence, the total computation time of the values for kn prepaths is $O(kn^2q^2)$. Because we use a heap structure, the run-time for selecting a prepath among at most kn prepaths and for removing/inserting the prepath on lines 10, 18, 22, and 24 is $O(kn\log(kn))$ for the entire course of the MPLMR algorithm [CoL90]. The for-loop between lines 11 and 24 should run at most k times to examine each link wu in the adjacency lists of w and u, respectively. Hence, the total number of iterations of the for-loop is $O(km)$. Each of these iterations takes $O(kq+n)$ time (without considering lines 18, 22, and 24) because of the checkup of looping and dominancy on lines 11 and 13. Thus, the run time of the for-loop between lines 11 and 24 for the entire course of the MPLMR algorithm is $O(km(kq+n))$ without considering lines 18, 22, and 24. Therefore, by adding all these contributions, we obtain the time complexity for MPLMR of $O(mq+nq\log n)+O(kn^2q^2)+O(kn\log(kn))+O(km(kq+n))=O(nq\log n+kn\log(kn)+k^2mq+kmn+kn^2q^2))$. Note that if the maximum number of prepaths per node (i.e., k) is fixed, this time complexity is polynomial. TAMCRA and H_MCOP have the time complexities of $O(kn\log(kn)+k^3mq))$ [NeM00] and $O(n\log n+km\log(kn)+m(k^2+1))$ [KoK01], respectively. Hence, the time complexity of MPLMR is comparable to those of TAMCRA and H_MCOP.

MPLMR has to store at most kn prepaths and qn postpaths. Because each path has at most n nodes, MPLMR needs $O(n^2(k+q))$ memory space. It is clear that the

EDR of MPLMR decreases as the value of k increases. Hence, MPLMR achieves low EDR at the expense of the increased run time and the memory space for an increased number of prepaths.

2.6 Performance evaluation

2.6.1 Simulation setup

To evaluate the performance of MPLMR, we perform our simulation for the QoS routing problem according to the following steps. First, we generate a random network topology. Next, we generate QoS attribute values randomly, and assign them to every link in the generated network topology, such that the values have a given distribution with a given correlation coefficient between each pair of QoS attributes. We also assign a constraint value to each QoS attribute. Then, we apply MPLMR (for several values of r), TAMCRA, H_MCOP, and MPMP[4] [ShC02] to compare their performance.

To check if there exists any feasible path, we also apply an exhaustive-search scheme, which is MPLMR without any limitation on the number of prepaths to be stored for each node (i.e., $k = \infty$). For the computation of EDR, we ascertain whether or not there is an erroneous decision for each scheme. Note that an erroneous decision in this case corresponds to a failure to find a feasible path when one exists, because we assume that all the information on a given network topology and QoS attribute values is known and fixed. We perform 10 000 simulation runs of the above procedure for each combination of the following four items: (a) the number of QoS attributes (i.e., q)—two or three, (b) the distribution of link values—two distributions that will be described, (c) the correlation coefficient between each pair of QoS attributes—the five values $-0.8, -0.4, 0, 0.4$, and 0.8, and (d) the maximum number of prepaths per node (i.e., k)—several values.

[4]We can regard MPMP as a special case of MPLMR, where r has an infinite value and the dominancy of prepaths is not checked.

We generate the random network topologies as follows: source and destination nodes are located at diagonally opposite corners of a square area of unit dimension, and then 198 nodes are spread randomly in the square area. Using the Waxman model [Wax88], we introduce a link between arbitrary nodes u and v with the following probability, which depends on the distance between them, $\delta(u, v)$:

$$Pr(uv) = \alpha \exp\left[\frac{-\delta(u, v)}{\beta\sqrt{2}}\right].$$

For the values of α and β in the above equation, we use 0.8 and 0.06, respectively. The above approach results in 200 nodes and approximately 567 links per network topology. Hence, the average node degree is 5.67.

We generate correlated random values using Randgen [MiL02], to assign each link QoS attribute values. We perform simulation for two kinds of distributions. For the first distribution, the link values with respect to every QoS attribute is distributed uniformly in $[1, 3]$, and thus the mean and standard deviation are 2 and 0.577, respectively. We set correlation between QoS attributes by the method explained in Section 7.1 of [MiL02]. The second distribution is a jointly normal distribution. The mean and standard deviation of the link values with respect to every QoS attribute are the same as in the first distribution (i.e., 2 and 0.577, respectively). Whenever we generate a negative value, we replace it by zero. Because very few values are replaced by zeros, QoS attribute values are still approximately normally distributed.

After assigning QoS attribute values, we assign constraint values. If some constraints are looser than other constraints, the multiconstraint routing problem may be easier to solve than other problems with the same number of constraints, because of the looser constraints. Hence, we assign the same value to all the constraints to keep every constraint equally difficult.

2.6.2 Simulation results

Table 2.3 shows the numbers of erroneous decisions versus correlation coefficients for the case of two QoS attributes. We obtain the EDR of each scheme for a given

Table 2.3

The number of erroneous decisions among 10 000 simulation runs for the routing problem with two QoS attributes, where MPLMR, TAMCRA, H_MCOP, and MPMP are applied to the randomly generated network topologies with QoS attribute values of (a) the first distribution and (b) the second distribution described in Section 2.6.1. The constraint value is 18 for every QoS attribute.

correlation coefficient	-0.8	-0.4	0.0	0.4	0.8
MPLMR ($k = 1, r = 5$)	3	1	0	0	0
TAMCRA ($k = 1$)	221	153	101	46	17
H_MCOP ($k = 1$)	127	74	43	19	1
MPMP ($k = 1$)	31	12	5	3	0
MPLMR ($k = 2, r = 5$)	0	0	0	0	0
TAMCRA ($k = 2$)	84	46	33	8	3
H_MCOP ($k = 2$)	88	48	25	13	1
MPMP ($k = 2$)	5	1	1	0	0

(a)

correlation coefficient	-0.8	-0.4	0.0	0.4	0.8
MPLMR ($k = 1, r = 5$)	5	2	0	2	0
TAMCRA ($k = 1$)	246	140	73	42	7
H_MCOP ($k = 1$)	128	69	40	22	8
MPMP ($k = 1$)	34	19	8	1	0
MPLMR ($k = 2, r = 5$)	0	0	0	0	0
TAMCRA ($k = 2$)	86	45	28	4	1
H_MCOP ($k = 2$)	95	44	26	14	4
MPMP ($k = 2$)	6	1	1	0	0

(b)

correlation coefficient by dividing the number of erroneous decisions by the number of simulation runs (i.e., 10 000). We can see that MPLMR has lower EDR than TAMCRA, H_MCOP, and MPMP, for all the correlation coefficients. This observation applies to both the distributions in (a) and (b). Table 2.4 shows simulation results for the case of three QoS attributes: the first two are the same as in Table 2.3, and the third QoS attribute is uncorrelated with each of the first two. Again we observe that MPLMR has lower EDR than the other schemes. We show results in Table 2.4 only for the first distribution, because the results for the second distribution are very similar.

For the above simulation, the used constraint value is 18 (recall that the same constraint value is used for every QoS attribute). As shown in Figure 2.6, the value of the most stringent constraint is close to 18. Hence, the EDR computed from Tables 2.3 and 2.4 is the value for a near-worst case. If the constraint value is smaller than 18, then the EDR decreases because the number of the instances without solutions increases. That is, the probability of missing a feasible path decreases because there is no feasible path in many simulation runs. If the constraint value is larger than 18, the EDR decreases because the constraints are loose.

In our simulation, the execution time of MPLMR is approximately 80% of the execution time of MPMP, and just 30-40% of the execution time of TAMCRA and H_MCOP. Recall that the asymptotic time complexity of MPLMR is comparable to those of TAMCRA, H_MCOP, and MPMP. However, MPLMR has a shorter execution time compared to the other schemes because of the following two reasons. First, in contrast to TAMCRA and MPMP, MPLMR stores multiple postpaths (not just the values of postpaths). Hence, if the full path consisting of a prepath and a postpath is feasible, MPLMR terminates the routing without extending the prepath toward the destination node. Next, in contrast to H_MCOP, MPLMR performs an eligibility test to discard ineligible prepaths. Thus, MPLMR reduces the search space where the scheme searches for a feasible path.

Table 2.4

The number of erroneous decisions among 10 000 simulation runs for the routing problem with three QoS attributes, where MPLMR, TAMCRA, H_MCOP, and MPMP are applied to the randomly generated network topologies with QoS attribute values of the first distribution in Section 2.6.1. The constraint value is 18 for every QoS attribute. The first line shows the correlation coefficients between the first and second QoS attributes. The third QoS attribute has zero correlation with the first and the second QoS attributes.

correlation coefficient	-0.8	-0.4	0.0	0.4	0.8
MPLMR ($k = 1, r = 5$)	1	1	2	1	0
TAMCRA ($k = 1$)	241	183	151	142	104
H_MCOP ($k = 1$)	140	99	78	54	59
MPMP ($k = 1$)	26	8	15	10	4
MPLMR ($k = 2, r = 5$)	0	0	0	0	0
TAMCRA ($k = 2$)	85	53	39	39	31
H_MCOP ($k = 2$)	105	66	42	28	40
MPMP ($k = 2$)	7	2	0	0	0

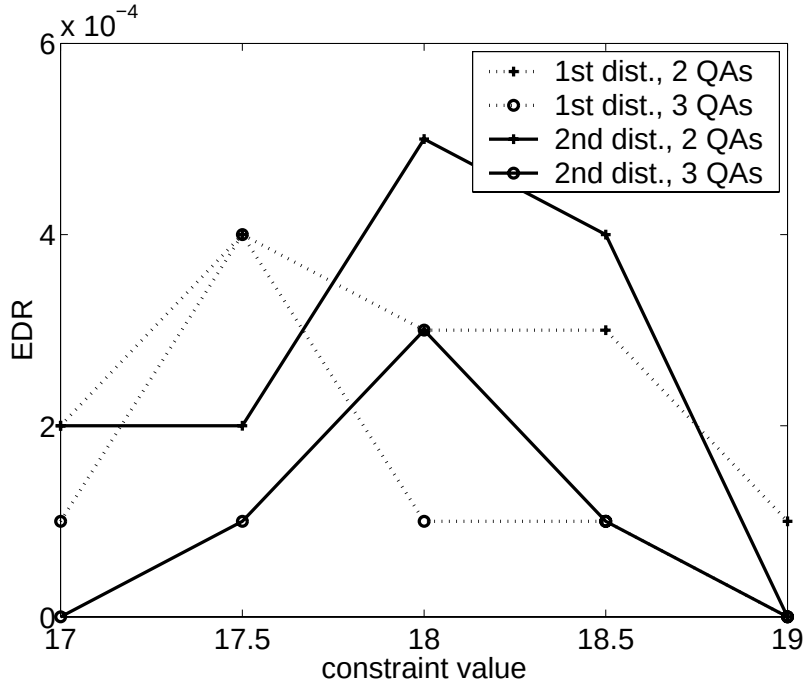


Fig. 2.6. Plots of EDR versus the constraint value for MPLMR ($k = 1$). 'QAs' represents 'QoS attributes'. Every QoS constraint has the same value. For the case of two QoS attributes, the correlation coefficient between the two is -0.8. For the case of three QoS attributes, the correlation coefficient between the first two is -0.8, and the third is uncorrelated with each of the first two.

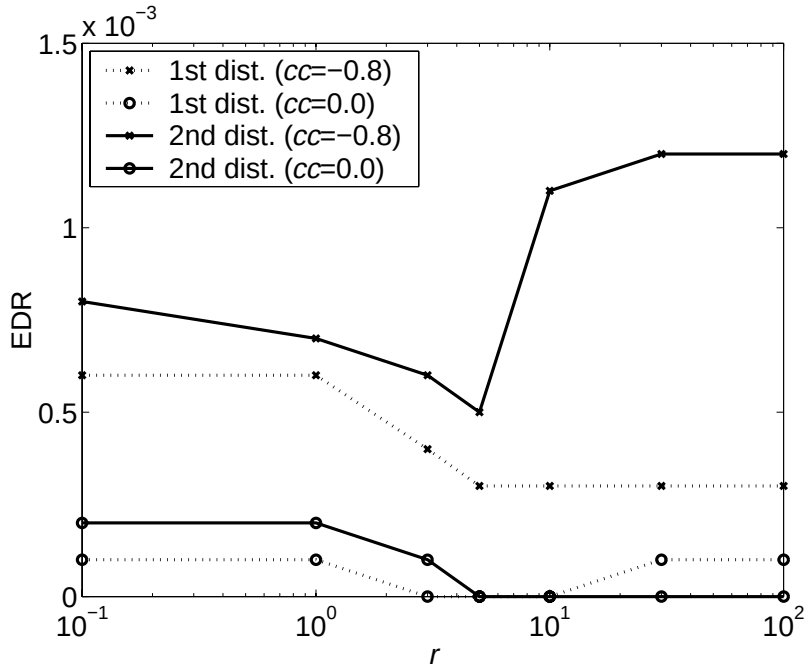


Fig. 2.7. Plots of EDR versus control variable r in (2.6) for the routing problem with two QoS attributes. *cc* denotes the correlation coefficient between the two QoS attributes. The maximum number of prepaths per node (i.e., k) and the constraint value with respect to each QoS attribute are 1 and 18, respectively.

Figure 2.7 shows plots of EDR versus r (the control variable in (2.6)) for the routing problem with two QoS attributes. We can see that the value r to minimize the EDR of MPLMR is approximately between 3 and 10.

2.7 Conclusions

Multiconstraint QoS (quality of service) routing is an essential mechanism for QoS-guaranteed services. We develop MPLMR, a multiconstraint QoS routing scheme using an extended shortest-path algorithm, with the assumption that a link-state protocol provides detailed link-state information to every node. MPLMR involves efficient features of previous schemes: the notion of nonlinear path length and the

dominancy check as in TAMCRA [NeM00], the eligibility test as in the randomized algorithm of [KoK99], and a lookahead feature as in H_MCOP [KoK01]. MPLMR uses not only these existing features but also an improved lookahead method. Using this lookahead method, MPLMR estimates the nonlinear path length of the shortest (in terms of nonlinear path length) full path to which each prepath is extended. Based on the estimated nonlinear path lengths, MPLMR selects and stores a limited number of prepaths that have higher likelihood than other prepaths to be extended to the shortest full path. The asymptotic worst-case complexity of MPLMR is comparable with those of TAMCRA and H_MCOP. However, we show via simulation that MPLMR achieves much lower EDR than the schemes. Furthermore, MPLMR achieves the low EDR with even smaller execution time than the competing schemes. Hence, MPLMR provides a promising solution for multiconstraint QoS routing, which will become an essential tool for high-quality communication/computer services in the near future.

3. DISTRIBUTED MULTICONSTRAINT QOS ROUTING USING A DEPTH-FIRST SEARCH METHOD BASED ON DISTANCE-VECTOR PROTOCOLS

3.1 Introduction

In this chapter, we deal with the same routing problem as in the previous chapter (i.e., the multiconstraint QoS routing problem). However, our goal in this chapter is to develop an efficient multiconstraint QoS routing scheme for routing environments where signaling overhead must be minimized (e.g., wireless ad-hoc networks where power and bandwidth are limited). Hence, we have different assumptions on information advertisement, which significantly affects the signaling overhead for routing.

We have three choices for information advertisement in multiconstraint QoS routing: (a) no advertisement of routing information, (b) the use of a link-state protocol, and (c) the use of a distance-vector protocol. If routing information is not advertised, "flooding" must be used for path search when a connection request occurs at a (source) node. That is, the source node forwards the connection request message to all the neighboring nodes, and every node that receives the message forwards it again to all its neighboring nodes. This forward of connection request messages terminates when some stopping condition is met. Hence, flooding-based path search usually causes a significant amount of signaling overhead during the path-search period, and is highly likely to involve many unnecessary nodes in the path-search process. In contrast, the use of a link-state protocol for information advertisement may cause heavy signaling overhead in the information-advertisement process because detailed routing information of each link is distributed to every node in a given network. To avoid heavy signaling overhead in both the information-advertisement and path-search processes, we assume that a distance-vector protocol is used for information

advertisement (recall that the use of a link-state protocol is assumed in the previous chapter).

If we use a distance-vector protocol for information advertisement, each node u has only the following information with respect to each of the attributes considered: (a) the estimated value of the best path between u and every other node, and (b) the next-hop node on the path. Thus, in multiconstraint QoS routing, the source node that receives a connection request cannot find a feasible path for the connection request, without the help of other nodes. Hence, distributed routing schemes must be used. Distributed routing schemes forward the connection request message from the source node toward the destination node. Whenever the connection request message is forwarded, the path along which the connection request message has passed is updated and recorded in the connection request message. Henceforth, we refer to this prepath as the *history path* of the connection request message. During the routing procedure, each connection request message whose history path is ineligible (i.e., not able to be extended into a feasible path) is discarded or sent back to the predecessor node. If any connection request message arrives the destination node without violating constraints, then the routing process reserves the network resources of the history path of the connection request message, and terminates.

To reduce the signaling overhead in the distributed path search, the connection request message should be forwarded "selectively". That is, if an arbitrary node receives a connection request message, this node should forward it only to its neighboring nodes that are highly probable to be on feasible paths. For the selection of such neighboring nodes, we first develop a metric, called the minimum normalized margin (NM_{min}), which measures the severity of the strictest constraint. The NM_{min} is computed from the routing information provided by distance-vector protocols. We then develop an efficient distributed multiconstraint QoS routing scheme, called SPMP (single-prepath multi-postpaths), which uses the NM_{min}.

As described in the previous chapter, there are many approaches for solving the multiconstraint QoS routing problem. However, a sequential path-search approach

has not been developed in the literature beyond simple depth-first search. Asymptotic exponential worst-case time complexity is the critical drawback of the sequential path-search approach. However, SPMP takes a sequential search approach using a depth-first search method that controls the worst-case time complexity. At any time during the path-search procedure, SPMP maintains only a single prepath, and attempts to extend it to a feasible path. By taking this sequential approach, SPMP minimizes the number of the nodes involved in path search at the expense of possible increase in the path-search time. Moreover, for the reduction of the path-search time, SPMP takes a multiple-postpath approach similar to that of MPLMR.

The rest of this chapter is organized as follows. In Section 3.2, we introduce our assumptions and notation. We define the NM_{min} in Section 3.3.1, and describe SPMP in detail in 3.4. In Section 3.5, we use simulation to evaluate the performance of SPMP. We conclude in Section 3.6.

3.2 Assumptions and definitions

For the routing information that a connection request contains, we make the same assumptions as in the previous chapter. Hence, we assume that the following are given: a network topology (which is represented by an undirected graph), a source node, a destination node, and the constraint that the routing path must satisfy with respect to each QoS attribute. We also assume that there is at most one link between any two nodes, that the network topology does not change throughout the routing procedure, and that every QoS attribute is nonnegative and fixed. However, in this chapter, we assume that a distance-vector protocol provides each node u with the following routing information for every pair of a node v and a QoS attribute: the value of the best path between u and v with respect to the QoS attribute, and the next-hop node on the best path (recall that we assume the use of a link-state protocol for information advertisement in the previous chapter).

Every QoS attribute is either a min/max attribute or a cumulative attribute (i.e., an additive attribute and a multiplicative attribute). In this chapter, we consider only additive attributes to develop our routing scheme, as in the previous chapter. However, with some minor changes, this scheme can be easily extended for the routing problems that have constraints on min/max attributes as well. Recall that multiplicative attributes can be regarded as additive by taking logarithm. Because of the additivity of QoS attributes considered, we can still regard the value of a path with respect to a QoS attribute as the "length" of the path with respect to the QoS attribute.

Other than the use of a distance-vector protocol (instead of a link-state protocol), we have the same assumptions in this chapter as in the previous chapter. Hence, we deal with the same multiconstraint QoS routing problem. This problem is restated as follows:

Definition 3.2.1 (Restatement of Multiconstraint QoS Routing Problem) *Suppose we are given a connected graph representing a network topology, $G = (V, E)$, where V and E represent sets of n nodes and m links, respectively. Suppose also that each link uv is characterized by nonnegative values with respect to q additive QoS attributes, $d_i(uv) \geq 0, i = 1, \ldots, q$. Given a source node s, a destination node t, and a constraint value C_i with respect to the ith QoS attribute for $i = 1, \ldots, q$, find a path $p = \langle s, w_1, \ldots, w_b, t \rangle$, where $w_j, j = 1, \ldots, b$, is an intermediate node on path p, such that the value of p with respect to the ith QoS attribute, i.e., $L_i(p) = d_i(sw_1) + d_i(w_1w_2) + \ldots + d_i(w_bt)$, is less than or equal to the corresponding constraint value C_i for every $i = 1, \ldots, q$.*

3.3 Elements of our approach

3.3.1 Minimum normalized margin

For arbitrary nodes u and v in a given network, let $A(u, v)$ be the set of all possible paths between u and v, a an arbitrary path in $A(u, v)$, $b(a)$ the number of

links on path a, $w_{a,i}$ the ith node along a, and $w_{a,i-1}w_{a,i}$ the link between $w_{a,i-1}$ and $w_{a,i}$. In the previous section, we assumed that a distance-vector protocol provides u the following value, denoted by $R_j(u,v)$, with respect to the jth QoS attribute for $j = 1, \ldots, q$ and for every node v in the network.

$$R_j(u,v) = \min_{a \in A(u,v)} \sum_{i=1}^{b(a)} d_j(w_{a,i-1}w_{a,i}),$$

where $w_{a,0} = u$ and $w_{a,b(a)} = v$.

Suppose that a connection request message arrives at u, with the following information: the history path p from s to u, destination node t, and constraint value C_j with respect to the jth QoS attribute for $j = 1, \ldots, q$. Note that p is a prepath of u. Based on the value of $R_j(u,t)$ and C_j, node u can compute the following value, denoted by $NR_j(u)$:

$$NR_j(u) = \frac{R_j(u,t)}{C_j}.$$

Henceforth, we call $NR_j(u)$ the *normalized requirement* of node u for the jth QoS attribute. Note that $NR_j(u)$ is the minimum path length with respect to the jth QoS attribute (as a fraction of C_j) of any postpath of node u. Because QoS attribute values of every link are nonnegative, $NR_j(u) \geq 0$.

Recall that $L_j(p)$ and $NL_j(p)$ be the length and the normalized length respectively, of path p with respect to the jth QoS attribute (see Section 2.2.2). The *normalized margin* of p with respect to the jth QoS attribute, denoted by $NM_j(p)$, is defined as follows:

$$\begin{aligned} NM_j(p) &= 1 - \Big[NL_j(p) + NR_j(u) \Big] \\ &= \frac{1}{C_j} \cdot \max_{a \in A(u,t)} \Big[C_j - L_j(p) - L_j(a) \Big] \end{aligned}$$

Hence, $NM_j(p)$ corresponds to the upper bound of the difference between the jth constraint value (i.e., C_j) and the length of a full path extended from p with respect to the jth QoS attribute, where the difference is normalized by the constraint value. We can easily see that if any NM of path p is negative, then no extension of p is feasible.

The *minimum normalized margin* of path p, denoted by $NM_{min}(p)$, is the smallest NM amongst all the NMs of path p with respect to each QoS attribute, where p is a prepath of u:

$$NM_{min}(p) = \min_{j=1,\ldots,q} NM_j(p).$$

The quantity $NM_{min}(p)$ provides a measure of the severity of the strictest QoS constraint in searching for a feasible path including path p. A lower value of $NM_{min}(p)$ indicates that it is less likely to find a feasible path that extends path p. Obviously, no extension of path p is feasible if $NM_{min}(p) < 0$. Hence, the eligibility test that we use for multiconstraint QoS routing checks the negativity of the NM_{min} of each prepath, and eliminates prepaths with negative NM_{min}s from consideration.

3.3.2 Sequential path search

Although networking technologies have been evolving constantly, bandwidth is still a limited resource in many routing domains (e.g., wireless communication networks). Sometimes, available power is also limited to routing applications. Due to many reasons, such as the limitation on bandwidth and power, signaling overhead should be minimized in multiconstraint QoS routing. For this purpose, distance-vector protocols are more advantageous than link-state protocols in information advertisement because a smaller amount of routing information is exchanged between nodes. However, the routing information forwarded by distance-vector protocols does not involve detailed link-state information associated to each link, and thus we should use distributed routing schemes for multiconstraint QoS routing.

If a distributed routing scheme is used, the source node distributes a given connection request message, and intermediate nodes forward the connection request message toward the destination node with the updated information on the history path. This forwarding of the connection request message terminates if the destination node receives it (and sets up the routing path along the history path of the connection

request message), or any other termination condition (e.g., timeout) is met. Hence, the path-search process is "distributed" to many node in a given network.

Path search in distributed routing schemes for multiconstraint QoS routing can be implemented in two ways: parallel or sequential. Most previous distributed routing schemes for QoS routing take the parallel approach (e.g., [ChN98b, ChN99, CiR97, GhS01, ReS00, ShC95, SoP00]). The parallel approach takes a shorter time in path search because multiple paths are explored in parallel. The weakness of the sequential approach is exponential time complexity, which may cause an excessively long path-search time. However, the sequential approach maintains a small number of nodes involved in routing, and thus minimizes the unnecessary effect to the nodes that will not be on the path to be set up. Hence, the sequential approach significantly reduces the signaling overhead in the path-search process.

To keep the advantage and avoid the disadvantage of the sequential path-search approach, we start with a sequential path-search algorithm that has exponential time complexity, and restrict the time required for its termination. The goal then is to design an algorithm that achieves sufficiently small EDR within this time restriction (see the definition of EDR in Section 2.1). To achieve this goal, we develop a distributed multiconstraint QoS routing scheme, called SPMP, which searches sequentially for a feasible path based on distance-vector protocols.

3.3.3 Depth-first search with limited crankbacks

In Section 3.2, we assume that when a connection request message arrives at an arbitrary node u, u has the value of the best (i.e., shortest) path between u and destination node t with respect to each QoS attribute. Note that this value corresponds to the value of the postpath with respect to the QoS attribute in MPLMR. Using the value with respect to each QoS attribute, SPMP takes some of the advantages of the multi-postpath approach used in MPLMR. Note that, different from MPLMR, SPMP does not store multiple prepaths for each node. At any time during the routing

procedure, SPMP maintains only a single prepath, called the *active path*. We call the endpoint node (which is not the source node) of the active path the *active node*.

SPMP constructs an active path from the source node toward the destination node using a depth-first search approach in a distributed manner as follows. From the source node toward the destination node, SPMP repeatedly selects a next-hop node to forward the connection request message, and extends the active path to the next-hop node, which then becomes the new active node. This extended active path is recorded in the connection request message as its history path. If, in the middle of the path search process, SPMP recognizes that it cannot find a feasible path by extending the active path constructed so far because the NM_{min} of the active path is negative, then it uses a *crankback*, which truncates the active path and re-extends the path through another outgoing node. Each crankback truncates a single link. However, if there are no more outgoing nodes to re-extend the truncated active path, then SPMP repeatedly uses crankbacks until it finds an outgoing node to which the active path is extended.

To minimize the number of crankbacks (and hence the total path-search time), it is clearly desirable to extend an active path to nodes that are likely to be on a feasible path. For this purpose, SPMP uses the NM_{min} as a metric to select the next-hop node of an active node. SPMP selects the outgoing node with the largest NM_{min} as the next active node. Hence, SPMP is a greedy routing scheme in the sense that it leaves as much of the NM_{min} as possible for the remaining process of extending the active path to the destination node.

Because of the sequential approach, SPMP has exponential worst-case time complexity. Figure 3.1 shows an example of a network topology where standard sequential path search schemes may get "stuck," if there is a time limit on its execution. Suppose that there is no feasible path through node v. If a standard sequential path-search scheme selects node v as the next-hop node of active node u in Figure 3.1, then the scheme must explore *all* the paths through node v before exploring paths through node w. SPMP prevents this situation and controls the worst-case time complexity by

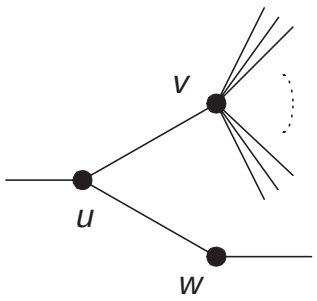


Fig. 3.1. An example network topology where sequential path search schemes without limiting the crankback degree may get stuck, if there is a time limit on its execution.

limiting the maximum number of crankbacks per node, which we call the *crankback degree* (at the expense of possibly increasingly the EDR). If the crankback degree is h, and if an active path is extended to an outgoing node of an arbitrary node u, then the active path can shrink to node u at most h times. Hence, an active node can explore at most $h + 1$ outgoing nodes. Furthermore, the $h + 1$ outgoing nodes explored, in general, will be them with the largest NM_{min} values. Although limiting the crankback degree cannot make the worst-case time complexity of SPMP polynomial, it can reduce the worst-case time complexity significantly at the expense of possibly increased EDR.

In general, the QoS attributes at a link are not independent of each other, and in many cases their correlation coefficients are known in advance. In these cases, we can take advantage of this knowledge in tuning the crankback degree. Basically, given a restriction on the time to find a feasible path, we adjust the crankback degree to achieve a desired EDR. By the following proposition, we can show that the EDR of SPMP decreases as the correlation coefficients between QoS attributes increase. If the correlation coefficients between QoS attributes are sufficiently high, the crankback degree can be set in such a way that the EDR is acceptably small for a reasonable limit on the path-search time.

Proposition 3.3.1 *The EDR of the proposed scheme decreases as the correlation coefficients between QoS attributes at each link increase.*

Proof Suppose that the active path has reached node u and one of its outgoing nodes, v, has been chosen as the next-hop node. Furthermore, suppose that the ith QoS constraint is the most stringent constraint of node v, i.e., $NM_{min}(v) = NM_i(v)$. As the correlation coefficient between the ith QoS attribute and the jth QoS attribute increases, it becomes more likely that the value of link uv with respect to the jth QoS attribute (i.e. $d_j(uv)$) decreases as $d_i(uv)$ decreases. Thus, it also becomes more likely that the sum of the jth QoS attribute values of the links on any postpath of node u decreases with the sum of the ith QoS attribute values of the same links. This increases the probability that a path satisfying the ith QoS constraint also satisfies the jth constraint. Because the EDR decreases as the probability of finding a feasible path increases, the EDR of SPMP decreases as the correlation coefficients between QoS attributes increase. ■

3.4 SPMP: single-prepath multi-postpaths

3.4.1 SPMP algorithm

The pseudocode for SPMP is given in Figure 3.2. When a connection request occurs, SPMP starts the routing procedure. We assume that the crankback degree is h (e.g., for achieving a desired EDR within some run-time limit). Lines 01–07 represent the initialization procedure for the depth-first search method on lines 08–20. Line 01–02 indicate the computations of *NR*s, based on (a) the routing information provided by a distance-vector protocol in the information-advertisement process, and (b) the constraint values included in the connection request. Lines 03–04 check if any *NR* of source node s is larger than one (note that, for source node s, *NR*s are equal to *NM*s, which SPMP uses for the eligibility test). If every *NR* of s is less than or equal to one, then SPMP starts constructing the active path from s toward t by repeatedly selecting a next-hop node in a depth-first search manner.

```
SPMP(G = (V, E), s, t, q, h, C_1, ..., C_q)

01 for every v ∈ V, do
02     compute NR_1(v), ..., NR_q(v)    /* using C_1, ..., C_q */
03 if any of NR_1(s), ..., NR_q(s) > 1, then
04     stop    /* routing failure: no feasible path */
05 actpath ← {⟨s⟩}    /* active path */
06 u ← s    /* initial active node */
07 Q(s) ← {at most h + 1 outgoing nodes of s with largest nonnegative NM_min s}
08 while actpath contains any nodes, do
09     if Q(u) is not empty, then
10         w ← node in Q(u) with largest NM_min
11         extend actpath to w
12         if w = t, then
13             stop    /* routing success: actpath is feasible */
14         Q(u) ← Q(u) − {w}
15         u ← w    /* new active node */
16         Q(u) ← {at most h + 1 outgoing nodes of u with largest nonnegative
               NM_min s that are not on actpath}
17     else
18         remove u (and its incident link on actpath) from actpath
19         u ← endpoint node of actpath    /* which was u's predecessor node */
20 stop    /* routing failure: no feasible path found */
```

Fig. 3.2. Pseudocode for SPMP.

To describe the depth-first search method of SPMP, suppose that SPMP has just extended the active path from s to an arbitrary node u, and that no outgoing nodes of u have been explored from the active path. Suppose also that u has outgoing nodes satisfying the following two conditions: (a) the outgoing nodes are not on the active path (to avoid loops), and (b) the path that we get by extending the active path to each of the outgoing nodes does not have a negative NM_{min}. For each node u on the active path, SPMP maintains a set $Q(u)$ to store the outgoing nodes of u satisfying these two conditions. If there are more than $h + 1$ such outgoing nodes, then only the $h + 1$ nodes with the largest NM_{min} values are stored in $Q(u)$. Let node w have the largest NM_{min} in $Q(u)$.

SPMP extends the active path to node w. That is, w becomes a new active node (lines 10–11). If w is the destination node, the routing procedure terminates because the active path is feasible (lines 12–13). Otherwise, SPMP keeps extending the active path by applying the following procedure. SPMP removes w from $Q(u)$ (line 14), updates the active node (line 15), and stores the outgoing nodes of w satisfying the previous two conditions in the set $Q(w)$ (line 16). If there are more than $h + 1$ outgoing nodes satisfying the conditions, then SPMP stores only the $h + 1$ nodes with the largest NM_{min} values in $Q(w)$, as in $Q(u)$. Then, the while-loop repeats, beginning at line 08.

Whenever SPMP explores each outgoing node of u, it is removed from $Q(u)$. Hence, if the number of crankbacks at u has reached the crankback degree h, or there are no more outgoing nodes satisfying the previous two conditions, then $Q(u)$ is empty. In this case, the active path shrinks to the predecessor node of u (lines 17–19). SPMP terminates the search when it finds a feasible path by extending the active path to destination node t (lines 12–13), or cannot proceed any further (line 20).

3.4.2 Complexity of SPMP

If the given network topology is not of a tree structure, it is possible that the active path leads to a node where crankbacks have occurred before. In this case, the active path of the node is different from its old active paths (when previous crankbacks occurred there). Because the (current) active path may indeed be part of a feasible path, the active path should revisit the node. The possibility of such revisits to a node makes the worst-case time complexity of the scheme exponential, as we shall see.

Consider a graph representing a network topology for which SPMP achieves its worst-case time complexity. If this graph is not a *complete graph* (where every pair of nodes is connected by a link), then it can be extended to a complete graph by adding links with sufficiently high QoS attribute values, such that the complete graph has the worst-case time-complexity as well. Therefore, it suffices to consider only complete graphs for the computation of the worst-case time complexity of SPMP. For the time being, suppose that there is no limit on the crankback degree (i.e., exhaustive search). When we construct an active path from a given source node at the beginning of the routing procedure, the first next-hop node of the source node can be any node except the source node itself ($n-1$ choices), because we can use crankbacks without restrictions. For the same reason, the second next-hop node can be any node except the source node and the first next-hop node ($n-2$ choices). Imagine continuing this argument, until the active path reaches a given destination node. Hence, the active path can be any path between the source and destination nodes in the network topology, and thus the worst-case time complexity of the exhaustive search (i.e., SPMP without the limit on crankback degree) is $(n-1)!$, which is of an exponential form [CoL90].

We now set the crankback degree to be h to compute the worst-case time complexity of SPMP. Unless all the nodes except h or fewer nodes are on the active path, then an active node can explore at most $h+1$ of its outgoing nodes. The last h nodes

can explore at most $h, h-1, \ldots, 1$ outgoing nodes, respectively. Thus, the worst-case time complexity of SPMP is $O((h+1)^{(n-h-1)} \cdot h!)$. As the crankback degree decreases, the worst-case time complexity also decreases. However, a decrease in the crankback degree may cause an increase in the EDR as SPMP skips paths that might be feasible. Thus, we should tune the crankback degree such that both the worst-case time complexity and the EDR are at acceptable levels.

Although the worst-case time complexity of SPMP decreases with h (i.e., crankback degree), it may still be impractically large even for small values of h because of the exponential term. However, as we shall see in the next section, the average-case time complexity of SPMP is small because of the efficient search order of SPMP (exploring the node with the largest nonnegative NM_{min}). When constraints are loose (i.e., constraint values are large), it is probable that SPMP will find a feasible path with few crankbacks. If constraints are stringent (i.e., constraint values are small), then SPMP can skip exploring a number of paths due to negative NM_{min}s. Therefore, SPMP finds a feasible path or recognizes there is no feasible path in a short time. In addition, the run time of SPMP may actually decrease as the number of constraints increases, because the number of skipped paths (with negative NM_{min}s) increases. In the next section, it will be shown by simulation that the average-case time complexity of SPMP is remarkably lower than its worst-case time complexity.

3.5 Performance evaluation

3.5.1 Generation of network topologies and QoS attribute values

To evaluate the performance of SPMP, we perform our simulation for the QoS routing problem with two QoS attributes according to the following steps, which are similar to those of MPLMR. First, we generate two kinds of random network topologies, which will be described later. Next, we assign QoS attribute values to every link in the generated network topologies. Finally, we apply SPMP for routing in the networks. In addition, we also apply an exhaustive-search scheme to check if

there exists any feasible path, for the purpose of computing the EDR. We refer to a sequence of the above steps as a *simulation run*. We perform 10 000 simulation runs.

To generate the two kinds of random network topologies, we use the Waxman model [Wax88] and the Inet Topology Generator [ChC00], respectively. For each simulation run, we generate a network topology by the Waxman model that is different from the network topologies for previous simulation runs. This network topology is generated as follows: source and destination nodes are located at diagonally opposite corners of a square area of unit dimension, and then all the other nodes are spread randomly in the square area. By the Waxman model, we introduce a link between arbitrary nodes u and v with the following probability, which depends on the distance between them, $\delta(u, v)$:

$$Pr\{(u, v)\} = \alpha \exp\left[\frac{-\delta(u, v)}{\beta\sqrt{2}}\right].$$

For the values of α and β in the above equation, we use 0.8 and 0.04, respectively, to generate each network topology of 400 nodes. The above approach results in approximately 1106 links per network topology. Hence, the average node degree is 5.53.

To generate the second kind of network topology, we use the Inet Topology Generator. The generated network topology has 4000 nodes and 7741 links over a square area, and thus the average node degree is 3.87. To reduce the run-time for the generation of this large Internet-like network topology, we change source and destination nodes randomly in the fixed network topology for all the 10 000 simulation runs, instead of creating 10 000 network topologies. This Internet-like network topology has smaller mean and larger variance of node degree than the network topologies generated by the Waxman model.

Next, we assign QoS attribute values to every link using a procedure that corresponds to the reverse of the "whitening process" [Fuk90]. Specifically, each link has QoS attribute values independent of other links, and the pair of QoS attribute values of a link has a given correlation coefficient. We assume link values for each QoS attribute to have a normal distribution. For every QoS attribute, we arbitrarily assume

a unit mean, and set the variance as 0.16 to keep the probability of generating negative values less than 1%. When we generate a negative value, we replace it by zero. Because very few QoS attribute values generated have zero values, link values for each QoS attribute are still approximately normally distributed. For the constraint value of every QoS attribute, we use 12 for the network topologies of 400 nodes, and 5 for the Internet-like network topology of 4000 nodes. These values have been chosen such that the constraints are not too loose or too stringent. That is, these constraint values have been chosen such that the exhaustive-search scheme just manages to find feasible paths in most cases. The fraction of the simulation runs that have no feasible path is approximately 10% (bigger for negative correlation coefficients and smaller for positive correlation coefficients than this value). Recall that if constraints are too loose or too stringent, SPMP either quickly finds a feasible path or recognizes that there is no feasible path.

After assigning QoS attribute values, we apply the exhaustive-search scheme to check if there exists any feasible path. Let h and Δ be the crankback degree and the maximum node degree of the generated network topologies, respectively. SPMP can perform an exhaustive search by setting the crankback degree to be greater than or equal to $\Delta - 2$, because every node has at most $\Delta - 1$ outgoing nodes (recall that SPMP explores at most $h + 1$ outgoing nodes of an active node). Then, for the same network topology and QoS attribute values, we apply SPMP for several crankback degrees. Finally, we ascertain whether or not there is an erroneous decision for each scheme. Recall that an erroneous decision in this case corresponds to a failure to find a feasible path when one exists, because we assume that all the information on a given network topology and QoS attribute values is fixed during the routing procedure.

The average-case time complexity of SPMP is calculated based on the following two factors: the number of computations for NRs, NMs, and NM_{min}s, and the number of explored nodes. When a network topology, QoS constraints, and QoS attribute values of the links are fixed, the number of computations for NRs, NMs, and NM_{min}s is also fixed, and the number of explored nodes is proportional to the number of

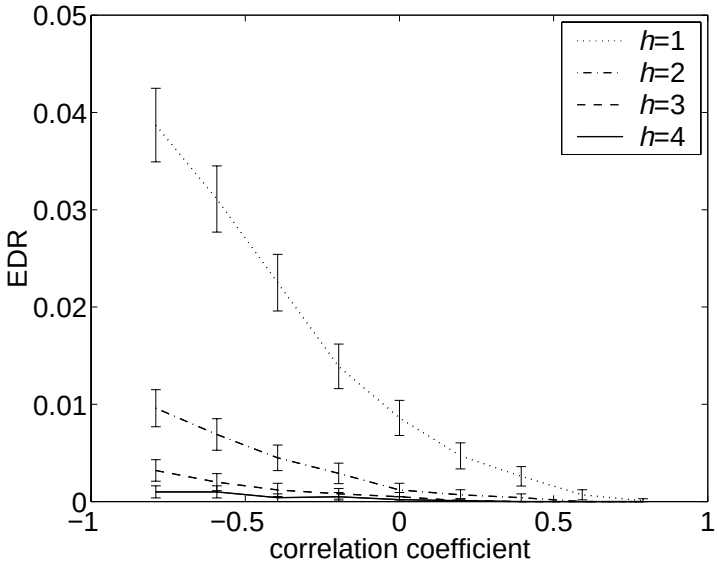
crankbacks for an entire path search. Thus, we use the average number of crankbacks for an entire path search as a metric to measure the average-case time complexity of SPMP.

3.5.2 Simulation results

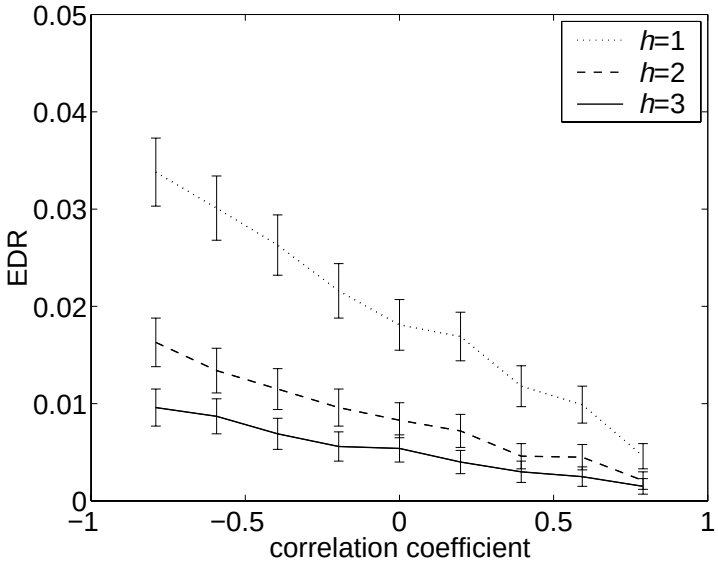
Figure 3.3 shows plots of EDR versus correlation coefficient for SPMP applied to the network topologies of 400 nodes generated by the Waxman model and to the Internet-like network topology of 4000 nodes. We can see that SPMP has low EDR for all the correlation coefficients. Note that the EDR for the Internet-like network topology is lower than for the network topologies generated by the Waxman model, despite the larger network size. This implies that SPMP rarely misses appropriate prepaths for each node during the course of the routing procedure. The underlying reason is that the Internet-like network topology has smaller average node degree and larger variance of node degree than the network topologies generated by the Waxman model. Hence, the maximum number of crankbacks at each node (i.e., h) does not need to be large.

In Figure 3.3, we can see that the EDR decreases rapidly with increasing crankback degree. As mentioned before, this is possible at the expense of the exponential worst-case time complexity. However, as shown in Figure 3.4, the average number of crankbacks for an entire path search, which we use as the measure of the average-case time complexity for SPMP, is remarkably lower than the network size (i.e., n or m). In addition, the average number of crankbacks for an entire path search does not increase much as the crankback degree increases. This results from the efficient depth-first search order, which explores first the outgoing node with the largest NM_{min}, and skips exploring paths with negative NM_{min}s.

Because SPMP has exponential worst-case time complexity, its performance when the termination time is restricted is important. The exhaustive search scheme, which corresponds to the SPMP with a crankback degree at least $\Delta - 2$ where Δ is the

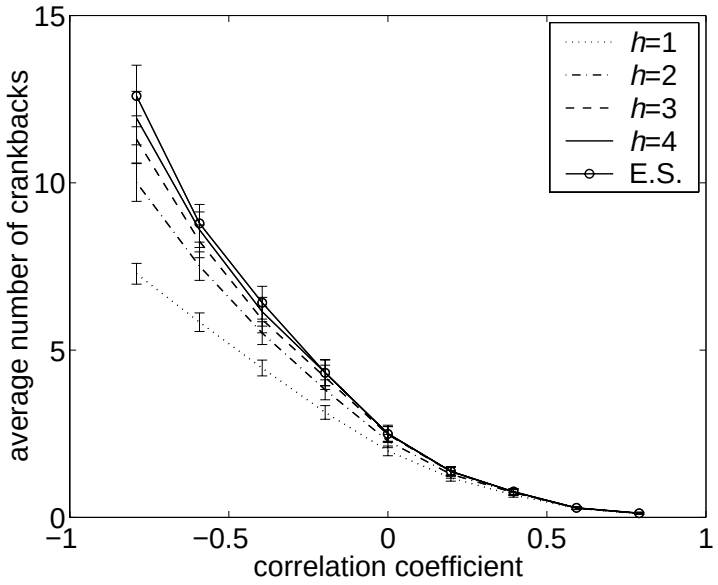


(a)

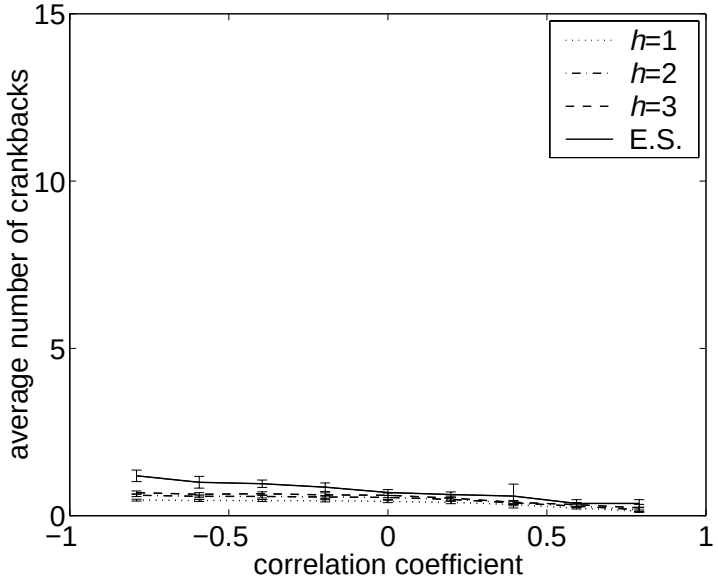


(b)

Fig. 3.3. Plots of the EDR versus the correlation coefficient, where SPMP is applied to (a) the 400-node network topologies generated by the Waxman model and (b) the Internet-like network topology of 4000 nodes. h denotes the crankback degree. No simulation for $h = 4$ in (b) was performed to reduce execution time. 95% confidence intervals are shown by the interval bars.



(a)



(b)

Fig. 3.4. Plots of the average number of crankbacks for an entire path search versus the correlation coefficient, where SPMP is applied to (a) the 400-node network topologies generated by the Waxman model and (b) the Internet-like network topology of 4000 nodes. h and 'E.S.' denote the crankback degree and the exhaustive search, respectively. 95% confidence intervals are shown by the interval bars.

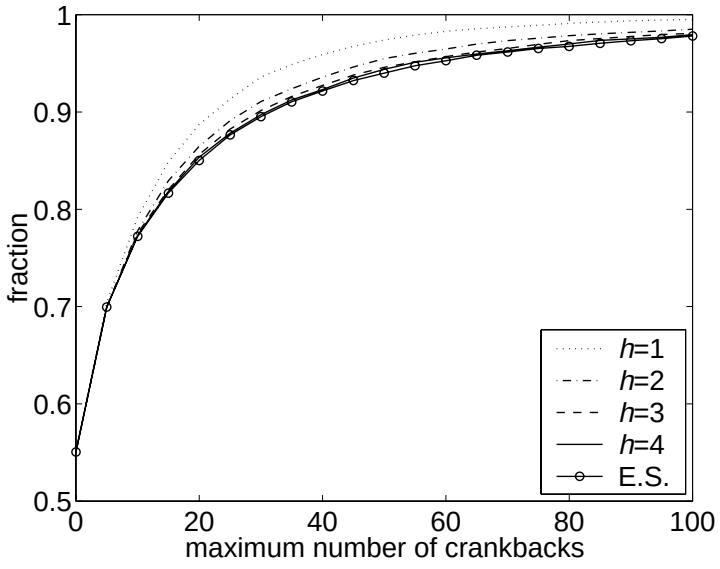
maximum node degree, takes up to a few minutes for a routing procedure, when we use a personal computer with a 600 MHz Intel Pentimum III processor and 40 Mbytes memory. Moreover, we should consider the time delay of forwarding connection request messages between nodes, which is assumed to be zero in our simulation. Thus, the exhaustive search scheme is not good for the routing systems where the termination time is strictly limited.

Figure 3.5 shows the fraction of the cumulative number of the simulation runs whose numbers of crankbacks do not exceed a given maximum number. We can see that for most of the simulation runs, the number of crankbacks is a small fraction of the network size. Thus, SPMP can achieve a low level of EDR, while keeping the average-case time complexity low. Therefore, despite the exponential worst-case time complexity, SPMP has reasonably good performance even when the termination time is restricted.

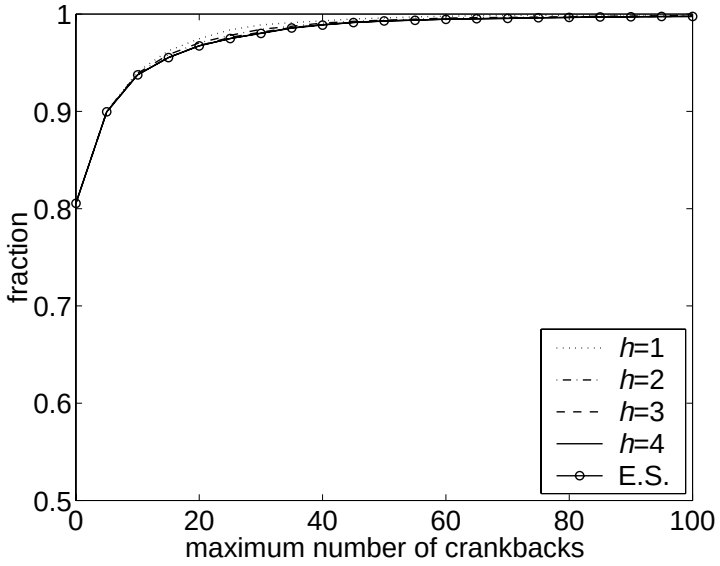
3.6 Conclusions

In this chapter, we have proposed a distributed multiconstraint QoS routing scheme, called SPMP. In contrast to MPLMR, which is introduced in the previous chapter, SPMP searches for a feasible path based on the routing information provided by a distance-vector protocol. Hence, SPMP is appropriate to the routing environments where signaling overhead must be minimized (e.g., wireless ad hoc networks).

To reduce the number of the nodes unnecessarily affected by the path-search process, SPMP takes a sequential path search approach using a depth-first search method. Because of the sequential path search approach, SPMP has exponential worst-case time complexity, which may cause an excessively long path-search time. However, this path-search time is significantly reduced by the use of an efficient path-search order based on NM_{min}. This NM_{min} is the metric to select the next-hop node to forward a given connection request message, and can be computed from the routing



(a)



(b)

Fig. 3.5. Plots for the fraction of the cumulative number of the simulation rounds whose numbers of crankbacks are less than or equal to a given maximum number of crankbacks, where SPMP is applied to the 400-node network topologies generated by the Waxman model, with correlation coefficient (a) -0.8 and (b) zero, respectively. h and 'E.S.' denote the crankback degree and the exhaustive search, respectively.

information provided by distance-vector protocols. Moreover, to control the path-search time, SPMP trades off its worst-case time complexity and EDR by controlling the crankback degree, which is the maximum number of crankbacks per node. The efficient path-search order and the control of the crankback degree make it possible for SPMP to keep average-case time complexity low. We showed by simulation that SPMP also has low EDR. Hence, SPMP provides promising solutions for multiconstraint QoS routing, which will become an essential tool in providing high-quality services for communication/computer systems in the near future.

4. SURVIVABLE MULTIPATH ROUTING USING PENALIZATION METHODS FOR WDM NETWORKS

4.1 Introduction

Wavelength division multiplexing (WDM) makes it possible to divide the huge transmission bandwidth of an optical fiber into many wavelength channels for independent operation of each channel. Hence, we can utilize the large bandwidth of an optical fiber for a number of connections without the need for high-speed opto-electronic devices. Because WDM networks offer the promise of meeting the high-bandwidth requirements of emerging communication applications, many long-distance carriers have already introduced point-to-point WDM transmission technologies for their networks. However, as the number of channels accommodated on a fiber increases, the following problem becomes more critical: the failure of a link can lead to severe disruptions in many channels. Hence, survivability is a critical issue in WDM networks. Moreover, as WDM technologies are used more widely in current point-to-point networks, dynamic establishment of channel demands becomes more important.

In this chapter, we address a survivable routing problem for a point-to-point connection in a WDM network. The routing problem is to find a set of lightpaths (henceforth, called paths) between a single pair of source and destination nodes on a given physical network topology, such that the paths accommodate the requested channels without violating the given constraints on channel demand, capacity, and survivability. We assume that the detailed routing information of every link is known by the use of a link-state protocol for information advertisement.

Implicitly or explicitly, many previous survivable routing schemes for WDM networks make two assumptions. The first assumption is that the maximum number

of simultaneous link failures is known (e.g., [CaP98, MoN02, RaM99, SeH02, SrR02, ZaO03]). In most cases, at most a single link failure is assumed. The second assumption is that any single path between a pair of source and destination nodes can support all the communication traffic between the nodes. Thus, the objective of the schemes is to make the network topology remain connected.

Based on the above assumptions, many schemes search for *link-disjoint* (henceforth, called *disjoint*, unless otherwise specified) paths between each pair of source and destination nodes (e.g., [CrB98, MoN02, SeH02, ZaO03]). However, these previous schemes do not consider the vulnerability and capacity of each link. Thus, they may require additional disjoint paths even for the connections through sufficiently reliable paths. This requirement not only wastes network resources, but also makes routing unnecessarily difficult. Furthermore, the schemes may not provide adequate survivability when the number of link failures is larger than the number of disjoint paths due to vulnerable links. Even if survivable paths are found, they may not be able to support the communication traffic due to capacity constraints. Because of the large bandwidth of optical fibers, previous schemes usually do not consider capacity constraints. However, because traffic volume keeps increasing due to the continuously growing Internet and "bandwidth-hungry" applications, it will become important to consider capacity constraints for networks that have already been deployed.

Our goals in this chapter are to overcome the limitations of previous schemes by considering the vulnerability and capacity of each link, and to develop survivable routing schemes based on more general assumptions. We use failure probability as the measure of vulnerability. We assume that each link has a given failure probability, and that a maximum allowable failure probability for the connection between a pair of source and destination nodes is also given (rather than assume that the maximum number of link failures is known). We consider the capacity requirement of the connection in terms of the requested number of channels, when all channels have the same fixed bandwidth. Hence, the connection may contain several channels between a pair of source and destination nodes, where each link has a given capacity. These

channels are established by a set of paths, which are not necessarily disjoint, between the pair of source and destination nodes. Unfortunately, the development of efficient routing schemes with all of these properties becomes hopelessly intractable as the number of source/destination pairs increases. Hence, we limit ourselves to survivable routing between a single pair of source and destination nodes in this chapter.

Using the maximum allowable failure probability and the requested number of channels, we formulate a survivable routing problem for WDM networks. This problem is to find a set of paths to accommodate requested channels (and possibly additional backup channels) between a given pair of source and destination nodes, such that the constraints on survivability and capacity are satisfied. The objective then is to minimize the number of backup channels that allow these constraints to be satisfied. In this problem, we do not limit routing paths to a set of disjoint paths. As we prove in the following section, our problem is NP-hard. Hence, we develop heuristic schemes, CPMR (conditional-penalization multipath routing) and SPMR (successive-penalization multipath routing), for this problem.

To deal with the difficulty of allowing each link to be used for several channels, we introduce a *link penalization* method. This method assigns every link a dynamic value, called a *penalty*. The penalty of a link is initialized to the failure probability of the link, and is updated to a higher value if it is determined that it is not desirable for the link to be contained in a routing path. Using a shortest-path algorithm (e.g., Dijkstra's algorithm or the Bellman-Ford algorithm) with respect to the penalty, our schemes repeatedly select a path to accommodate a channel and add the path to the set of selected paths. Whenever a path is selected and added, our schemes update the penalties of the links on the selected path (before selecting the path for the next channel). This procedure to select/add a path and update link penalties terminates if (a) the total number of channels is at least the requested number of channels, and (b) the probability that the number of failed channels is greater than the number of backup channels is at most a given maximum value.

The procedure to update link penalties in CPMR involves a complicated computation of conditional probabilities; the scheme achieves a high routing success rate but has a relatively long execution time. In contrast, SPMR has a simple penalty-update procedure to reduce the execution time at the expense of a possible reduction in the routing success rate. We show by simulation that the routing success rates of our schemes are significantly higher than a routing scheme searching for disjoint paths, and are almost the same as the routing success rate of a refinement to our scheme using a simulated-annealing method, which searches for a near-optimal solution at the expense of a much longer execution time.

The rest of this chapter is organized as follows. We discuss previous work on survivable multipath routing for WDM networks in Section 4.2. In Section 4.3, we present our definitions and assumptions, formulate the survivable routing problem, and prove its NP-hardness. We summarize our approach in Section 4.4, and describe CPMR and SPMR in detail in Sections 4.5 and 4.6, respectively. In Section 4.7, we use simulation to evaluate and compare our schemes with the scheme searching for disjoint paths and the scheme using simulated-annealing for a near-optimal solution. We conclude in Section 4.8.

4.2 Previous work

Multipath routing has been used not only for survivability but also for several other purposes, such as delay minimization (e.g., [ChC99, RoS91, Xue00]), congestion reduction or load balancing (e.g., [HsH01, MuG96, ZhZ02]), and security (e.g., [LoF01]). However, as optical communication networks replace traditional high-capacity networks, the protection of optical communication networks against link failures has increased the interest in multipath routing. Thus, there is a significant amount of work on the protection of WDM networks using multipath routing capabilities.

Most previous work in survivable routing for WDM networks focuses on providing 100% protection with the assumptions that the maximum number of simultaneous

link failures is known, and that a single path is sufficient to cover all communication traffic between any pair of source and destination nodes. In [MoN02], Modiano and Tam propose a routing approach for WDM networks that performs routing on a given physical network topology with multiple pairs of source and destination nodes. They assume that at most a single link fails, and seek routing paths such that any single link failure does not disconnect any pair of source and destination nodes. Although they ignore the capacity constraint, their routing problem is still NP-complete. Hence, they take an approach that relaxes the constraints of their routing problem to reduce the time for finding survivable paths. Sen et al. [SeH02] consider the routing problem with the same assumption, and propose a heuristic algorithm for routing on a given network topology. Zang et al. [ZaO03] also deal with a similar routing problem, and develop off-line algorithms for the protection of WDM networks under a single link failure.

In contrast to the above papers, which deal with routing on a given network topology, many previous papers focus on designing a survivable WDM network, but have the same assumptions on the maximum number of link failures. Sridharan et al. [SrS02] propose a heuristic algorithm to design a survivable WDM network with the objective to minimize the total capacity to be consumed on all links. This algorithm also assumes that two node-disjoint paths between each pair of source and destination nodes are sufficient to provide survivability. Caenegem et al. [CaP98] study the techniques for routing, planning of working capacity, rerouting, and planning of spare capacity to design a WDM network that withstands any single link failure. Ramamurthy and Mukherjee [RaM99] investigate several approaches to protecting WDM networks from a single link failure, and formulate a routing and wavelength assignment problem for each approach.

Some schemes provide less stringent protection, for the sake of achieving other goals (e.g., cost reduction). These schemes adopt similar assumptions on the maximum number of link failures and the sufficiency of a single path to cover the communication traffic between any pair of source and destination nodes. Crochat and

Boudec [CrB98] propose a routing scheme, called the disjoint alternate path (DAP) algorithm, which does not guarantee 100% protection for all the traffic, but minimizes the number of source/destination pairs that would become disconnected when a single link fails. Protection schemes that allow primary channels to share backup channels for the efficient use of network resources are proposed in [DoD99,GhD99,HaL02]. Our schemes differ from these in that we allow for multiple primary channels between a given pair of source and destination nodes. In addition, we incorporate with failure probabilities.

The assignment of failure probabilities to all failure-prone components has been studied for general networks in several papers (e.g., [ChC95,FoS99]). However, previous problem formulations differ from ours, and thus we cannot apply these previous schemes to our routing problem.

4.3 Survivable multipath routing problem

4.3.1 Definitions and assumptions

We first define the terminology that we will use to formulate our routing problem and to develop our routing schemes.

- channel: a 3-tuple consisting of a source node, a destination node, and a channel bandwidth to support the communication traffic between the source and destination nodes.
- path: a sequence of alternating nodes and links that begins and ends at nodes.
- channel realization (CR) for a given channel: a path assigned to the given channel.
- session: a set of requested (primary) channels and extra backup channels between a given pair of source and destination nodes.
- session realization: a set of CRs for a session.

- session failure probability: the probability that the number of failed channels in a session is larger than the number of backup channels in the session.

By the above definition of CR, the number of channels in a session must be the same as the number of CRs in the corresponding session realization, but the number of distinct paths associated with a session can be smaller than the number of channels of the session (because several channels can be mapped to the same path). We focus on providing "channels" between the source and destination nodes, which are established by routing schemes that search for "paths." Hence, we will often use terms "CR" and "session realization" rather than terms "channel" and "session" to show that we deal with the paths associated with the channels.

We assume the use of a link-state protocol for the advertisement of the capacity and failure probability of each link. Hence, a network topology where every link has an associated capacity and a failure probability is given. We consider a connection request that contains the following information: a pair of source and destination nodes, the number of requested (primary) channels, and the maximum allowable session failure probability. To formulate our routing problem, we assume that the given network topology and link values (i.e., link capacities and link failure probabilities) are known and fixed throughout the routing procedure. We also assume that each pair of arbitrary nodes u and v can have at most one undirected (i.e., bi-directional) link uv between them in a given network topology (even if there are multiple fibers between u and v, we regard them as a single link).

As is typical in the literature on survivable routing (e.g., [ChC95, MoN02]), we are concerned only with link failures. Thus, every node is assumed to be ideal, i.e., have infinite capacity and zero failure probability. We assume that link failures are independent from each other. That is, the failure of a link is assumed not to affect the failures of other links. For simplicity, we assume that each channel takes a fixed amount of capacity, and that we can quantify the requested capacity by the number of channels between the source and destination nodes. In other words, each channel is assumed to take a single unit of capacity.

4.3.2 Problem formulation

We wish to find a set of paths to set up a requested session with the minimum number of channels such that the given capacity and survivability constraints are satisfied. Henceforth, we call this routing problem the *survivable multipath routing* (SMR) problem.

Definition 4.3.1 (Survivable Multipath Routing Problem) *Consider an undirected graph $G = (V, E)$ representing a given network topology, where V and E are sets of n nodes and m links, respectively. Suppose that each link uv has capacity $C(uv)$ and failure probability $P_f(uv)$, and that the following are given: source node s, destination node t, requested number of channels N, and maximum allowable session failure probability P_{MASF}. Find a session realization X with the smallest number of channels, such that the following three conditions are satisfied. (a) The total number of channels is at least N. (b) The number of channels accommodated in each link does not exceed the capacity of the link. (c) The session failure probability of X does not exceed P_{MASF}.*

Consider session realization X consisting of L CRs $x_1, \ldots, x_L$, where M of them are for backup channels. That is,

$$L = N + M. \tag{4.1}$$

Let $A(uv)$ be the number of channels accommodated in link uv, $H_L = \{1, \ldots, L\}$, and $P(x_{j_1}^{(F)}, \ldots, x_{j_k}^{(F)}, x_{j_{k+1}}^{(W)}, \ldots, x_{j_L}^{(W)})$ be the probability that CRs $x_{j_1}, \ldots, x_{j_k}$ fail and CRs $x_{j_k+1}, \ldots, x_{j_L}$ work. The probability that any k of the L CRs in X fail, denoted by $P(X, L, k)$, is represented as follows:

$$P(X, L, k) = \sum_{\substack{\{j_1, \ldots, j_k\} \subset H_L, \\ \{j_{k+1}, \ldots, j_L\} = H_L - \{j_1, \ldots, j_k\}}} P(x_{j_1}^{(F)}, \ldots, x_{j_k}^{(F)}, x_{j_{k+1}}^{(W)}, \ldots, x_{j_L}^{(W)}). \tag{4.2}$$

For the summation, the first set $\{j_1, \ldots, j_k\} \subset H_L$ represents all possible subsets of k failed channels. We describe how to compute $P(X, L, k)$ of (4.2) in Appendix A. Using (4.2), we can represent the session failure probability of X as follows:

$$P_f(X) \;=\; \sum_{k=M+1}^{L} P(X, L, k). \tag{4.3}$$

Now, we can restate the SMR problem as follows: Given the setup of the SMR problem, find a session realization $X = \{x_1, x_2, \ldots, x_L\}$ that minimizes L subject to the following inequalities:

$$L \geq N, \tag{4.4}$$

$$A(uv) \leq C(uv) \qquad \text{for every} \;\; uv \in E, \;\text{and} \tag{4.5}$$

$$P_f(X) \leq P_{MASF}. \tag{4.6}$$

Equations (4.4), (4.5), and (4.6) represent the constraints on channel demand, capacity, and survivability, respectively. A session realization is *feasible* if it satisfies (4.4), (4.5), and (4.6).

Theorem 4.3.1 *The SMR problem is NP-hard.*

Proof To show that the SMR problem is NP-hard, we reduce the "k link-disjoint paths" problem (henceforth, k-LDP problem) to the SMR problem. Given an undirected graph with k pairs of source and destination nodes (s_i, t_i) for $i = 1, \ldots, k$, the k-LDP problem is to find a path between s_i and t_i for every $i = 1, \ldots, k$ such that no two paths share a link. This is a well-known NP-complete problem [Fra90].

To reduce the k-LDP problem to the SMR problem, we form a new graph for the SMR problem from the graph of the k-LDP problem in the following procedure, as illustrated in Figure 4.1. First, we add source and destination nodes s and t. We then add a unique node u_i between s and s_i, and a unique node v_i between t_i and t for $i = 1, \ldots, k$. That is, if $i \neq j$, then u_i and u_j (or v_i and v_j) are distinct nodes. Note that, in contrast, any node s_i (or t_i) may be used for several pairs of source and

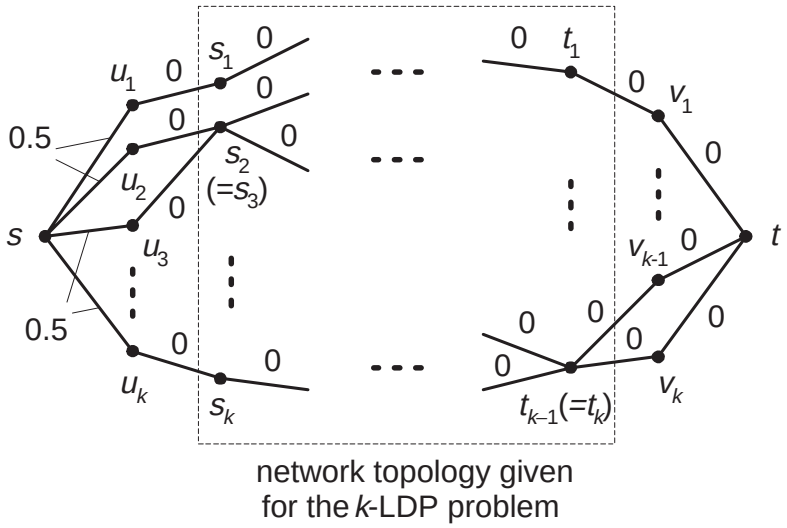


Fig. 4.1. An illustration for the proof of Theorem 4.3.1, where the number on each link is the failure probability of the link

destination nodes in the k-LDP problem, and thus s_i and s_j (or t_i and t_j) may be the same node even if $i \neq j$. We add links su_i, u_is_i, t_iv_i and v_it for $i = 1, \ldots, k$. To every link in the resulting graph, we assign a unit capacity. We assign failure probability of 0.5 to links su_i for $i = 1, \ldots, k$. To all the other links in the graph, we assign zero failure probabilities.

Consider an SMR problem with $N = k$ and $P_{MASF} = 1 - 0.5^k$. Because of the assignment of a unit capacity to every link, any solution to the SMR problem must comprise at most k disjoint CRs between s and t. Note that the failure probability of any CR between s and t is 0.5. Hence, we need at least k CRs between s and t to satisfy the survivability constraint of the SMR problem. In addition, any k CRs can satisfy the survivability constraint, because the probability that any of the k CRs fails is $1 - 0.5^k$, which is equal to P_{MASF}. Because $N = k$, k is the smallest number of CRs that a solution to the SMR problem can have. Thus, the solution to the SMR problem comprises exactly k CRs between s and t. Because these k CRs between s and t always contain disjoint paths connecting s_i and t_i for every $i = 1, \ldots, k$, the solution to the SMR problem gives rise to a solution to the k-LDP problem. Hence,

the k-LDP problem is solvable if the SMR problem is solvable. Finally, it is easy to see that this reduction takes polynomial time. ■

4.4 Elements of the proposed routing techniques

4.4.1 Link penalization

In this section, we focus on the survivability constraint. To find a feasible session realization, our basic approach is to repeatedly add a channel to the session (and select a CR for the channel and add it to the corresponding session realization). Each time we add a channel to a session, the session failure probability decreases or does not change. We repeat the procedure of adding a channel one-by-one, until the session failure probability falls below P_{MASF} or no more channels can be realized due to the capacity limit between the source and destination nodes. Because our goal is to minimize the number of channels in the session, it is important to select CRs of low path failure probabilities for lowering the session failure probability. Hence, CRs should contain links of low failure probabilities. However, our schemes allow each link to be used for several channels, and thus several CRs may share a link with low failure probability. This may cause a high session failure probability even though the link failure probability is low, because several channels will fail together if the shared link fails. Therefore, we need to control (but, not prohibit) link-sharing.

To control link-sharing, our approach is to assign every link a dynamic value, called a *penalty*. The penalty of a link is initially equal to the failure probability of the link. We repeatedly select a CR using a shortest-path algorithm with respect to the penalty and update the penalties of the links on the selected CR before the selection of the next CR. The penalty of a link must be set to a high value if it is not desirable for the link to be contained in a CR. Hence, if a link shared by several CRs causes the session to be vulnerable to failure, the penalty of the link must be increased. That is, we may have to increase the penalties of the links on CRs to *penalize* the selection of the links for other CRs. Details on how to increase the link

penalties will be described in the following sections (CPMR and SPMR use different methods for setting penalty values).

Penalties and failure probabilities share some common properties. Specifically, the penalty values are always in [0,1], and the penalty of a CR is defined from the penalties of the links on the CR in the same way that the failure probability of a path is computed from the failure probabilities of the links on the path. Let $PN(x)$ be the penalty of CR x, $E(x)$ the set of all the links on x, and $PN(uv)$ the penalty of link uv. Then,

$$PN(x) = 1 - \prod_{uv \in E(x)} [\ 1 - PN(uv)\ ]. \tag{4.7}$$

For finding the first CR, we set the penalty of each link to be equal to its failure probability, and then select the path that has the smallest penalty. If the session realization containing only this CR does not satisfy the constraints of (4.4) and (4.6), then we repeat the following procedure until these constraints are satisfied or no more CRs can be found due to the capacity limit between source and destination nodes: (i) update the penalties of the links on the CR just selected (described later), (ii) select a new CR with the smallest penalty to add into the session realization, and (iii) compute the session failure probability to check if the survivability constraint is satisfied.

4.4.2 Residual networks and link cancellation

In this section, we focus on the capacity constraint. To find a session realization satisfying the capacity constraint, we use the notions of residual networks and link cancellation, which were originally introduced for the maximum flow problem [AhM93, CoL90]. To apply the idea of residual networks to our problem, convert the given undirected graph G to a corresponding directed graph D_1 by replacing each undirected link uv with a pair of directed links with opposite directions, i.e., $\overrightarrow{uv}$ and $\overrightarrow{vu}$. These links $\overrightarrow{uv}$ and $\overrightarrow{vu}$ are assigned the same failure probability as link uv, and they always have the same penalty. Then, perform a routing procedure on

this directed graph. After finishing the routing procedure, reconvert directed links to undirected links.

For an arbitrary undirected link uv in G, each of directed links $\overrightarrow{uv}$ and $\overrightarrow{vu}$ in D_1 initially has the same capacity that uv has. After selecting the first CR x_1 in D_1, if we need more CRs for a feasible session realization, we compute the residual network with respect to the selected CR, denoted by D_2. In D_2, every directed link $\overrightarrow{uv}$ on x_1 has capacity smaller by one than in D_1, and the reverse link $\overrightarrow{vu}$ has capacity larger by one than in D_1. We repeat this procedure (i.e., selection of a CR and computation of the residual network) until the session realization becomes feasible or no more CRs can be found due to the capacity limit between source and destination nodes.

Example residual networks are shown in Figure 4.2. Suppose that we are given undirected graph G in Figure 4.2(a). The number on each link represents the capacity of the link. D_1 in Figure 4.2(b) is the directed graph that corresponds to G. Suppose also that we set up CR $x_1 = \langle s, u, v, t \rangle$ in D_1. Then, as is shown in Figure 4.2(c), the capacities of (forward) links $\overrightarrow{su}, \overrightarrow{uv}$, and $\overrightarrow{vt}$ decrease by one, respectively, in the residual network of D_1 with respect to x_1, denoted by D_2, and the capacities of the reverse links $\overrightarrow{us}, \overrightarrow{vu}$, and $\overrightarrow{tv}$ increase by one, respectively, in D_2.

The increase in the capacities of reverse links in a residual network represents the possibility of *link cancellation*. For example, consider a pair of directed links with opposite directions (i.e., $\overrightarrow{uv}$ and $\overrightarrow{vu}$). The operation of link cancellation involves replacing the two CRs containing $\overrightarrow{uv}$ and $\overrightarrow{vu}$ respectively, with two new CRs as follows: first remove the two opposite links from the two given CRs, and then swap the subpaths after these links. This results in two new CRs between the source and destination nodes. Figure 4.2(d) shows this example that CRs x_1 and x_2 change to new CRs x_1' and x_2' by link cancellation. The use of residual networks with link cancellation makes it possible to add CRs into a session realization up to the capacity limit between the source and destination nodes, even though the selected CRs have already occupied links that would bottleneck the addition of new CRs.

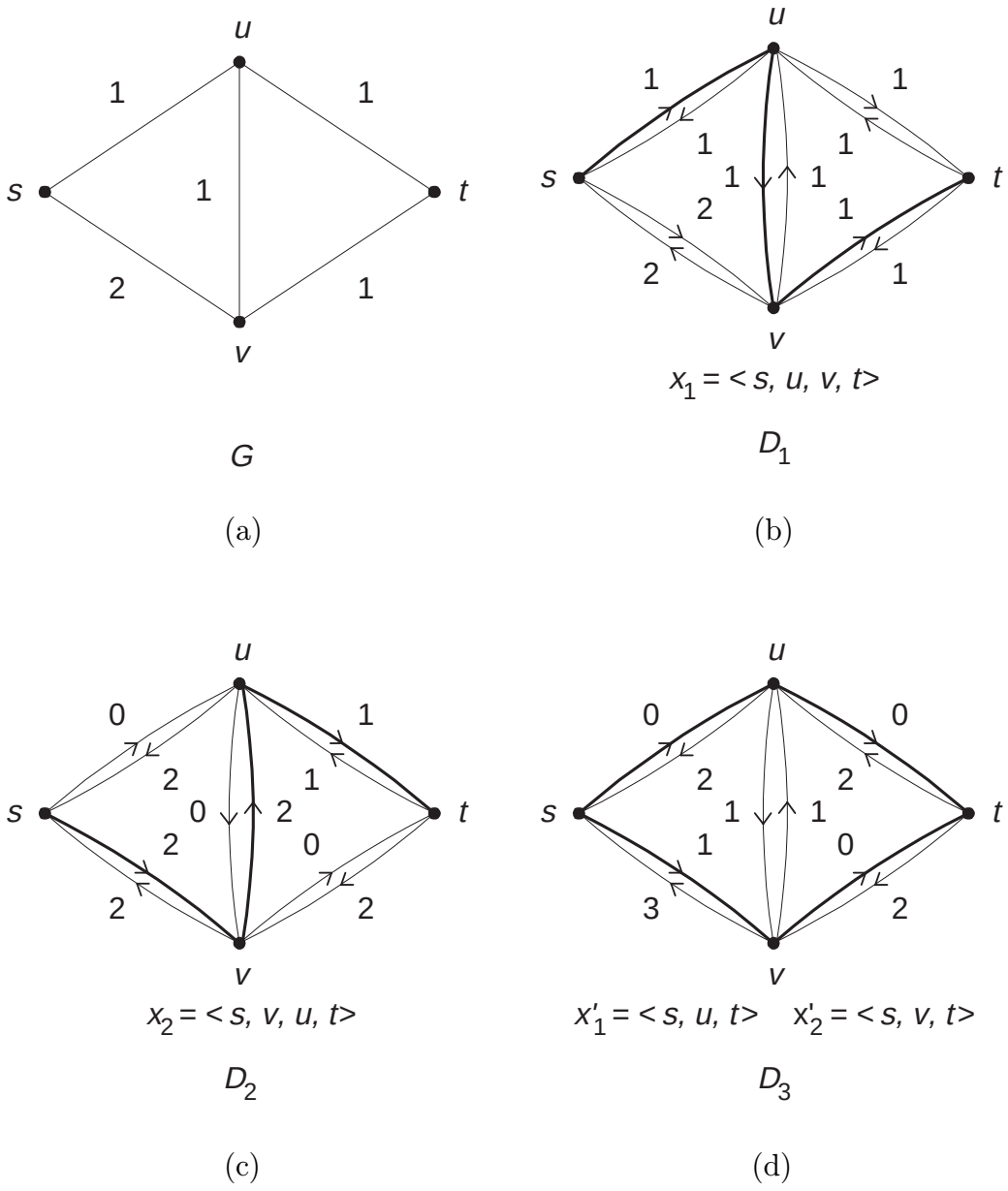


Fig. 4.2. An example for residual networks and link cancellation, where the number on each link represents the capacity of the link. (a) A given undirected graph G, (b) the corresponding initial directed graph D_1, (c) the residual network of D_1 with respect to CR x_1, denoted by D_2, and (d) the residual network of D_2 with respect to CR x_2, denoted by D_3. Note that CRs x_1 and x_2 change to new CRs x_1' and x_2' by link cancellation.

Link cancellation may be unnecessary in some cases. For an arbitrary pair of opposing directed links $\overrightarrow{uv}$ and $\overrightarrow{vu}$, let n_1 and n_2 be the numbers of CRs containing $\overrightarrow{uv}$ and $\overrightarrow{vu}$, respectively, and c the original link capacity of undirected link uv. If $c \geq n_1 + n_2$, we may choose not to perform link cancellation, because the capacity constraint of (4.5) is not violated. However, if $c < n_1 + n_2$, we must perform link cancellation for at least $\lceil (n_1 + n_2 - c)/2 \rceil$ pairs of CRs containing $\overrightarrow{uv}$ and $\overrightarrow{vu}$, respectively, where $\lceil i \rceil$ denotes the smallest integer that is larger than or equal to i. Thus, if the capacity constraint is not violated, link cancellation should be done only when the session failure probability decreases as a result of the link cancellation.

4.5 CPMR: conditional-penalization multipath routing

4.5.1 Two phases

CPMR is a heuristic multipath routing scheme to find a solution to the SMR problem. To search for a session realization that satisfies the constraints of the SMR problem, CPMR uses link penalization, residual networks, and link cancellation, described in the previous sections. CPMR consists of two phases, which have different procedures to update link penalties, according to the number of channels in a session. In phase 1, CPMR searches for a feasible session realization containing exactly N CRs (i.e., without backup channels). Recall that, by (4.4), any feasible session realization should have at least N CRs. If the session realization found in phase 1 is not feasible, then CPMR searches for a feasible session realization with more than N CRs (i.e., with backup channels) in phase 2.

4.5.2 Phase 1: no backup channels

Let K_c be the capacity limit[1] between source and destination nodes, and K_p be a practical limit on the total number of channels (due to limited resources or

[1]We can find the capacity limit by solving the *maximum flow problem*, which is solvable in polynomial time [CoL90].

maintenance cost). If N does not exceed K_c and K_p, then CPMR starts the search for a feasible session realization. Because a session realization in phase 1 does not have CRs for backup channels, the failure of any link on a CR results in the failure of the session (i.e., the number of working channels is less than the number of requested channels). Hence, to reduce the session failure probability, we must not only select CRs with low path failure probabilities, but also reduce the number of links on the CRs. To select CRs with low path failure probabilities, CPMR uses a shortest-path algorithm with respect to penalty. To reduce the number of links on CRs, CPMR encourages CRs to share links by setting the penalties of the links on the CRs found so far to be zero. In addition, CPMR performs as many link cancellations as possible. Until the number of CRs reaches N, CPMR repeatedly selects and adds a CR in this way. Figure 4.3 shows the flowchart for phase 1 of CPMR.

4.5.3 Phase 2: with backup channels

In phase 2, CPMR searches for a session realization with more than N CRs. It is generally undesirable that the session realization contains the CRs found in phase 1. Because phase 1 encourages link-sharing, the CRs found in phase 1 may share many links. Failure of such a link causes the failure of all the CRs sharing this link, and results in the failure of the session if the number of these CRs is larger than the number of backup channels. Therefore, at the beginning of phase 2, CPMR discards the CRs found in phase 1, and starts the path search from the first CR.

Figure 4.4 shows the flowchart for phase 2 of CPMR. In contrast to the encouragement of link-sharing in phase 1, CPMR discourages (but not prohibits) link-sharing in phase 2, and thus the penalties of the links on selected CRs should increase before the selection of each additional CR. To describe how the link penalties are assigned, assume (a) that a session realization already has k CRs, (b) that we should determine the penalties of links for the selection of the $(k+1)$st CR to be added into the session realization, and (c) that the session realization is expected to have $N + M$ CRs at

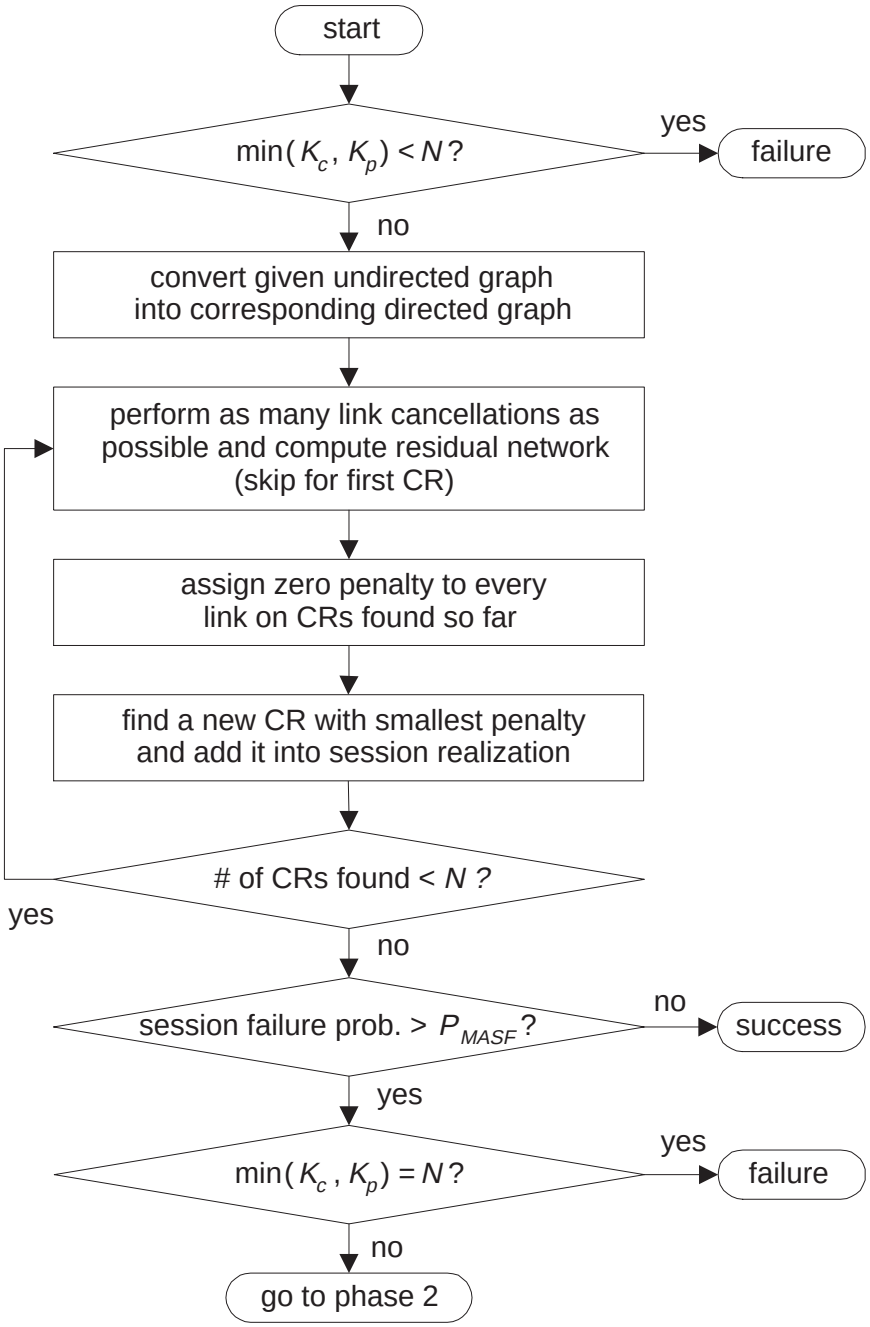


Fig. 4.3. Flowchart for phase 1 of CPMR

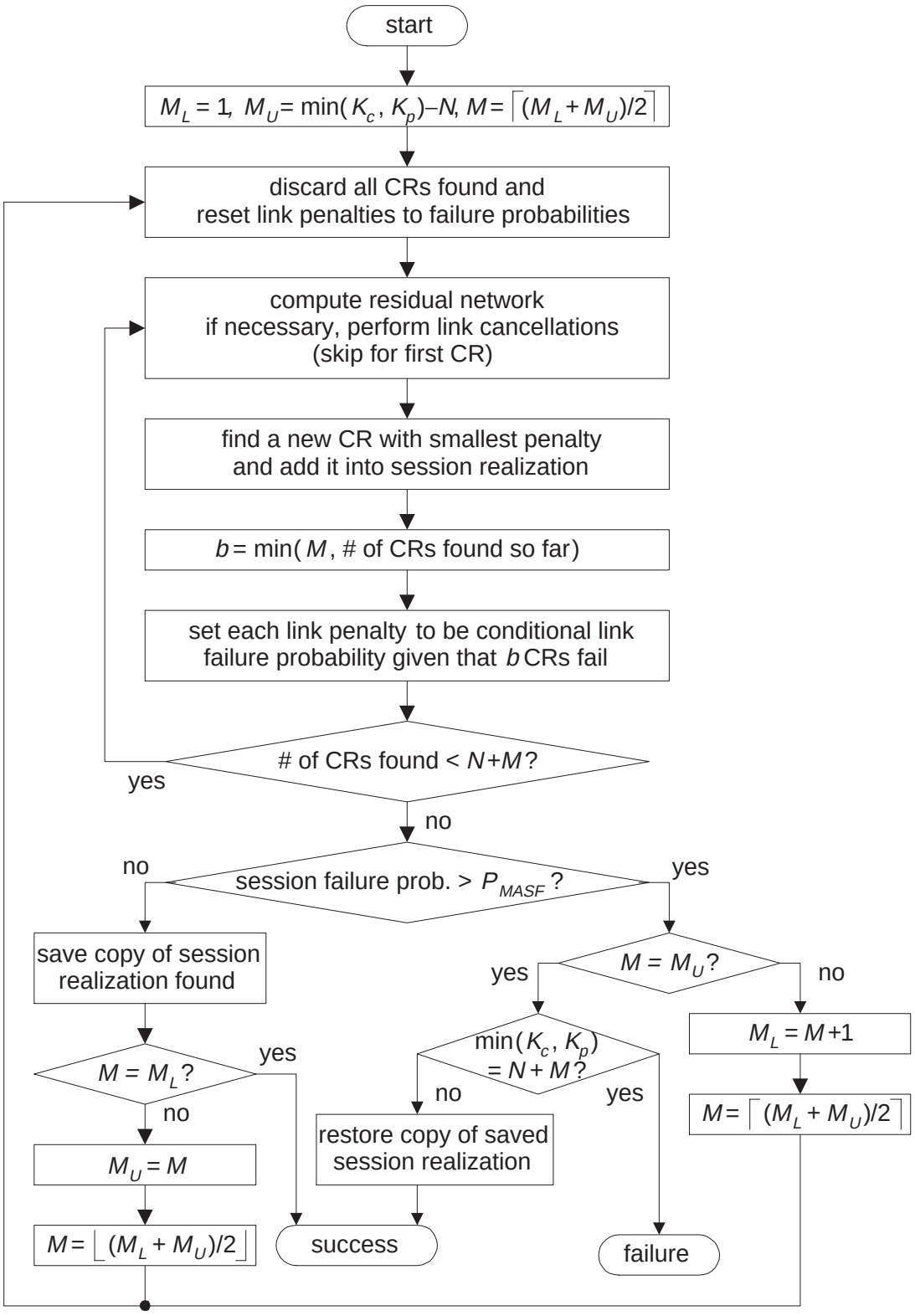


Fig. 4.4. Flowchart for phase 2 of CPMR

the end of the routing procedure (we describe later how to determine M). If more than M CRs among the k CRs fail, then the session fails even though the next CR to be selected works. Hence, CPMR selects the $(k+1)$st CR to be the one with the smallest failure probability given that any $\min(M,k)$ of the k CRs fail. This implies that the penalty of each link in the residual network to select the $(k+1)$st CR should be the conditional failure probability of the link given that $\min(M,k)$ CRs among the k CRs fail. Let $P_f(uv)$ be the failure probability of uv, $b = \min(M,k)$, $P(X,k,b)$ be given as defined in (4.2), and $P(X,k,b \mid uv \text{ fails})$ be the conditional probability of $P(X,k,b)$ given that link uv fails. If we know that the number of backup channels is M, CPMR assigns the following conditional failure probability to each link uv as its penalty $PN(uv)$ for the selection of the $(k+1)$st CR:

$$\begin{aligned} PN(uv) &= P_f(uv \mid b \text{ CRs fail among } k \text{ selected CRs in } X) \\ &= P_f(uv) \cdot \frac{P(X,k,b \mid uv \text{ fails})}{P(X,k,b)}. \end{aligned} \tag{4.8}$$

The second equality in (4.8) comes from Bayes' rule. We describe how to compute the penalty of (4.8) in Appendix B.

To determine link penalties using (4.8), we have to know the value of M, which should be minimized. CPMR uses a binary search method to determine the value of M, described as follows. Let M_L and M_U represent lower and upper bound values that M can take, respectively. Initially, $M_L = 1$, $M_U = \min(K_c, K_p) - N$, and M takes an integer average value between M_L and M_U (i.e., $\lceil (M_L + M_U)/2 \rceil$ or $\lfloor (M_L + M_U)/2 \rfloor$). CPMR then checks if this M is the smallest value for which there is a feasible session realization with $N+M$ CRs, using the following procedure. CPMR iteratively updates link penalties using (4.8) with this value of M, finds the CR with the smallest penalty via a shortest-path algorithm, and adds the CR into the session realization, until the session realization has $N+M$ CRs.

If the session failure probability of this session realization is larger than P_{MASF}, then the selected value of M must increase. Hence, CPMR updates the value of M_L to be $M+1$, and then sets M to $\lceil (M_L + M_U)/2 \rceil$. Otherwise, CPMR saves the found

(feasible) session realization, updates the value of M_U to be M, and then decreases M to $\lfloor (M_L + M_U)/2 \rfloor$. When M increases or decreases, CPMR discards all the CRs found and repeats the above procedure. This binary search process terminates when $M = M_U$ and the session failure probability is larger than P_{MASF}, or when $M = M_L$ and the session failure probability is smaller than or equal to P_{MASF}. The output of phase 2 is the feasible session realization saved lastly or the infeasible session realization with the $\min(K_c, K_p)$ CRs produced by the binary search method. In phase 2, link cancellation occurs only when the session failure probability decreases, or when the cancellations are mandatory due to the capacity constraint of (4.5).

4.5.4 Complexity of CPMR

The complexity of CPMR is dependent on the number of channels in a session (i.e., L in (4.1)). If we do not limit the number of channels, then the possible number of channels between a given pair of source and destination nodes may increase exponentially with the number of nodes (or links). Thus, CPMR has exponential complexity with respect to the network size (i.e., the number of nodes or links). Specifically, the exponential complexity of CPMR comes from the following factors: (a) the computation of the session failure probability in (4.3), (b) the search for opposing links for which link cancellation should be performed, and (c) the update of link penalties by (4.8).

First, the computation of the session failure probability is inevitable to check if the survivability constraint is satisfied. As described in Appendix A, we may reduce this computation time[2] if the number of channels is small, which is typical in practical situations. Next, the procedure to search for opposing links for link cancellation does not affect the execution time significantly because CPMR uses a shortest-path algorithm to select CRs. If a CR x that contains an arbitrary link $\overrightarrow{uv}$ is "short" (i.e.,

[2]There are several studies on efficient algorithms to compute network reliability, which can be used for the computation of the session failure probability (e.g., [SiG94]). However, the development of efficient algorithms to compute the session failure probability is beyond the scope of this research. We used the computation method introduced in Appendix A for our simulation in Section 4.7.

of low path failure probability), then another CR containing $\overrightarrow{vu}$ is likely to be "long" compared to x because the $\overrightarrow{vu}$ is not likely to be directed toward the destination node. Hence, few CRs in a session realization are likely to contain opposing links, and thus link cancellation rarely occurs. Last, we can compute the conditional failure probability of (4.8) in a similar way that we compute the session failure probability (see Appendix B). The update of all the penalties of the links on a newly added CR has the same complexity as the computation of the session failure probability. Therefore, if the total number of channels in the session is small, then the exponential complexity of CPMR is not likely to result in a prohibitively long execution time. In contrast to the previous two factors (one of which is inevitable and the other occurs rarely), we can reduce the effect of the third factor on the execution time by updating link penalties in a simpler way. This is the basic idea of SPMR, which is described in the next section.

4.6 SPMR: successive-penalization multipath routing

SPMR is a simplified version of CPMR. SPMR also consists of two phases, and phase 1 of SPMR is the same as phase 1 of CPMR. However, phase 2 of SPMR has a different procedure to update link penalties. Recall that in phase 2, CPMR predicts a value of M, and based on this value, computes the conditional failure probability of (4.8) to update link penalties. However, SPMR updates link penalties in a simpler way, and thus reduces the run-time at the expense of a possible increase in the number of backup channels.

Figure 4.5 shows the flowchart for phase 2 of SPMR. As in CPMR, SPMR discourages link-sharing in phase 2. If no link cancellation occurs, SPMR updates link penalties as follows. Let x be the CR just found, $E(x)$ the set of links on x, $PN_o(uv)$ the old penalty of link $uv \in E(x)$ (which has been used to find x), $PN_o(x)$ the old penalty of x (which is computed from the old penalties of the links on x), and $PN_n(uv)$

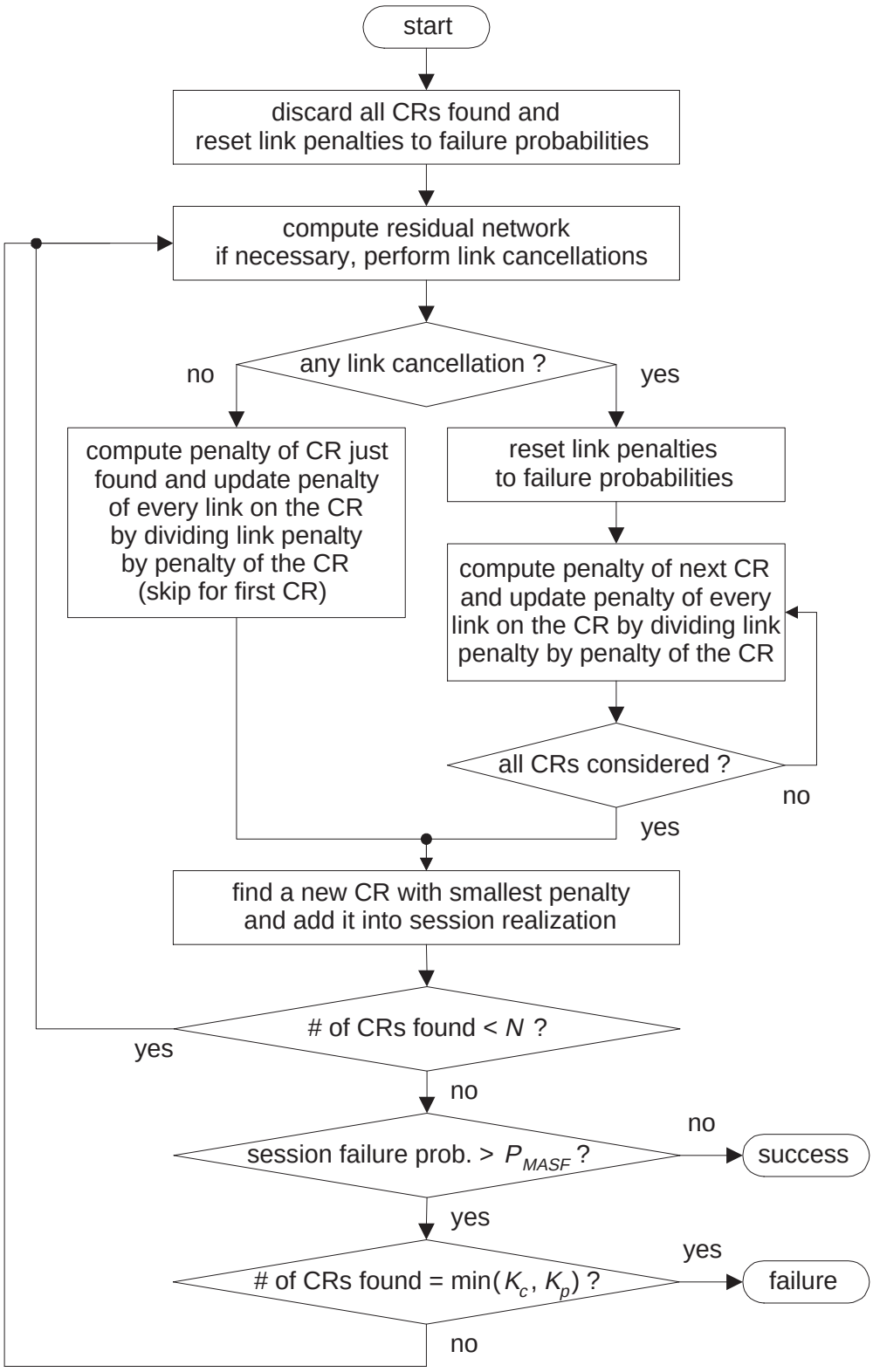


Fig. 4.5. Flowchart for phase 2 of SPMR

the new penalty of link uv (which should be determined before selecting the next CR). Then,

$$PN_n(uv) = \frac{PN_o(uv)}{PN_o(x)} = \frac{PN_o(uv)}{1 - \prod_{ab \in E(x)}[1 - PN_o(ab)]}. \tag{4.9}$$

The second equality in (4.9) is derived from (4.7). The link penalty of (4.9) corresponds to the conditional failure probability of the link given that the CR just found (i.e., x) fails. Equation (4.9) guarantees that updated penalties keep the general properties of a penalty, described in Section 4.4.1. Moreover, this equation increases the link penalties because it is not desirable for the links to be contained in other CRs (recall that link-sharing is discouraged in phase 2).

If link cancellation occurs, then SPMR cannot update link penalties using (4.9) because the link cancellation changes some CRs that have already been found. To describe the link-penalty update of SPMR for this case, suppose that SPMR has found r CRs $x_1, \ldots, x_r$ and link cancellation occurred when the last CR was found.[3] SPMR first resets the penalty of each link to be the failure probability of the link. SPMR then computes the penalty of x_1 based on these link penalties—SPMR changes the penalty of each link on x_1 by dividing the link penalty by the penalty of x_1. SPMR then computes the penalty of x_2 based on these changed link penalties, and then updates the penalties of links on x_2 accordingly. SPMR repeats this procedure until the link penalties of all links on $x_1, \ldots, x_r$ are updated.

SPMR repeatedly selects a CR based on the updated link penalties described as above, until a feasible session realization is found or no additional CR can be added into the session realization. Note that, in contrast to CPMR, SPMR does not repeat the procedure to find a feasible session realization based on the predicted values of M.

[3]The ordering of CR $x_1, \ldots, x_r$ is arbitrary. However, in our implementation of SPMR in Section 4.7, we ordered the CRs according to the order in which they were found.

4.7 Performance evaluation

4.7.1 Performance metrics

We perform simulation experiments to evaluate the performance of CPMR and SPMR, and compare them with competing schemes. To evaluate the performance of a routing scheme for the SMR problem, we use the following two metrics: the routing success rate and the average number of channels in a realized session. The *routing success rate* of a scheme is defined as the fraction of instances that the scheme finds a feasible session realization.

For the simulation, we let N varies from 1 to 5, and assume that the maximum number of backup channels (i.e., M_U) is limited to five. Hence, the number of channels in the session is at most $N + 5$. If a routing scheme needs more than this number of channels, or cannot find a feasible session realization due to the capacity limit between the source and destination nodes, then we regard the scheme as having failed in routing.

4.7.2 Upper bound

For comparison purposes, it is useful to compute an upper bound on the maximum routing success rate. Let d be the maximum number of channels in a session, K the capacity limit between source and destination nodes, and P_s the smallest failure probability of a path between the source and destination nodes. Because the maximum number of backup channels is five, $d = \min[N + 5, K]$. According to the value of d, we can identify three of the cases where any routing scheme cannot find a feasible session realization as follows: (a) when $d < N$, (b) when $d = N$ and $P_s > P_{MASF}$, and (c) when $d > N$ and $\sum_{i=d-N+1}^{d} \binom{d}{i} P_s^i (1 - P_s)^{d-i} > P_{MASF}$.

In case (a), no feasible session realization can be found due to the constraint of inequality (4.4). In case (b), the session failure probability is not smaller than P_s because there is no backup channel, and thus the survivability constraint of (4.6) is

violated. In case (c), the session failure probability is minimized when the following conditions are met: (i) a session realization has the maximum number (i.e., d) of CRs, (ii) the CRs are disjoint (to avoid increasing the session failure probability due to link-sharing), (iii) and every CR has the smallest path failure probability (i.e., P_s). The sum in case (c) represents this minimum session failure probability, and thus the survivability constraint is violated. By considering these three cases (a), (b), and (c), we can compute an upper bound for the routing success rate, which we will use for comparison purpose.

4.7.3 Refining CPMR using simulated-annealing

The upper bound described in the previous section may not be sufficiently tight in some cases for useful comparison. Hence, we also compare CPMR and SPMR with a refinement over CPMR, called CPMR-SA, which uses a simulated-annealing method. If CPMR terminates with a feasible session realization that has more than N CRs, we attempt to find a feasible session realization with a smaller number of CRs using CPMR-SA. If CPMR cannot find a feasible session realization with up to $d = \min[N + 5, K]$ CRs, then we also use CPMR-SA to attempt to find a solution with d or fewer CRs.

Figure 4.6 shows the framework of CPMR-SA. After the initialization procedure, CPMR-SA repeatedly applies a search procedure and an action-determination procedure. During the search procedure, CPMR-SA searches for a feasible session realization with a given number of CRs, using a simulated-annealing algorithm. During the action-determination procedure, CPMR-SA terminates its procedure if a stopping condition is met. Otherwise, CPMR-SA reruns the search procedure to find a feasible session realization with the number of CRs reduced by one.

To describe CPMR-SA in more detail, let X be the session realization found when CPMR terminates, which may be feasible or infeasible. If X is feasible, CPMR-SA selects randomly one CR in X and removes it from X to make X infeasible. At

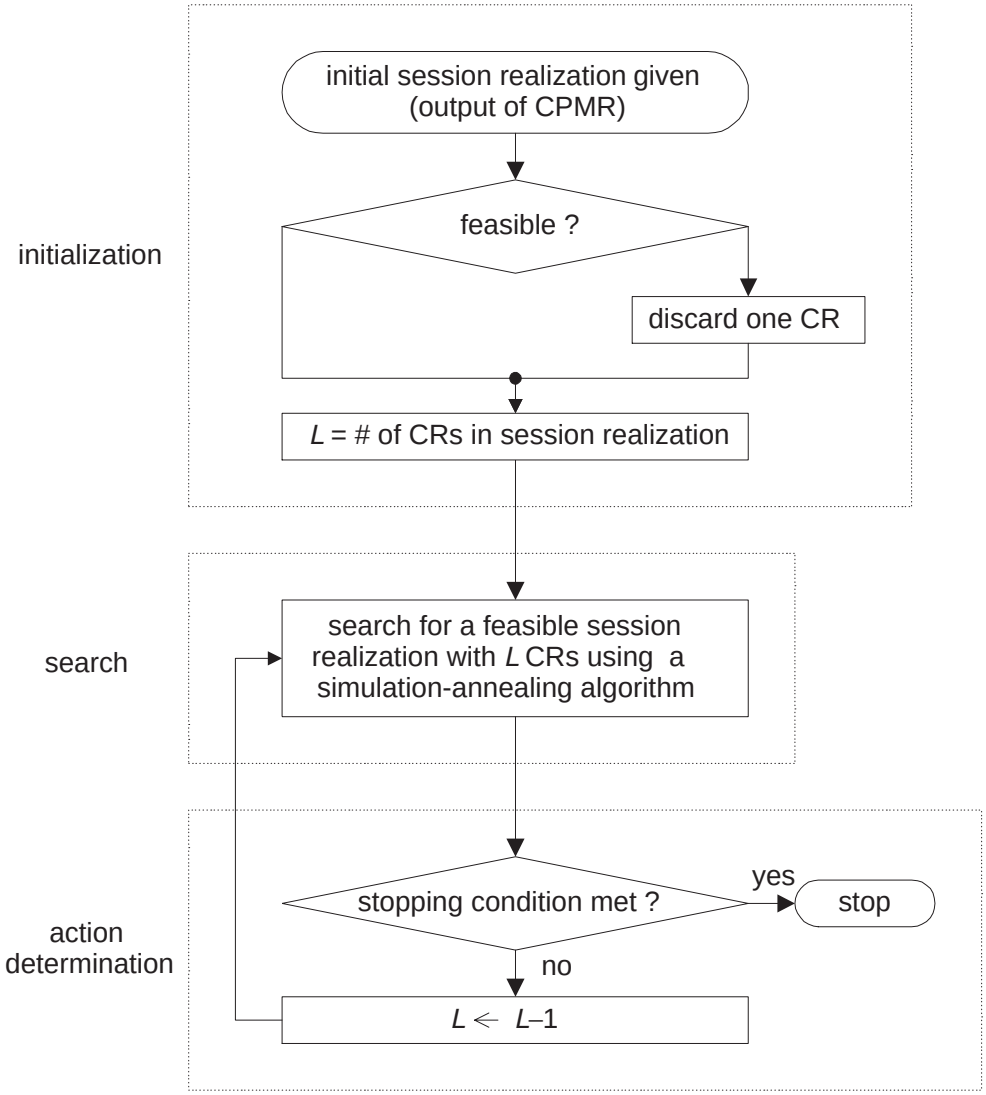


Fig. 4.6. Framework of CPMR-SA

this point, either X was originally infeasible, or has been changed to be infeasible. Suppose that X now has L CRs. Now, the search procedure of CPMR-SA attempts to find a feasible session realization with L CRs, using a simulated-annealing algorithm as follows.

CPMR-SA repeatedly replaces some CRs in X through the following three steps. (i) First, CPMR-SA randomly selects the number of the CRs in X to be replaced. Let L_c represent this number. CPMR-SA then removes L_c CRs by repeatedly extracting a random CR from X. For each extraction, the probability that CR x_i is extracted, denoted by $P_e(x_i)$, is proportional to the path failure probability of x_i (i.e., $P_f(x_i)$). To elaborate, suppose that X has r CRs $x_1, \ldots, x_r$ at a certain time during this extraction process. To select a CR x_i to be extracted from $x_1, \ldots, x_r$, we use

$$P_e(x_i) = \frac{P_f(x_i)}{\sum_{j=1}^{r} P_f(x_j)}. \tag{4.10}$$

Note that the CRs with higher path failure probabilities are more likely to be removed. (ii) CPMR-SA then selects L_c new (replacement) CRs using the same procedure used in CPMR. That is, CPMR-SA repeatedly updates the residual network and adds a CR into X, as described in Sections 4.5.2 (if $L = N$) and 4.5.3 (if $L > N$). (iii) Last, CPMR-SA determines if this replacement of CRs is acceptable. If the new session realization has a lower session failure probability than the original session realization, then the replacement is always accepted. Otherwise, CPMR-SA accepts the replacement in a probabilistic way.

The probability of accepting the replacement, denoted by P_a, is a function of two variables: (a) the difference of the session failure probabilities between the new session realization and the original session realization, denoted by Δ, and (b) the control temperature, denoted by T (the value of T changes with the number of iterations). This probability is given by $P_a = \exp(-\Delta/T)$. The initial value of T, denoted by T_o, is set to be sufficiently high such that the replacement of CRs is very likely to be accepted. For our simulation, we use a value of T_o that is 100 times larger than the difference between the initial session failure probability and P_{MASF}. CPMR-SA updates the value of T whenever a replacement of CRs is accepted. If we denote the

temperature at the nth update by T_n, CPMR-SA updates the temperature such that $T_n = T_o / \log_{10}(10 + n)$ [Haj88].

If the replacement in step (iii) is not accepted, CPMR-SA restores the session realization and link values, and repeats the above three steps to replace another set of CRs in the session realization. If the replacement is accepted, but if the resulting session realization is still infeasible, then CPMR-SA repeats the above three steps with the new session realization. The search procedure terminates if one of the following two cases holds: (A) when the replacement CR is accepted, and the resulting session realization is feasible, (B) when the replacement of CRs is not accepted 10 times in a row, or when the replacement of every possible set of CRs is not accepted (note that if $N \leq 3$, the number of all the possible replacements is less than 10).

In case (a), CPMR-SA checks the number of CRs in the session realization. If it is N, then CPMR-SA terminates. Otherwise, CPMR-SA removes a CR from the session realization, and repeats the search procedure to search for a feasible session realization with the number of CRs reduced by one. In case (b), CPMR-SA terminates and outputs the "best" session realization found (i.e., a feasible session realization with the smallest number of CRs).

4.7.4 DPR: disjoint-paths routing

We compare our schemes CPMR and SPMR with a scheme called DPR (disjoint-paths routing). DPR is a routing scheme that searches for a feasible session realization with the smallest number of disjoint CRs. Similar to CPMR and SPMR, DPR repeatedly selects the CR with the smallest path failure probability and adds it into the session realization. DPR also uses residual networks and link cancellation. However, DPR assumes that each link has a unit capacity regardless of the original link capacity, and thus any session realization found by DPR consists of disjoint CRs. Accordingly, DPR does not need to use the penalization methods of CPMR and SPMR. Because of the unit capacity assumption, link cancellation must occur when a link is

contained in any two CRs (always in opposite directions). We compare DPR with CPMR and SPMR to determine the impact of link-sharing on routing success rates.

4.7.5 Simulation setup

We perform our simulation experiments according to the following procedure. First, we generate a random network topology. Next, we assign a capacity and a failure probability to every link in the generated network topology. Finally, we apply routing schemes to find feasible session realizations. We perform 1000 simulation runs of this procedure for each pair of values of N and P_{MASF}, and then compute the routing success rate and the average number of channels in a realized session for each routing scheme.

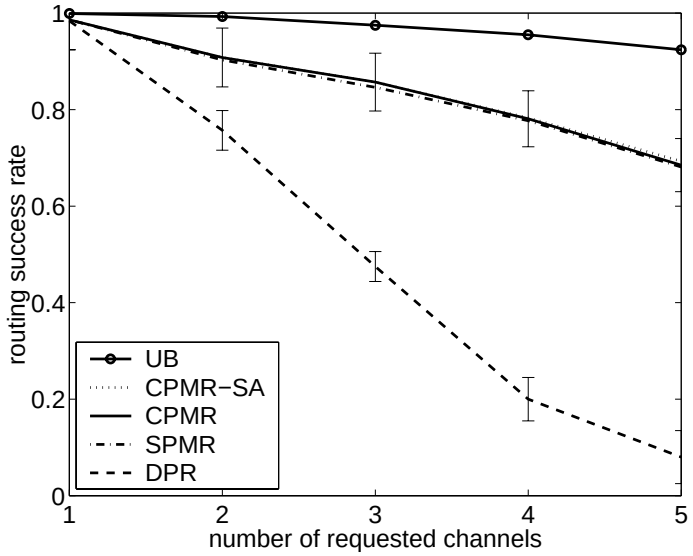
We use the Waxman model [Wax88] to generate a connected network topology for each simulation run. We disperse 200 nodes uniformly (randomly) in a unit square area, and then introduce a link between arbitrary nodes u and v with the following probability, which depends on the distance between them, $\delta(uv)$:

$$Pr(uv) = \alpha \exp\left[\frac{-\delta(uv)}{\beta\sqrt{2}}\right].$$

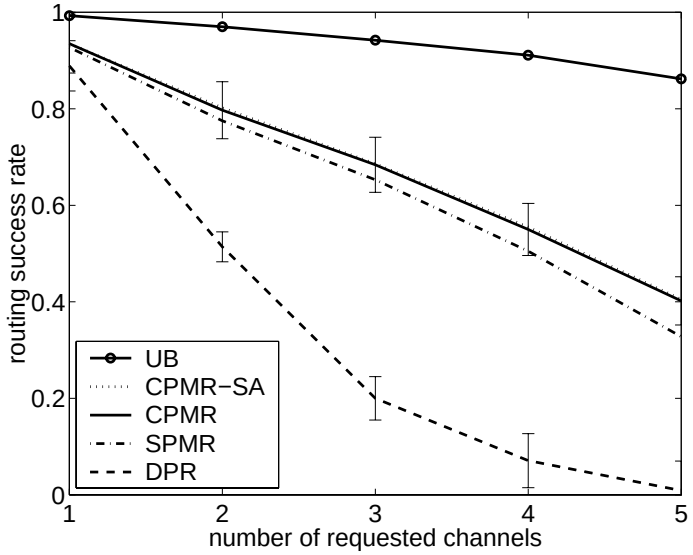
For the values of α and β in the above equation, we use 0.8 and 0.06, respectively. This approach results in approximately 574 links per network topology, for an average node degree is 5.74. We select source and destination nodes randomly. We then assign each link an integer capacity randomly, such that the link capacities are distributed uniformly in the range of $[1, 5]$. We also assign link failure probabilities randomly such that they have a uniform distribution in a log domain between 0.001 and 1.0.

4.7.6 Simulation results

Figures 4.7 and 4.8 show plots of the routing success rate versus the number of requested channels, and plots of the routing success rate versus the maximum allowable session failure probability, respectively. We can see that SPMR has almost



(a)



(b)

Fig. 4.7. Plots of the routing success rate versus the number of requested channels (a) when $P_{MASF} = 0.1$, and (b) when $P_{MASF} = 0.01$. 95% confidence-interval bars are shown. UB represents the upper bound described. Because CPMR, SPMR, and CPMR-SA have almost the same confidence intervals, only the confidence intervals of CPMR are shown. Note that the plots for CPMR, SPMR, and CPMR-SA overlap in (a).

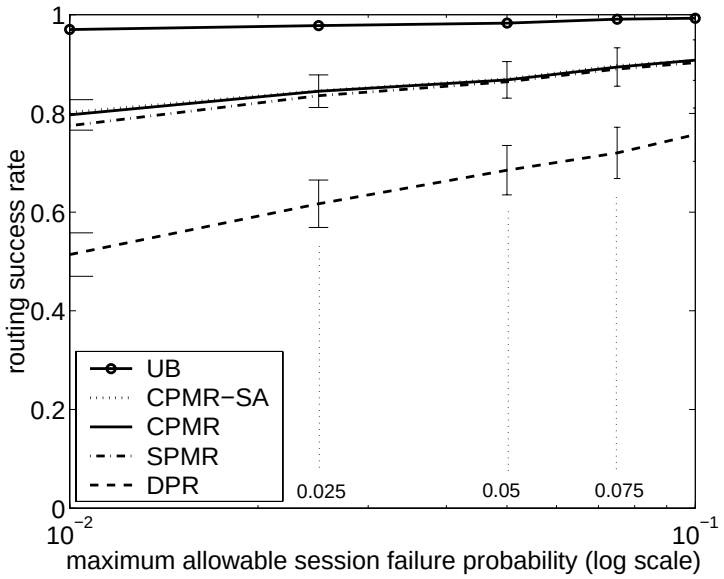


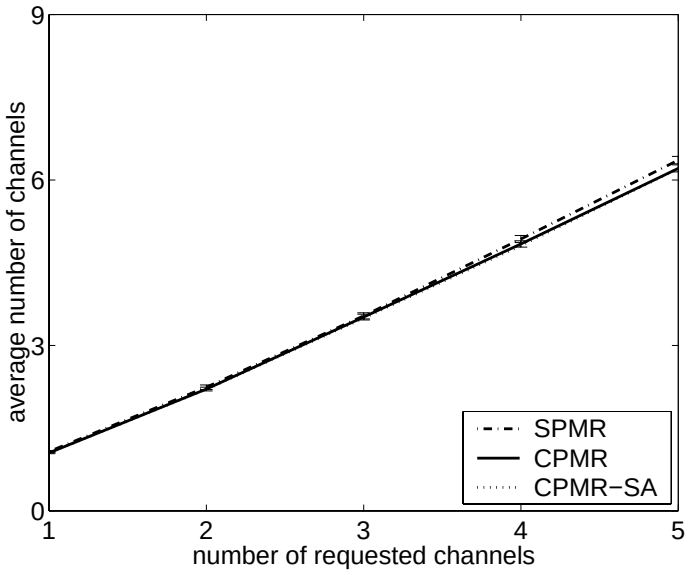
Fig. 4.8. Plots of the routing success rate versus the maximum allowable session failure probability (i.e., P_{MASF}) when the numbers of requested channels are two (i.e., $N = 2$). 95% confidence-interval bars are shown. UB represents the upper bound described. Because CPMR, SPMR, and CPMR-SA have almost the same confidence intervals, only the confidence intervals of CPMR are shown. Note that the plots for CPMR, SPMR, and CPMR-SA overlap.

the same routing success rate as CPMR, and that the difference in routing success rates between DPR and CPMR (or SPMR) is large. In addition, CPMR and SPMR also have almost the same routing success rates as that of CPMR-SA, which attempts to find a near-optimal solution at the expense of a longer run-time.

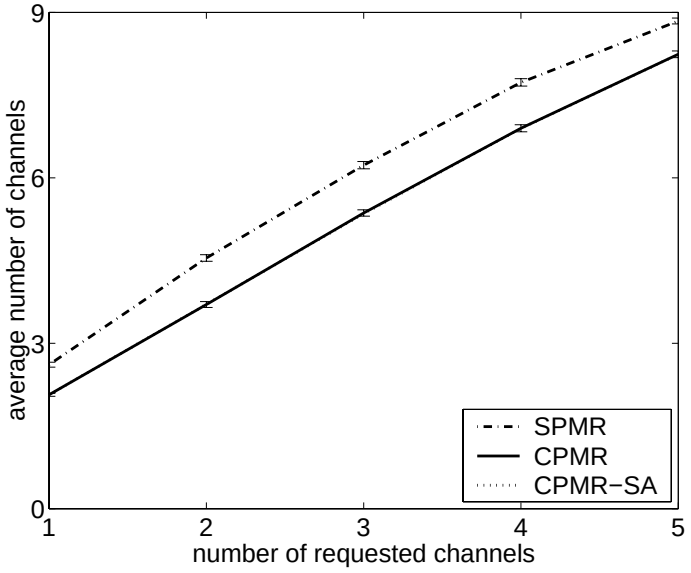
Figure 4.9 shows plots of the average number of channels in a realized session versus the number of requested channels. We can see that CPMR has almost the same average number of channels in a realized session as CPMR-SA, regardless of the value of P_{MASF}. SPMR also has almost the same average number of channels in a realized session as CPMR-SA for large value of P_{MASF} (i.e., for a loose survivability constraint). However, for small value of P_{MASF} (i.e., for a tight survivability constraint), SPMR has a slightly larger average number of channels in a feasible session than CPMR and CPMR-SA.

Figure 4.10 shows plots of the average number of links in a CR versus the number of requested channels. If the value of P_{MASF} is large (i.e., the survivability constraint is loose), a feasible session realization may contain long CRs (i.e., CRs with many links). Hence, the average number of links in a CR increases with the number of requested channels for all the schemes except for DPR. The exception of DPR is due to its low routing success rate. On the contrary, if the value of P_{MASF} is small (i.e., the survivability constraint is tight), a session realization with long CRs is likely to be infeasible. Thus, the average number of links in a CR becomes smaller as the number of requested channels exceeds a certain value.

Figure 4.11 shows plots of the number of terminations of the search procedure (using the simulated annealing algorithm) in CPMR-SA by stopping criteria (A) and (B), which are introduced in Section 4.7.3. The numbers of the terminations of the search procedure by each of criteria (A) and (B) increase with the number of requested channels because the total number of the runs of the search procedure increases. However, if the value of P_{MASF} is large, then the number of CRs in a session realization is small. Hence, this number is probable to be currently equal or close to the number of requested channels. Therefore, the number of terminations of

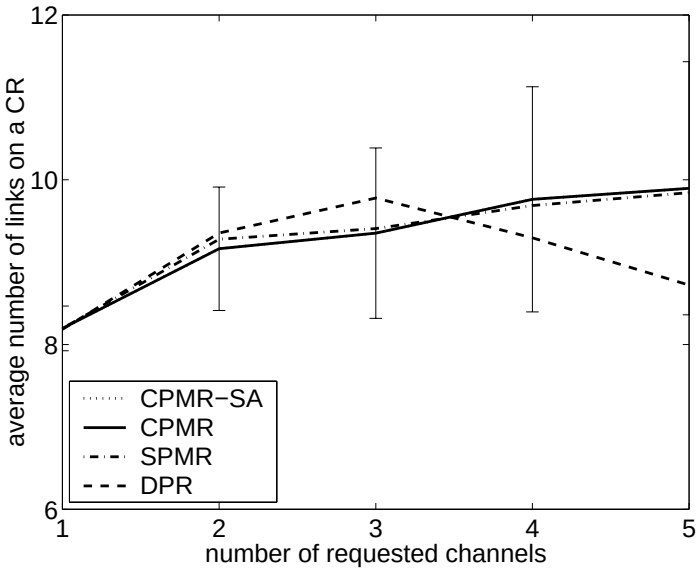


(a)

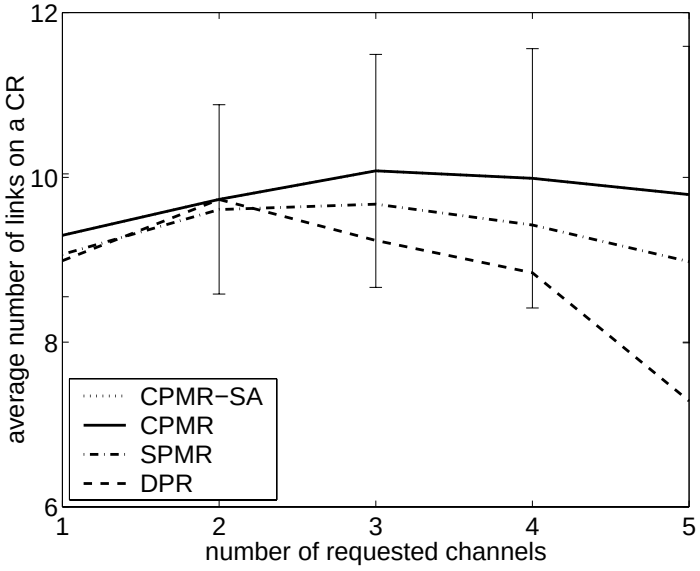


(b)

Fig. 4.9. Plots of the average number of channels in a realized session versus the number of requested channels (a) when $P_{MASF} = 0.1$, and (b) when $P_{MASF} = 0.01$. 95% confidence-interval bars are shown. Because CPMR and CPMR-SA have almost the same confidence intervals, only the confidence intervals of CPMR are shown. Note that the plots for CPMR, SPMR, and CPMR-SA overlap in (a), and the plots for CPMR and CPMR-SA overlap in (b).

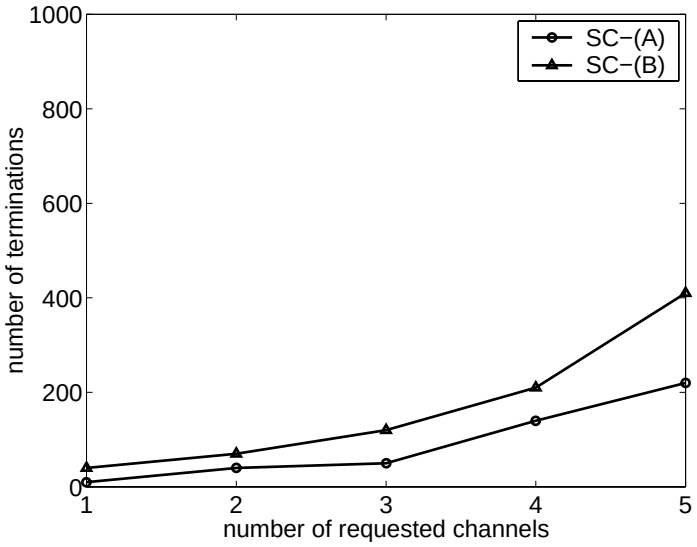


(a)

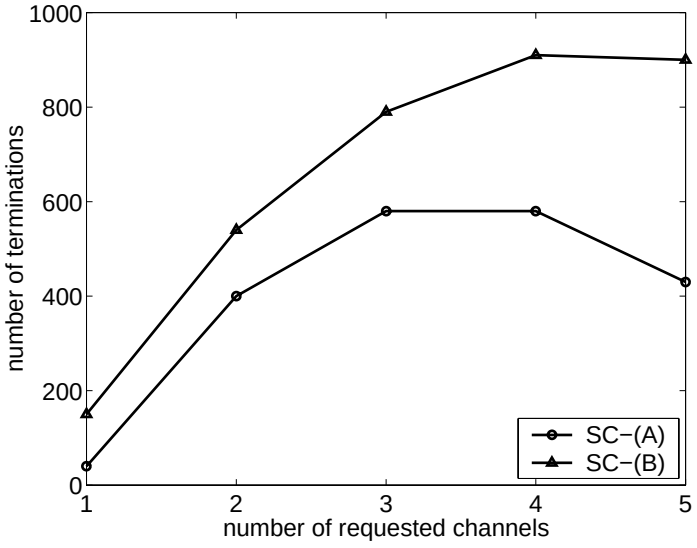


(b)

Fig. 4.10. Plots of the average number links on a CR versus the number of requested channels (a) when $P_{MASF} = 0.1$, and (b) when $P_{MASF} = 0.01$. 95% confidence-interval bars are shown. Because the widths of confidence intervals are almost the same for all the schemes, only the confidence intervals of CPMR are shown. Note that the plots for CPMR and CPMR-SA overlap in (a) and (b).



(a)



(b)

Fig. 4.11. Plots of the number of terminations of the search procedure (using the simulated annealing algorithm) in CPMR-SA by stopping criteria (A) and (B), (a) when $P_{MASF} = 0.1$, and (b) when $P_{MASF} = 0.01$. SC-(A) and SC-(B) denote the stopping criteria (A) and (B), respectively.

the search procedure is small because the search procedure (to reduce the number of CRs in the session realization without violating constraints) is executed no more or just a few times. The decrease in the number of terminations at the largest number of requested channels (i.e., 5) in Figure 4.11(b) is due to the low routing success rate.

In our simulation, the run-time of SPMR is approximately 20% of the run-time of CPMR. The run-time of CPMR-SA is approximately 10 times longer than that of CPMR. Hence, compared to CPMR-SA, CPMR and SPMR have good performance in solving the SMR problem, but with much shorter execution time.

4.8 Conclusion

If we do not consider the vulnerability and capacity of each link in survivable routing for WDM networks, we may waste network resources for unnecessary paths, or may not provide adequate survivability in practice. To develop survivable routing schemes without this weakness, we used link failure probabilities to account for the vulnerability of links in WDM networks, instead of assuming that the maximum number of link failures is known beforehand. Because our survivable routing problem is NP-hard, we proposed heuristic schemes, CPMR and SPMR. These schemes allow link-sharing (i.e., they do not limit routing paths to be disjoint), and thus enjoy increased routing success rates, compared with schemes without link-sharing. However, this link-sharing makes routing difficult. Hence, we developed link penalization methods to deal with this difficulty. These methods make it possible to assign every link a dynamic value, called a penalty, and update this value to control link-sharing.

CPMR has a longer run-time than SPMR, because of the complicated procedure to update link penalties. In contrast, SPMR reduces the run-time by the use of a simple penalization method, but may sacrifice slightly the routing success rate and the average number of channels in a feasible session. We compared our schemes with DPR (which searches for disjoint paths) and with CPMR-SA (which uses a simulated-annealing method to search for a near-optimal solution at the expense of

a longer run-time). Via simulation, we showed that our schemes have higher routing success rates than DPR, and achieve (with shorter execution times) almost the same routing success rate and average number of channels in a realized session as CPMR-SA. Future work could involve examining how these schemes may be adapted to the situations where there are multiple pairs of source and destination nodes.

5. SUMMARY AND DIRECTIONS FOR FUTURE RESEARCH

In this thesis, we dealt with two routing problems. The first problem, called the multiconstraint QoS routing problem, is to find a single path that satisfies multiple QoS (quality of service) constraints. We develop two routing schemes, called MPLMR and SPMP, for this problem. The second problem, which we call the survivable multipath routing problem, is to find a minimum number of paths that can collectively satisfy the constraints on channel demand, capacity, and survivability, between a given pair of source and destination nodes in a WDM (wavelength division multiplexing) network. We also develop two schemes, CPMR and SPMR, for the second problem.

MPLMR uses an extended shortest-path algorithm based on the notion of the nonlinear path length, with the assumption that detailed routing information is provided by a link-state protocol. Like previous schemes using extended shortest-path algorithms for polynomial complexity, MPLMR stores a limited number of prepaths, and extends them toward the destination node. However, unlike the previous schemes, MPLMR uses an efficient "look-ahead" method to predict the nonlinear path length of the full path to which each prepath is extended, and selects and stores the prepaths that have higher likelihood than other prepaths to be extended to feasible paths. MPLMR has a significantly low EDR with even smaller execution time than the competing schemes in the literature. Hence, MPLMR provides a promising solution for multiconstraint QoS routing when detailed routing information is provided by a link-state protocol. Future research related to MPLMR may include the following topics: (1) estimation of the optimal value of k (i.e., the maximum number of prepaths to be stored for each node), (2) improvement of the look-ahead method using statistical data about link values (e.g., correlation between QoS attributes), and (3) analysis

of the sensitivity of MPLMR to inaccurate routing information and development of enhanced routing schemes robust to dynamic routing environments.

SPMP is also a multiconstraint QoS routing scheme based on the notion of the nonlinear path length. However, SPMP assumes that routing information is provided by a distance-vector protocol to reduce the signaling overhead in both the information-advertisement process and the path-search process. Moreover, SPMP takes a sequential path-search approach to minimize the number of the nodes unnecessarily affected by the path-search process. Because of the sequential path-search approach, SPMP has exponential worst-case time complexity. However, by the use of an efficient path-search order and the control of the crankback degree, SPMP shows low EDR while keeping average-case time complexity low. Hence, SPMP can be a useful tool for multiconstraint QoS routing when the signaling overhead is a concern (e.g., wireless ad hoc networks). SPMP can be extended to the corresponding parallel path-search scheme for the reduction of path-search time. It may be valuable to compare quantitatively the advantages and disadvantages of both SPMP and the corresponding parallel search scheme. In addition, the development of an efficient multiconstraint QoS routing scheme with no information advertisement may also be a valuable research topic for the elimination of the signaling overhead in the information-advertisement process.

Both CPMR and SPMR are survivable multipath routing schemes to find a set of routing paths that accommodate the minimum number of channels without violating the constraints. Implicitly or explicitly, most previous survivable routing schemes for WDM networks assume that the maximum number of simultaneous link failures is known. However, CPMR and SPMR take an alternative approach by using failure probability for more general assumption on survivability. These schemes do not limit routing paths to be disjoint to increase routing success rates. To control the difficulty caused by link-sharing, we develop link penalization methods for CPMR and SPMR. We compare these schemes with DPR (which searches for disjoint paths) and with CPMR-SA (which uses a simulated-annealing method to search for a near-optimal

solution at the expense of a longer run-time). Via simulation, we show that CPMR and SPMR have higher routing success rates than DPR, and achieve (with shorter execution times) almost the same routing success rate and average number of channels in a realized session as CPMR-SA. Future work could involve examining how these schemes may be adapted to situations where there are multiple pairs of source and destination nodes.

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APPENDIX

APPENDIX A
COMPUTATION OF THE PROBABILITY IN (4.2)

If we can compute $P(x_1^{(F)}, \ldots, x_k^{(F)}, x_{k+1}^{(W)}, \ldots, x_L^{(W)})$, then we can compute the probability of (4.2) by applying the same computation to all the terms in the equation. By Bayes' rule,

$$\begin{aligned} &P(x_1^{(F)}, \ldots, x_k^{(F)}, x_{k+1}^{(W)}, \ldots, x_L^{(W)}) \\ &= P(x_1^{(F)}, \ldots, x_k^{(F)} |\ x_{k+1}^{(W)}, \ldots, x_L^{(W)}) \cdot P(x_{k+1}^{(W)}, \ldots, x_L^{(W)}). \end{aligned}$$

The computation of $P(x_{k+1}^{(W)}, \ldots, x_L^{(W)})$ is straightforward, as follows. Let E_w be the set of links on CRs $x_{k+1}, \ldots, x_L$, and let $P_f(uv)$ be the failure probability of link $uv \in E_w$. If CRs $x_{k+1}, \ldots, x_L$ work, all the links on these CRs must be working. Hence,

$$P(x_{k+1}^{(W)}, \ldots, x_L^{(W)}) = \prod_{uv \in E_w} [\ 1 - P_f(uv)\ ]. \tag{A.1}$$

Next, we consider the computation of $P(x_1^{(F)}, \ldots, x_k^{(F)} |\ x_{k+1}^{(W)}, \ldots, x_L^{(W)})$. Let E_k be the set of the links on CRs $x_1, \ldots, x_k$. We do not need to consider the failure probabilities of the links on CRs $x_{k+1}, \ldots, x_L$, because these links are assumed to be working. Thus, we consider only the links in $E_k - E_w$. Let h be the number of these links. We can compute $P(x_1^{(F)}, \ldots, x_k^{(F)} |\ x_{k+1}^{(W)}, \ldots, x_L^{(W)})$ by investigating the 2^h cases where each link works or fails, and summing up all the probabilities of the cases for which CRs $x_1, \ldots, x_k$ fail. For this computation, let $H_h = \{1, \ldots, h\}$, B_i the set of the CRs containing link l_i, and $P_f(l_i)$ the failure probability of link l_i for $i = 1, \ldots, h$. Then,

$$\begin{aligned} &P(x_1^{(F)}, \ldots, x_k^{(F)} |\ x_{k+1}^{(W)}, \ldots, x_L^{(W)}) \\ &= \sum_{i=1}^{h} \sum_{\substack{\{j_1, \ldots, j_i\} \subset H_h \text{ s. t.} \\ B_{j_1} \cup \ldots \cup B_{j_i} = \{x_1, \ldots, x_k\}, \\ \{j_{i+1}, \ldots, j_h\} = H_h - \{j_1, \ldots, j_i\}}} P_f(l_{j_1}) \cdots P_f(l_{j_i}) \cdot [1 - P_f(l_{j_{i+1}})] \cdots [1 - P_f(l_{j_h})]. \end{aligned} \tag{A.2}$$

The computation of (A.2) has the exponential complexity of $O(2^h)$, and may require long computation time.

If k is sufficiently small compared to h (as described below), then we can reduce the computation time of (A.2) as follows. First, we group the h links into 2^k groups according to their associated CRs among $x_1, \ldots, x_k$, such that all the links in each group are on the same subset of CRs, and not on any other CRs (the total number of subsets of k CRs is 2^k). In general, some of these groups are empty. If we use link penalization, then typically the majority of the groups are empty because link-sharing is discouraged. Note that if any of the links in a group fails, then all of the CRs associated with the group fail. It is easy to compute the probability that any of the links in each group fails, which we call the *group failure probability*. We can compute the group failure probability of group g_i, denoted by $P_f(g_i)$, as in (A.1). That is,

$$P_f(g_i) = 1 - \prod_{uv \in g_i} [\ 1 - P_f(uv)\ ].$$

Let the number of the groups containing at least one link be r. The computation of the group failure probabilities for all the groups takes $O(h)$ time. Using the group failure probabilities (rather than the failure probabilities of links $l_1, \ldots, l_h$), we can compute $P(x_1^{(F)}, \ldots, x_k^{(F)} |\ x_{k+1}^{(W)}, \ldots, x_L^{(W)})$ as follows. Let $H_r = \{1, \ldots, r\}$, and C_i be the set of the CRs associated with group g_i for $i = 1, \ldots, r$. Then,

$$\begin{aligned} &P(x_1^{(F)}, \ldots, x_k^{(F)} |\ x_{k+1}^{(W)}, \ldots, x_L^{(W)}) \\ &= \sum_{i=1}^{r} \sum_{\substack{\{j_1,\ldots,j_i\} \subset H_r \text{ s.t.} \\ C_{j_1} \cup \ldots \cup C_{j_i} = \{x_1,\ldots,x_k\}, \\ \{j_{i+1},\ldots,j_r\} = H_r - \{j_1,\ldots,j_i\}}} P_f(g_{j_1}) \cdots P_f(g_{j_i}) \cdot [1 - P_f(g_{j_{i+1}})] \cdots [1 - P_f(g_{j_r})]. \end{aligned} \quad \text{(A.3)}$$

Hence, the computation of (A.3) has the complexity of $O(h + 2^r)$, which, like (A.2), is also exponential. However, if $r < h$ (i.e., the number of groups is smaller than the number of links), then the computation time is smaller than that of (A.2).

APPENDIX B

COMPUTATION OF THE PENALTY IN (4.8)

By the method explained in Appendix 1, we can compute $P(X, k, b)$. Using the notation used in (4.2), we can represent $P(X, k, b \mid uv \text{ fails})$ as follows:

$$P(X, k, b \mid uv \text{ fails}) = \sum_{\substack{\{j_1,\ldots,j_b\}\subset H_k,\\ \{j_{b+1},\ldots,j_k\}=H_k-\{j_1,\ldots,j_b\}}} P(x_{j_1}^{(F)}, \ldots, x_{j_b}^{(F)}, x_{j_{b+1}}^{(W)}, \ldots, x_{j_k}^{(W)} \mid uv \text{ fails}). \tag{B.1}$$

Hence, if we can compute $P^* = P(x_1^{(F)}, \ldots, x_b^{(F)}, x_{b+1}^{(W)}, \ldots, x_k^{(W)} \mid uv \text{ fails})$, then we can compute the link penalty of (4.8) by applying the same computation to all the terms in (B.1).

If link uv is not on any of CRs $x_1, \ldots, x_k$, then $P^* = P(x_1^{(F)}, \ldots, x_b^{(F)}, x_{b+1}^{(W)}, \ldots, x_k^{(W)})$. Obviously, P^* is zero if link uv is on any of the working CRs $x_{b+1}, \ldots, x_k$. Hence, it remains to consider the case where link uv is on some of CRs $x_1, \ldots, x_b$ but not on any of CRs $x_{b+1}, \ldots, x_k$. Without loss of generality, we assume that link uv is only on CRs $x_1, \ldots, x_a$ $(a \leq b)$. Then, $P^* = P(x_{a+1}^{(F)}, \ldots, x_b^{(F)}, x_{b+1}^{(W)}, \ldots, x_k^{(W)})$. By the method explained in Appendix 1, we can also compute this P^*.

VITA

VITA

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