Telecommun Syst (2013) 52:1043–1055
DOI 10.1007/s11235-011-9611-4

Simultaneous optimization of unicast and anycast flows and replica location in survivable optical networks

Krzysztof Walkowiak · Jacek Rak

Published online: 1 September 2011

Abstract Most of previous works related to survivable networks have been focused on unicast communications. In this paper, we address the problem of network survivability in the context of anycast communications, which has not attracted much attention recently. Anycast transmission is defined as *one-to-one-of-many*. To assure the network survivability, we use the single backup path approach, i.e., each demand has two node-disjoint paths to provide protection against a single link failure. We formulate new ILP models to find the optimal paths for anycast and unicast connections, as well as to find the optimal location of replica servers. To test the proposed approach, we run extensive numerical experiments using CPLEX solver on four example network topologies with different scenarios of replica server count and the proportion between unicast and anycast traffic. Results prove the efficiency of our solution in terms of various parameters including cost, path length, resource utilization, and time of computation.

Keywords Survivable networks · Anycast communications · ILP modeling · Replica location · High-speed networks · WDM networks

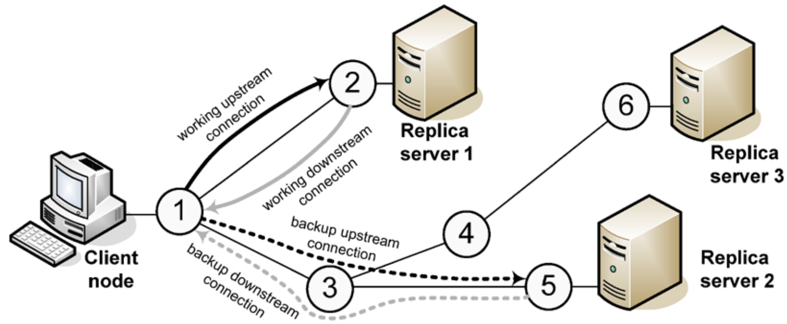
K. Walkowiak
Department of Systems and Computer Networks, Wroclaw University of Technology, Wroclaw, Poland
e-mail: krzysztof.walkowiak@pwr.wroc.pl
url: http://www.kssk.pwr.wroc.pl/walkowiak/

J. Rak (✉)
Department of Computer Communications, Gdansk University of Technology, Gdansk, Poland
e-mail: jrak@pg.gda.pl
url: http://www.pg.gda.pl/~jrak/

1 Introduction

Our discussion in this article centers on survivability of *anycast* and *unicast* flows in high-speed communication networks. Anycast—a one-to-one-of-many transmission technique, has recently become very important in parallel to deployment of many significant network services, e.g., Content Delivery Networks (CDNs), DNS, peer-to-peer systems (P2P), video streaming, and others [1–3]. Anycasting can remarkably decrease the network load, compared to the unicast transmission (a typical one-to-one technique). Moreover, since any user can select the source of data from among many replica servers, anycasting also improves the network resilience [4, 5]. We focus on connection-oriented networks capable of providing the required QoS, as well as fault tolerance. In particular, the proposed solutions are devoted to high-speed WDM networks, where each optical link offers a set of non-overlapping *channels*, called *wavelengths* [6]. Each channel is capable of transmitting the data independently at a speed of several Gbps (e.g., 10 or more). Therefore, a failure of even a single network element may lead to severe data and revenue losses. One of the key aspects in recent high-speed networks design is the *network survivability*, being the capability to deliver services in the presence of failures [7]. Failures of single network elements are mostly considered. Survivability is achieved by means of additional *backup paths* used to restore the *primary* (*working*) *paths* of broken connections [8]. Backup paths are required to have no common links (or transit nodes) to provide protection against a single link (or a single node) failure, accordingly. Two major methods developed to provide network survivability are: *protection* and *restoration* [7]. Protection utilizes backup paths found in advance (when setting up the connection), while restoration calculates the backup paths dynamically (after a failure). Under both scenarios, we may

Fig. 1 An example of a survivable anycast connection with different primary and backup replicas



distinguish *path* and *link protection/restoration*. Several intermediate solutions exist, e.g. *area protection* [9]. More information on network survivability may be found in [6].

In anycast communications, information is replicated and stored in several *replica servers*. A particular replica server may be chosen based on several criteria, e.g. delay, or QoS. In case of a failure, a backup path may lead to the same or the other replica server. The latter case is shown in Fig. 1.

1.1 Motivations

In the beginning, we want to express that anycasting is a powerful approach to improve the network performance. Notice that using the anycast service, the user can choose one of many replica servers (locations) providing the same content. Various criteria (also including Quality of Service parameters) can be applied in the process of replica selection. Therefore, anycasting—when compared to the traditional unicast transmission—reduces the overall network traffic and congestion, what in consequence decreases the delay of data delivery. An additional benefit of the anycast approach is that replica servers provide more resilient service, as users can select another replica server offering the same data, and even a failure of one replica server does not cause the data to be unreachable.

Survivability has become one of the key aspects in the design of reliable communication networks. This follows from the fact that currently many important aspects of our life rely on various networking services. Thus, a failure—especially occurring in the backbone network carrying large volumes of data—can lead to many severe consequences related to economics, security, health, etc. A lot of research has been conducted in the field of unicast traffic survivability. However, the growing popularity of anycast services (e.g., a CDN system provided by Akamai serves about 20% of the whole Internet traffic [10]) triggers the need to develop survivability mechanisms also for anycast traffic.

In this work we focus on anycasting in optical networks. This decision is reasonably well explained by the fact that most of current backbone networks are based on optical techniques including WDM. Moreover, our results presented below can be applied to other connection-oriented network techniques, e.g., MPLS (MultiProtocol Label Switching) [11].

1.2 Our contributions

The main goal of our paper is twofold. First, we formulate new ILP (Integer Linear Program) models related to survivable optical networks with simultaneous optimization of unicast and anycast flows. In particular, we consider optimization of flows, as well as joint optimization of flows and replica location. Unicast and anycast demands are protected by the single backup path method. The case of protection against a single link failure is considered. Second, we apply numerical evaluation using the MIP solver of CPLEX [12] to show the performance of the proposed approaches in terms of system cost, path length, resource utilization, and time of computation. Note that the main novelty of this work—compared to our previous papers [5, 9]—is the application of a single backup path method to provide 100% protection for both anycast and unicast demands. This method was applied in the context of unicast flows in [9], while in [5] we used the restoration method to minimize the lost flow function. Moreover, in [13] we formulated and examined models for joint optimization of unicast and anycast flows protected by single backup paths against a single node failure. To our best survey, this is the first study to formulate the ILP model of joint optimization of unicast and anycast flows and replica location in survivable networks.

1.3 Overview of paper

The rest of the paper is organized as follows. Section 2 presents the related work. In Sect. 3 we focus on unicast and anycast flow optimization in survivable networks. We formulate the respective ILP models and report the optimal results of modeling obtained using CPLEX 11.0 solver [12]. Section 4 is related to the problem of joint optimization of flows (unicast and anycast) extended by the issue of replica server location in survivable networks, where we show ILP models and the optimal results. We conclude our discussion in Sect. 5.

2 Review of related work

Anycasting is a technique that usually uses various solutions based on caching or replication. Content Delivery Network (CDN) is a popular example of a caching approach that is based on anycast traffic. CDN is defined as mechanisms to distribute a range of content to end users on behalf of the origin Web servers. Information is offloaded from source sites to other content servers located at different nodes in the network. For each request, the CDN tries to connect to the closest server offering the requested Web page. Each CDN system is responsible for delivering the content from the origin server to the replicas that are much closer to end users. A popular example of a CDN system is Akamai [1, 2, 10].

Most of previous works on anycasting concentrate on IP networks using connectionless transmission modeled as bifurcated multicommodity flows, e.g. [1, 14]. There are not many papers related to optimization of connection-oriented networks (e.g. MPLS, WDM) using unicast and anycast flows.

The authors of [15] formulate the WDM anycast routing problem (WARP) to find a set of lightpaths (one for each source) for anycasting the messages to one of the members in the anycast destination group such that not any path using the same wavelength traverses the same link. The goal is to minimize the number of used wavelengths. Heuristic algorithms including simulated annealing are developed. In [5], anycast communications is analyzed in the context of the network survivability. A new optimization problem is formulated. The objective is the joint optimization of unicast and anycast flows in a connection-oriented network using the restoration approach to provide the network survivability. The proposed heuristic algorithm is used to show that anycasting can improve the network survivability in terms of amount of traffic that could not be served. Authors of [13] formulate new ILP models to find the optimal paths for anycast and unicast connections protected against a single node failure. Extensive numerical experiments using CPLEX are run to verify the proposed approach.

The problem of replica server location has been addressed in many works, e.g., in [16–23]. However, most of papers focus on well-known optimisation problems: the k-facility location problem and the k-median problem (see e.g. [17, 19–22], and [17, 22] accordingly). The former problem relates to the assignment of clients to k facilities that are to be located at network nodes. The objective is to minimize the total cost including the connection cost of each client and the facility cost. The k-median problem generally differs from the facility problem in one thing: there is no cost for opening the facilities. The main issue of both discussed problems is location of k facilities, i.e., selection of k network nodes for hosting a facility. The assignment of individual clients to a particular replica server is solved in a simple way, i.e., the client is assigned the closest replica server in terms of connection cost. Consequently, the flow is not optimized in order to improve the performance metrics, e.g. cost or survivability. Li et al. in [18] formulate a problem of proxies location in a tree topology with the objective function of cost associated with the selection of proxies and propose a dynamic programming algorithm. The cost can be calculated as the overall latency, if the link length is associated with the cost function. In [16], Krishnan et al. consider the cache location problem for transparent caches. The objective function is the minimization of the total cost of demands using a cache in selected location. The general problem is NP-complete. Therefore, only regular topologies are analyzed: homogenous line, general line, and ring. The authors of [17] formulate the problem of the placement of web server replicas as an uncapacitated k-median problem connected with the facility location problem. They restrict the maximum number of replicas, but do not restrict the number of requests served by each replica. The objective function is to minimize the total cost of all requests. A greedy algorithm and an optimal algorithm are developed. Guha et al. consider a generalization of the standard facility problem and introduce the requirement of fault-tolerant mechanisms [19]. Every demand is served by a number of facilities instead of just one. The cost is a weighted combination of facilities locations. An algorithm using the filtering technique and fractional demands is provided. Authors of [20] present a simple and natural greedy algorithm for the metric uncapacitated facility location problem and the k-median problem. Arya et al. analyze in [21] a local search heuristics for facility location and k-median problems. The main operation of the proposed algorithm is swapping, which consists of closing one facility and opening another (clients of the closed facility are assigned to other facilities). In [22], improved combinatorial approximation algorithms for the uncapacitated facility location and k-median problems are proposed and discussed. The paper [23] focuses on the problem of simultaneous assignment of replica server location, link capacities and flows in wide area computer networks. The objective is to minimize the average delay per packet with additional budget constraint related to the network cost. A branch and bound method is used to construct the exact algorithm. An approximate algorithm is also proposed. Based on numerical experiments, several properties of the considered problem are formulated.

3 Optimization of unicast and anycast flows in survivable networks

3.1 Basic model

The considered network is modeled as a graph $\Gamma(N, A)$, where: N is a set of nodes; A is a set of directed arcs. Replica servers are located at some nodes. Constant u_n is 1, if node n hosts a replica server, and 0 otherwise. We assume that all replica servers provide the same content. Each network link is represented by pairs of unidirectional arcs: $a_h = (i, j)$ and $a_{h'} = (j, i)$. Each arc $a_h \in A$ is characterized by parameter ξ_h denoting the cost (length) and offers Λ unidirectional channels, each of a standard capacity.

Optimization models presented in this section are dedicated to connection-oriented WDM networks. Therefore, all network flows are modeled as non-bifurcated multicommodity flows. Let D denote a set of all demands (both anycast and unicast) indexed by r. For each demand $r \in D$, we assume that the requested capacity f_r is equal to the capacity of a single WDM channel. Therefore, for each demand we have $f_r = 1$. The set of anycast demands is denoted as D^{AN}. Anycast demand can be of two types: upstream (set D^{US}) or downstream (set D^{DS}). Each anycast demand r is defined by the client node (s_r—source node in the case of the upstream demand, or t_r—destination node in the case of the downstream demand). Each anycast downstream (upstream) demand $r \in D^{DS}(D^{US})$ is associated with another upstream (downstream) anycast demand that has the same client node denoted as $\tau(r)$. Since all replica servers located in the network provide the same content, each anycast demand can be connected to any of replica nodes. However, both associated anycast demands r and $\tau(r)$ must use the same replica node. Unicast demands are included in the set D^{UN}. Each unicast demand $r \in D^{UN}$ is defined by the source node s_r and the destination node t_r.

In this section we assume that network nodes included in set N can be assigned three roles, i.e., a node of a backbone network, replica node and demand source (destination) node. Moreover, we make an assumption that a particular node $n \in N$ is either a replica node (i.e., $u_n = 1$), or a client node of an anycast demand, i.e., any node cannot be both a replica node and a client node of anycast demand. This follows from the fact that if the client node of anycast demand is located at a replica node, the flow of this demand is not to be sent in the network and thus we can ignore such a demand.

Dedicated protection is applied, i.e., for each demand we establish two paths: working and backup. Protection against a failure of a single link is considered. Consequently, working and backup paths must be link-disjoint. We apply the link-node notation of multicommodity flows, thus all possible candidate paths are considered. In the case of unicast demands, optimization refers to the selection of paths. In the case of anycast demands, in addition to path assignment for each demand we must select the working and backup replica node. The objective of the model is to find paths for demands (unicast and anycast) transporting the required flows, protecting them against a single link failure by means of single backup paths and minimizing the network cost. The following notation is used in the mathematical representation of the problem.

Sets:

- N set of network nodes
- A set of arcs representing the directed links
- D set of demands
- D^{UN} set of unicast demands
- D^{AN} set of anycast demands
- D^{DS} set of anycast downstream demands
- D^{US} set of anycast upstream demands

Indices:

- n network node
- h arc
- r demand

Constants:

- $s_r (t_r)$ source (destination) node of the r-th demand. For downstream anycast demands we are given only the destination node t_r, while for upstream anycast demands we are given only the source node s_r
- Λ capacity of arc (number of unidirectional optical channels)
- $\tau(d)$ index associated with demand r
- u_n $= 1$, if node n is a replica node; 0, otherwise
- ξ_h cost (length) of arc h
- $\delta_{r,n}$ $= 1$, if node n is the closest replica node for anycast the r-th demand; 0, otherwise

Variables:

- $x_{r,h}$ $= 1$, if a channel of arc h is used by a working path of the r-th demand; 0, otherwise
- $y_{r,h}$ $= 1$, if a channel of arc h is used by a backup path of the r-th demand; 0, otherwise
- $z_{r,n}$ $= 1$, if a replica server located at node n is selected as a working replica of the r-th anycast demand; 0, otherwise
- $v_{r,n}$ $= 1$, if a replica server located at node n is selected as a backup replica of the r-th anycast demand; 0, otherwise

The UAFA (Unicast and Anycast Flow Assignment in survivable networks) problem can be formulated as follows:

$$\min \quad \varphi = \sum_{r \in D} \sum_{h \in A} \xi_h (x_{r,h} + y_{r,h}) \tag{1}$$

subject to:

$$\sum_{\substack{h \in \{h: a_h \equiv (n,j) \in A;\\ j \in N;\, j \neq n\}}} x_{r,h} - \sum_{\substack{h \in \{h: a_h \equiv (i,n) \in A;\\ i \in N;\, i \neq n\}}} x_{r,h} = \begin{cases} 1 & \text{if } n = s_r \\ -1 & \text{if } n = t_r \\ 0 & \text{otherwise} \end{cases} \quad \forall r \in D^{UN},\ \forall n \in N, \tag{2}$$

$$\sum_{\substack{h\in\{h:a_h\equiv(n,j)\in A;\\ j\in N;j\neq n\}}} y_{r,h} - \sum_{\substack{h\in\{h:a_h\equiv(i,n)\in A;\\ i\in N;i\neq n\}}} y_{r,h} = \begin{cases} 1 & \text{if } n=s_r \\ -1 & \text{if } n=t_r \\ 0 & \text{otherwise} \end{cases} \quad \forall r\in D^{UN},\ \forall n\in N, \tag{3}$$

$$\sum_{\substack{h\in\{h:a_h\equiv(n,j)\in A;\\ j\in N;j\neq n\}}} x_{r,h} - \sum_{\substack{h\in\{h:a_h\equiv(i,n)\in A;\\ i\in N;i\neq n\}}} x_{r,h} = \begin{cases} -1 & \text{if } n=t_r \\ z_{r,n} & \text{if } n\neq t_r \end{cases} \quad \forall r\in D^{DS},\ \forall n\in N, \tag{4}$$

$$\sum_{\substack{h\in\{h:a_h\equiv(n,j)\in A;\\ j\in N;j\neq n\}}} y_{r,h} - \sum_{\substack{h\in\{h:a_h\equiv(i,n)\in A;\\ i\in N;i\neq n\}}} y_{r,h} = \begin{cases} -1 & \text{if } n=t_r \\ v_{r,n} & \text{if } n\neq t_r \end{cases} \quad \forall r\in D^{DS},\ \forall n\in N, \tag{5}$$

$$\sum_{\substack{h\in\{h:a_h\equiv(n,j)\in A;\\ j\in N;j\neq n\}}} x_{r,h} - \sum_{\substack{h\in\{h:a_h\equiv(i,n)\in A;\\ i\in N;i\neq n\}}} x_{r,h} = \begin{cases} 1 & \text{if } n=s_r \\ -z_{r,n} & \text{if } n\neq s_r \end{cases} \quad \forall r\in D^{US},\ \forall n\in N, \tag{6}$$

$$\sum_{\substack{h\in\{h:a_h\equiv(n,j)\in A;\\ j\in N;j\neq n\}}} y_{r,h} - \sum_{\substack{h\in\{h:a_h\equiv(i,n)\in A;\\ i\in N;i\neq n\}}} y_{r,h} = \begin{cases} 1 & \text{if } n=s_r \\ -v_{r,n} & \text{if } n\neq s_r \end{cases} \quad \forall r\in D^{US},\ \forall n\in N, \tag{7}$$

$$z_{r,n} \le u_n \quad \forall r\in D^{AN},\ \forall n\in N, \tag{8}$$

$$v_{r,n} \le u_n \quad \forall r\in D^{AN},\ \forall n\in N, \tag{9}$$

$$z_{r,n} = z_{\tau(r),n} \quad \forall r\in D^{DS},\ \forall n\in N, \tag{10}$$

$$v_{r,n} = v_{\tau(r),n} \quad \forall r\in D^{DS},\ \forall n\in N, \tag{11}$$

$$\sum_{n\in N} z_{r,n} = 1 \quad \forall r\in D^{AN}, \tag{12}$$

$$\sum_{n\in N} v_{r,n} = 1 \quad \forall r\in D^{AN}, \tag{13}$$

$$\sum_{r\in D}(x_{r,h}+y_{r,h}) \le \Lambda \quad \forall h\in A, \tag{14}$$

$$(x_{r,h}+y_{r,h}) \le 1 \quad \forall r\in D,\ \forall h\in A, \tag{15}$$

$$(x_{r,h}+y_{\tau(r),h}) \le 1 \quad \forall r\in D^{AN},\ \forall h\in A. \tag{16}$$

The objective function (1) is a linear cost of overall flow allocated in the network. Conditions (2) and (3) are flow conservation constraints for the working and backup paths of unicast demands, respectively. In the case of anycast demands, we have to formulate separate flow conservation constraints for downstream (constraints (4)–(5)) and upstream demands (constraints (6)–(7)). Notice that in (4) if the considered node is the destination node of demand d (for downstream demands the client node is the destination node of the demand) the left-hand side of (4) must be -1. In all other cases, the left-hand side equals $z_{r,n}$, which is 1 if the current node n is selected as a working replica of demand d, and 0 otherwise. Since we assume that a given node cannot be at the same time the replica node and the client node of anycast demand, this formulation is correct. In analogous way we formulate constraints (5)–(7). Conditions (8) and (9) assure that the working and backup replica nodes can be selected among nodes $n\in N$ that host replicas ($u_n = 1$). Since both associated anycast upstream and downstream demands r and $\tau(r)$ must use the same working replica node, we add to the model the constraint (10). In a similar way, in (11) we guarantee that associated anycast demands use the backup replica node. Constraints (12) and (13) assure that exactly one node is selected as the working and backup replica for each anycast demand, respectively. (14) is the arc capacity constraint. Since we want to protect the networks against a single link failure, we include the constraint (15), to assure that working and backup paths are link-disjoint. Moreover, in the case of anycast demands, we add condition (16) to guarantee that also the backup path of associated demand $\tau(r)$ is link-disjoint with the working path of demand r. This follows from the fact that if a working path of anycast demand is broken, both associated demands (downstream and upstream) are switched to backup paths.

In the model (1)–(16) presented above, there is no coupling between the working and backup replica server. Two cases are possible for each anycast demand: (i) working and backup replica servers are located at different nodes, and (ii) working and backup replica servers are located at the same node. For ease of reference we call (1)–(16) as the Any Replica (AR) model.

3.2 Replica scenarios

In this section we introduce some additional constraints on the selection of working and backup replica nodes. In the first case we assume that the working and backup replica nodes must be disjoint for each anycast demand.

$$\sum_{n\in N}(z_{r,n}+v_{r,n}) \le 1 \quad \forall r\in D^{AN}. \tag{17}$$

Thus, by adding the constraint (17), we obtain the model called Disjoint Replica (DR) given by (1)–(17). The next constraint (18) assures that the working and backup replica node is the same for anycast demand:

$$z_{r,n} = v_{r,n} \quad \forall r\in D^{AN},\ \forall n\in N. \tag{18}$$

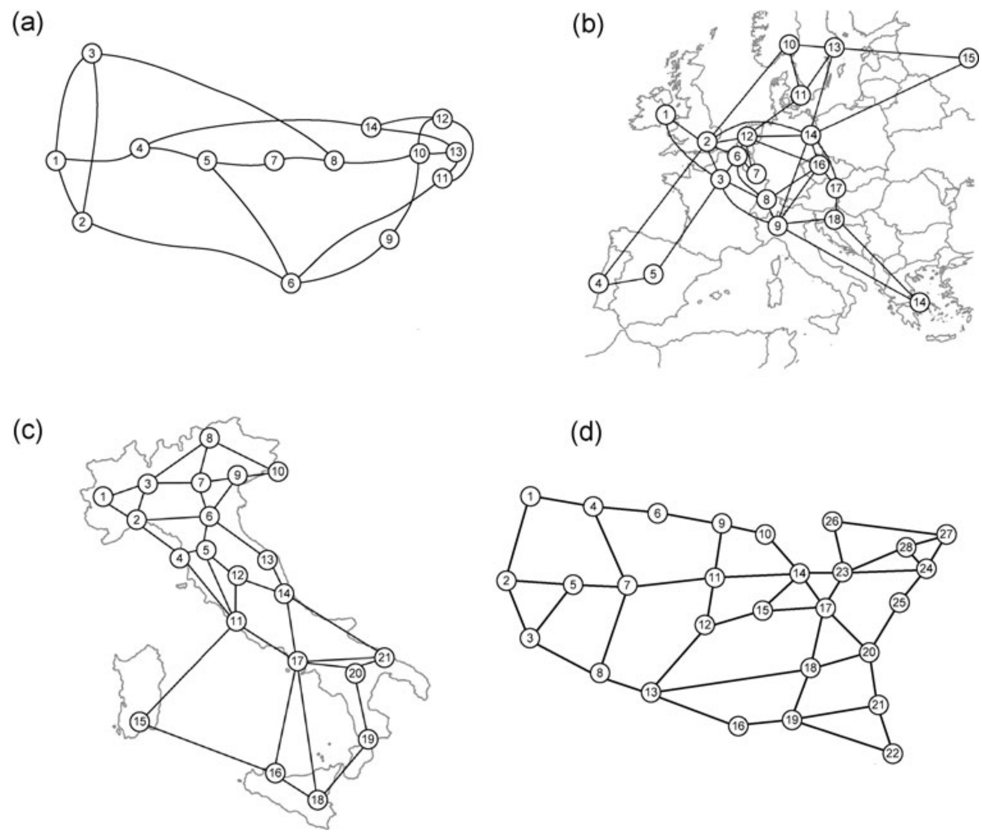


Fig. 2 Network topologies used in simulations: (**a**) NSF Network, (**b**) COST 239 Network, (**c**) Italian Network, and (**d**) US Long-Distance Network

Model (1)–(16), (18) is referred to as CR (Common Replica). Constraint (19) assures that the working and backup replica node is the nearest replica node of anycast demand:

$$z_{r,n} = v_{r,n} = \delta_{r,n} \quad \forall r \in D^{AN},\ \forall n \in N. \qquad (19)$$

The last model named NR (Nearest Replica) given by (1)–(16) and (19) follows from the fact that in many anycasting systems, the client is connected to the nearest replica node [1]. Note that all flow assignment models formulated above remain NP-complete, since the simpler version—the task to find $|D|$ working paths in capacitated networks is NP-complete [6].

3.3 Results

We run the numerical experiments to examine the efficiency of the introduced approach according to two parameters including time of computation and network cost. All four optimization models introduced in the previous sections were implemented in CPLEX 11.0 [12].

Topologies of four networks are analyzed, namely the NSF Network, COST 239 Network, Italian Network, and US Long-Distance Network, all shown in Fig. 2. All WDM links are assumed to have $\Lambda = 160$ channels. Channel capacity unit is considered to be equal for all the network links. Network nodes have a full wavelength conversion capability (which is a common assumption). We investigate several

Table 1 Location of replica servers (node indices)

Network	2 replicas	3 replicas	4 replicas
NSF	6, 10	4, 6, 10	4, 5, 6, 10
COST 239	2, 14	2, 3, 14	2, 3, 9, 14
Italian	6, 17	6, 11, 17	6, 7, 11, 17
US Long-Distance	14, 17	14, 17, 23	7, 14, 17, 23

scenarios referring to different numbers of replica servers, i.e. 2, 3, and 4 (see Table 1). Replica servers are located at nodes having a relatively large number of adjacent nodes.

Three scenarios of network load are investigated. In each case, a single set of anycast demands D^{AN} contains all the network nodes. The set of unicast demands D^{UN} consists of the respective number of randomly chosen node pairs, such that the anycast ratio (i.e. the number of anycast demands $|D^{AN}|$ divided by the total number of demands $|D|$) is equal to 10%, 20%, and 30%, respectively. In each numerical experiment determined by: the given network topology, the number of replica servers, and the number of demands $|D|$, computations were performed for 50 different sets of demands.

In Table 2 we report on the average execution time for each UAFA model and each network. We may observe that three models DR, NR and AR provide comparable running times. Only the CR model needs much more execution time

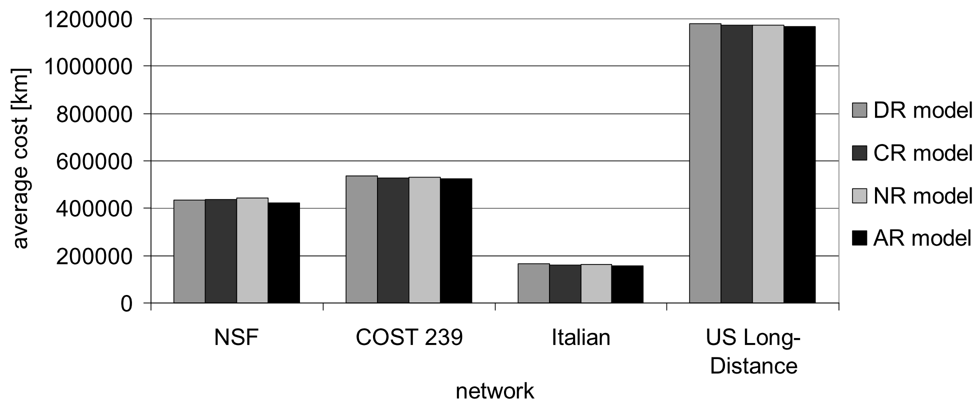


Fig. 3 UAFA models—average cost for 2 replica servers as a function of network topology and optimization model

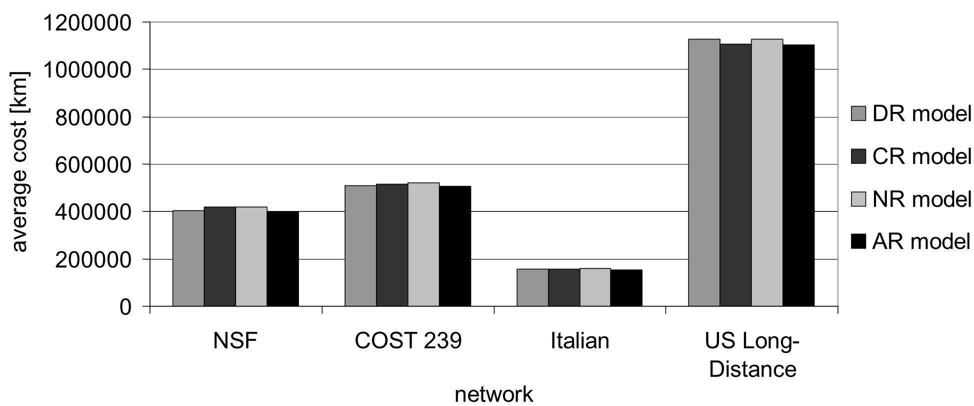


Fig. 4 UAFA models—average cost for 4 replica servers as a function of network topology and optimization model

Table 2 Average execution time for UAFA models

Network	Model			
	DR (s)	CR (s)	NR (s)	AR (s)
NSF	0.41	2.80	0.43	0.43
COST 239	1.38	2.53	1.44	1.41
Italian	1.69	3.98	1.68	1.67
US Long-Distance	3.34	5.55	3.37	3.40

than the other models. This is probably a consequence of constraint (18) which binds the working and backup replica variables.

The main objective of numerical experiments is to evaluate all presented models in terms of the network cost function (1), and examine the impact of the number of replica servers on the cost. In Figs. 3–4 we present the cost of all models for all tested networks in terms of 2 replicas and 4 replicas, respectively. The anycast demands ratio ($|D^{AN}|/|D|$) is 30%.

AR model outperforms the remaining three models. This follows from the fact it the model is the most flexible, since it does not include any additional constraints on the replica server selection. In the case of 2 replicas (Fig. 3) the worst performance is obtained for the NR model (NSF network), or DR model (COST 239, Italian, and US Long-Distance networks). In the case of 4 replica servers (Fig. 4), the largest cost is reported for the NR model. Recall that NR model assumes that each anycast demand is permanently assigned to the nearest (in terms of the path length) replica server. However, each demand requires two paths (working and backup) and both of them have an impact on the objective cost function. In some cases the closest replica server for the working path is not equivalent to the cheapest selection taking into account the length of both working and backup path, which must be link disjoint. When comparing Fig. 3 against Fig. 4, we can see that the cost is reduced with the increase of the replica server count (i.e., paths tend to be shorter).

4 Simultaneous optimization of unicast and anycast flows and replica location in survivable networks

In this section we formulate the ILP model of joint optimization of unicast and anycast flows and replica location in survivable optical networks. Compared to the previous section, we additionally assume that the location of replica servers is not given and we optimize the replica location to minimize the linear cost of flows and provide protection against a single link failure. We presume that location of replica servers does not generate additional costs, since the number of replicas to be assigned to network nodes is fixed and given by constant R.

To formulate the flow conservation constraints of anycast demands, we must modify the network model compared to the previous section. Recall that in Sect. 3 we assumed that a network node cannot be both a replica node and a client node of anycast demand. This was reasonable since in the previous model the location of replica nodes is fixed. In the current section the replica location is not known a priori, thus we cannot ignore (as in previous section) anycast demands with client nodes located at replica nodes. Consequently, it can happen that the same node is the source (destination) node of anycast demand and hosts the replica node what means that constraints (4)–(7) are not valid here. Therefore, we must introduce some additional elements to the original network graph. To make the notation of constraints consistent with Sect. 3, we assume that N' denotes a set of backbone (original) nodes and, correspondingly, let A' denote a set of backbone (original) arcs. Recall that in Sect. 3 these sets were denoted as N and A, respectively. For each node $n \in N'$, we create an auxiliary node m connected with node n by an auxiliary link consisting of directed arcs (n, m), and (m, n). Auxiliary nodes represent the end nodes of demands (both unicast and anycast). Set N'' includes all auxiliary nodes and correspondingly set A'' contains all auxiliary links. We assume that for each auxiliary link $h \in A''$ the arc cost ξ_h is zero and the link capacity is much larger than capacity of backbone arcs (i.e., an auxiliary link cannot be a bottleneck in the network). This is motivated by the fact that auxiliary nodes represent the user end nodes. The auxiliary links are thus local network connections of short distance and very low cost compared to backbone links connecting distant cities or countries.

Since end nodes of demands (source s_r or destination t_r) are located at auxiliary nodes (set N'') and replicas can be located only at backbone nodes (set N'), we assure that every network node cannot be at the same time the replica node and the demand end node. Consequently, we can formulate flow conservation laws for anycast demands. To keep as many as possible of constraints formulated in Sect. 3 in the current model, we abuse the notation and assume that N denotes a set of all nodes (original and auxiliary) ($N = N' \cup N''$), and, correspondingly, A denotes set of all arcs (original and auxiliary) ($A = A' \cup A''$). Moreover, in this section we assume that u_n denotes a variable (not a constant as in previous model) related to the location of replica nodes. Similarly, $\delta_{r,n}$ is also a variable, since the location of replicas is not known a priori. To mathematically represent the problem, we use the following notation. Note that we present only additional notation, compared to the previous section.

4.1 Model

Sets (additional):

- N' set of backbone network nodes
- N'' set of auxiliary nodes representing the end nodes of demands
- N set of all network nodes, $N = N' \cup N''$
- A' set of backbone network arcs
- A'' set of auxiliary arcs connecting auxiliary nodes and backbone nodes
- A set of all arcs representing network directed links, $A = A' \cup A''$

Constants (additional):

- R number of replica nodes

Variables (additional):

- u_n = 1, if node n is a replica node; 0, otherwise
- $\delta_{r,n}$ = 1, if node n is the closest replica node for the r-th anycast demand; 0, otherwise

The UAFARL (Unicast and Anycast Flow Assignment and Replica Location in survivable networks) problem can be formulated as follows:

$$\min \quad \varphi = \sum_{r \in D} \sum_{h \in A'} \xi_h (x_{r,h} + y_{r,h}), \tag{20}$$

subject to (2)–(13) and:

$$\sum_{r \in D} (x_{r,h} + y_{r,h}) \le \Lambda \quad \forall h \in A', \tag{21}$$

$$(x_{r,h} + y_{r,h}) \le 1 \quad \forall r \in D, \forall h \in A', \tag{22}$$

$$(x_{r,h} + y_{\tau(r),h}) \le 1 \quad \forall r \in D^{AN}, \ \forall h \in A', \tag{23}$$

$$\sum_{n \in N'} u_n = R, \tag{24}$$

$$\sum_{n \in N''} u_n = 0. \tag{25}$$

The objective function (20) denotes the linear cost of network flows allocated in the network. Notice that we take into account only backbone arcs $h \in A'$, since auxiliary links $h \in A''$ are assigned with zero cost. We use the same flow conservation constraints as in previous section (i.e., constraints (2)–(7)). However, recall that definitions of sets N and A have been modified. Also constraints related to selection of replica nodes are not changed (i.e., conditions (8)–(13)). Nevertheless, spot that in the current section, u_n is a variable denoting the location of replica nodes. Thus, the right-hand side of (8) and (9) is now a variable, not a constant as in UAFA problem. We include a new capacity constraint (21), since the capacity is to be checked only for backbone arcs $h \in A'$. Similarly, the constraints related to

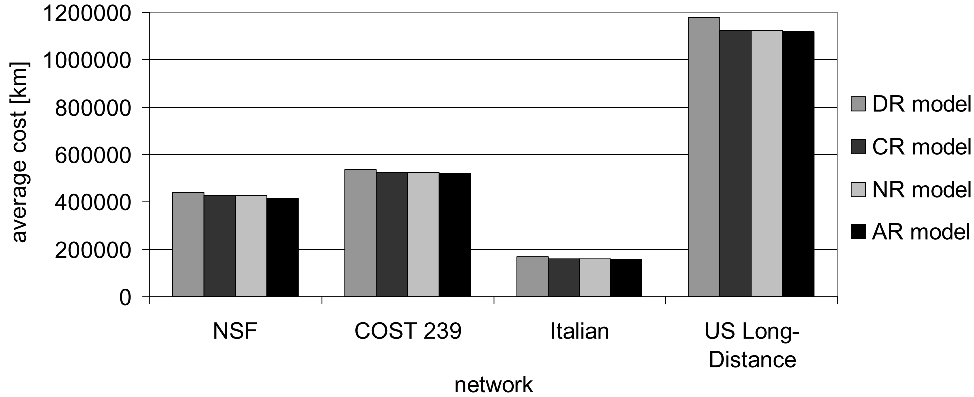


Fig. 5 UAFARL models—average cost for 2 replica servers as a function of a network topology and optimization model

survivability issues are modified, as the working and backup paths must be disjoint only in the context of backbone arcs $h \in A'$. Auxiliary links $h \in A''$ denoting local connection are assumed—compared to backbone arcs—to be more reliable (with larger values of MTBF (Mean Time Between Failures) and lower values of MTTR (Mean Time to Repair)). Finally, constraint (24) assures that R replicas are to be located at backbone nodes $n \in N'$, while auxiliary nodes $n \in N''$ cannot host the replica servers (constraint (25)).

The model (2)–(13), (20)–(25) presented above includes no coupling between the working and backup replica server. Therefore we call it Any Replica (AR) model. Moreover, similar to Sect. 3, in the basic model (2)–(13), (20)–(25), we can apply additional constraints related to replica location scenarios. Therefore, Disjoint Replica (DR) model is defined here by (2)–(13), (17), (20)–(25); CR model (Common Replica) is given by (2)–(13), (18), (20)–(25) and NR model (Nearest Replica) is defined as (2)–(13), (19)–(25). Note that all four versions of UAFARL problem are NP-complete, as they can be reduced to corresponding UAFA problems formulated in Sect. 3.

4.2 Results

To evaluate the performance of UAFARL models, we use the same experiment scenarios as in Sect. 3 including 4 networks shown in Fig. 2 and various demand patterns with 3 values of anycast ratio equal to 10%, 20%, and 30%, respectively. We test three possible numbers of replica servers (constant R) : 2, 3 and 4. Thus, for each network and replica scenario model, we run 450 tests, what gives 7200 unique experiments in total. Numerical experiments were performed to analyze the performance of the proposed approach according to various parameters including: time of computation, network cost, working and backup path length, and ratio of network resource utilization.

In Table 3 we present the average running time for each UAFARL model and each network. We can notice that the reported values are more varied compared to the UAFA model (Table 2). For all tested networks, the DR model needs the shortest execution time. This can be explained by the fact that the additional requirement to provide disjoint replica nodes in parallel with a relatively small number of replica servers (2, 3 or 4) causes that the size of feasible solution space is considerably smaller for the DR model, compared to other models. Moreover, additional optimization of replica location (UAFARL models) causes that the execution time shown in Table 3 is much larger, compared to UAFA models providing only flow optimization and reported in Table 2. This follows from the fact that UAFARL models include additional auxiliary nodes and links, what significantly increases the size of the corresponding models in terms of variables and constraints.

Table 3 Average execution time for UAFARL models

Network	Model			
	DR (s)	CR (s)	NR (s)	AR (s)
NSF	2.69	44.54	52.26	10.91
COST 239	7.88	29.97	28.13	63.62
Italian	7.75	20.95	20.92	26.80
US Long-Distance	18.13	92.73	92.55	182.62

The first goal of experiments is to compare the network cost for all replica models as a function of the number of replica servers. In Figs. 5–6 we show the performance of all models and all tested networks in terms of 2 replicas and 4 replicas, respectively. The anycast demands ratio ($|D^{AN}|/|D|$) is 30%.

The best performance (i.e., the lowest cost) is provided by the AR model, while the worst results (i.e., the largest cost) offers the DR model. The largest reported difference between these two models is 6.37% obtained for the case of two replica servers available in the Italian network. Bring to mind that AR model is the most flexible—there are no additional constraints on the replica selection. In opposite, the DR model assures that the working and backup replica nodes must be disjoint. Consequently, backup paths leading

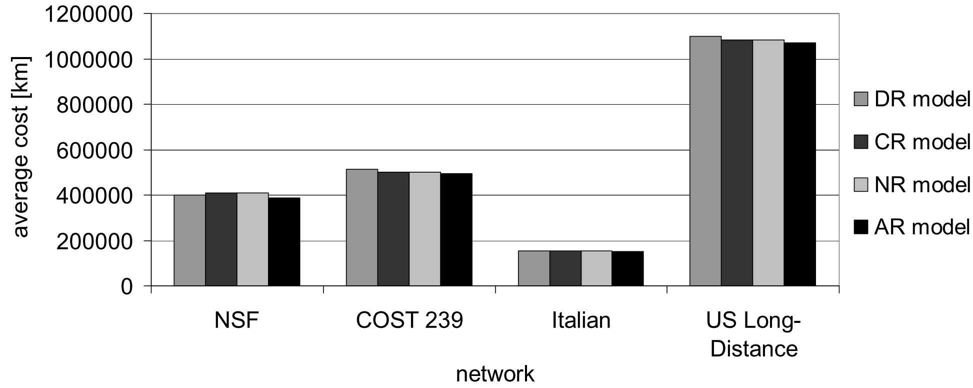


Fig. 6 UAFARL models—average cost for 4 replica servers as a function of network topology and optimization model

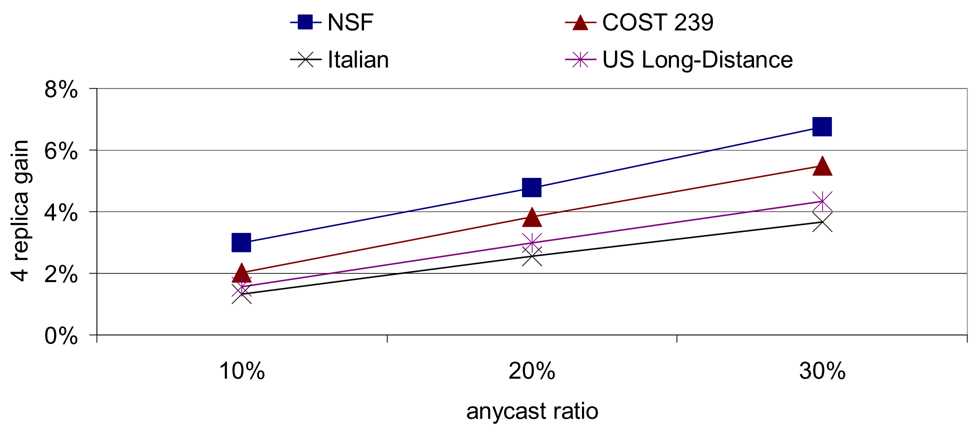


Fig. 7 4 replica gain of cost for all networks as a function of anycast ratio for the UAFARL-AR model

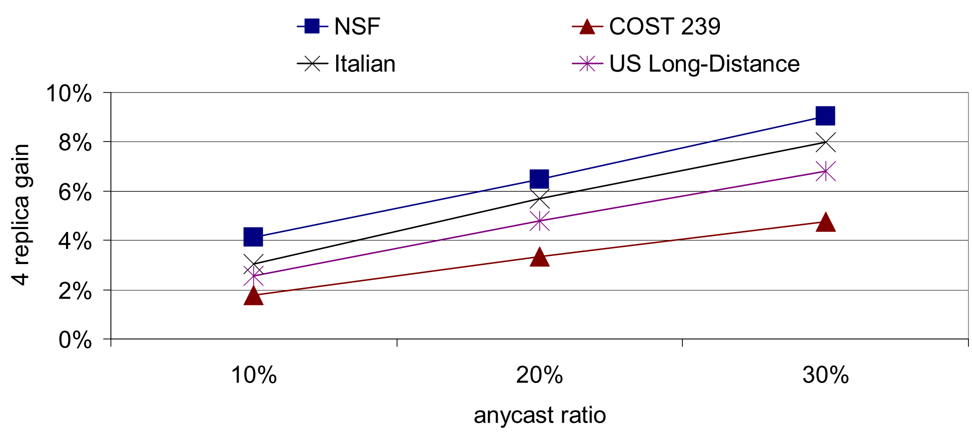


Fig. 8 4 replica gain of cost for all networks as a function of anycast ratio for the UAFARL-DR model

to backup replica servers are usually longer, what implies a larger cost.

To demonstrate the impact of the number of replica servers, we introduce a parameter called 4 (3) replica gain of the cost. This parameter denotes the value of the cost reduction following from increasing the number of replica servers from 2 to 4 (3) replicas. In other words, it shows the amount of cost we can save by increasing the number of replica servers relative to the basic scenario with 2 replicas. In Figs. 7–8 we show the 4 replica gain for all networks as a function of the anycast traffic ratio of the AR and DR models, respectively. We can watch that the 4 replica gain grows as the anycast traffic ratio increases. For all tested networks the growth is almost linear.

The next goal of numerical experiments is to examine the impact of replica servers count on the path length in terms of the metric ξ_h. The yielded average path length of unicast demands is similar, regardless of the number of replica servers and anycast ratio. However, we observe some interesting trends for anycast demands. We present here the detailed results generated for the US Long-Distance Network. We focus on DR and AR models. In Fig. 9 we show the aver-

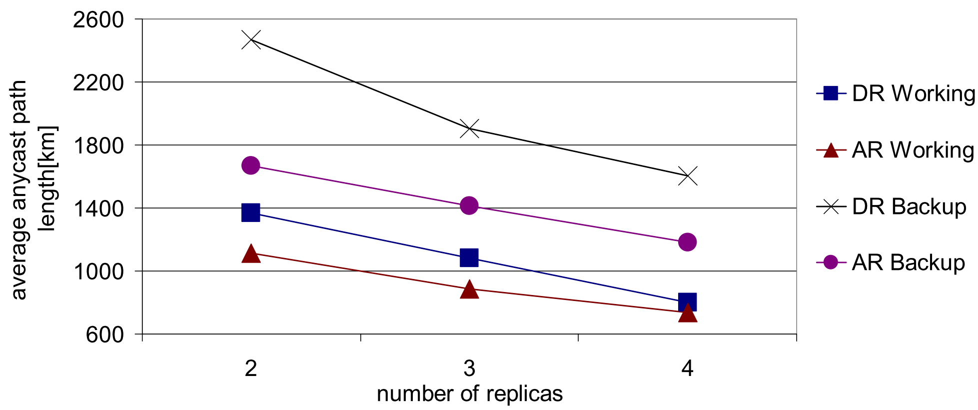


Fig. 9 Average length of anycast paths for US Long-Distance Network, 30% anycast ratio and UAFARL model

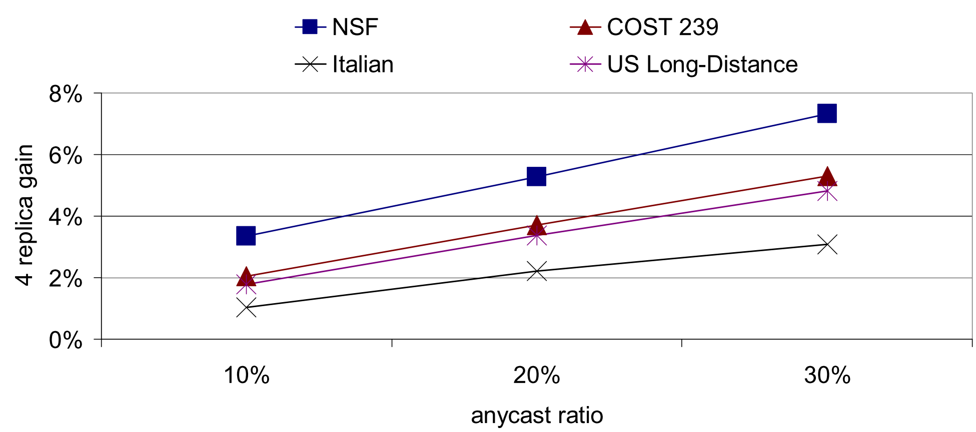


Fig. 10 4 replica gain of capacity utilization for all networks as a function of anycast ratio for the UAFARL-AR model

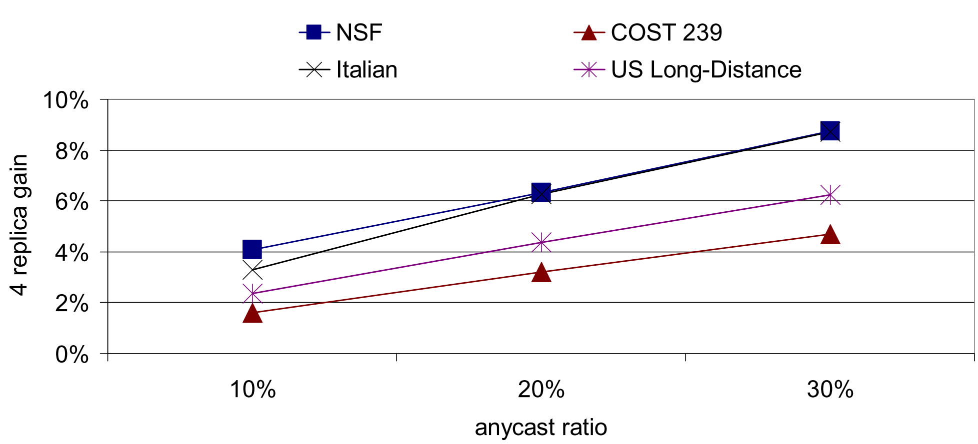


Fig. 11 4 replica gain of capacity utilization for all networks as a function of anycast ratio for the UAFARL-DR model

age path length (working and backup) for anycast demands as a function of the replica server count for 30% of anycast ratio.

We can easily notice that as the number of replica servers grows, the average length of anycast paths decreases. Nevertheless, there are some differences between both examined models. In the case of the DR model, the average 4 replica gain is 41.8% for working paths and 34.9% for backup paths. Corresponding values for the AR model are: 34.0% and 29.2%. It means that backup paths in the DR model are relatively long in the case of 2 replicas. Thus, adding new replica servers offers a greater reduction in the path length than in the case of the AR model. Moreover, as shown in Fig. 9, AR model provides shorter paths for anycast demands. For working paths, the average difference between both models taking into account all replica locations is 14.8%. The equivalent difference for backup paths is 28.1%. Experimental results are reasonably well explained by the formulation of both analyzed models. The DR model—when compared to the AR model—includes the additional constraint (17) assuring that the working and backup replica servers are disjoint. The worse performance of the

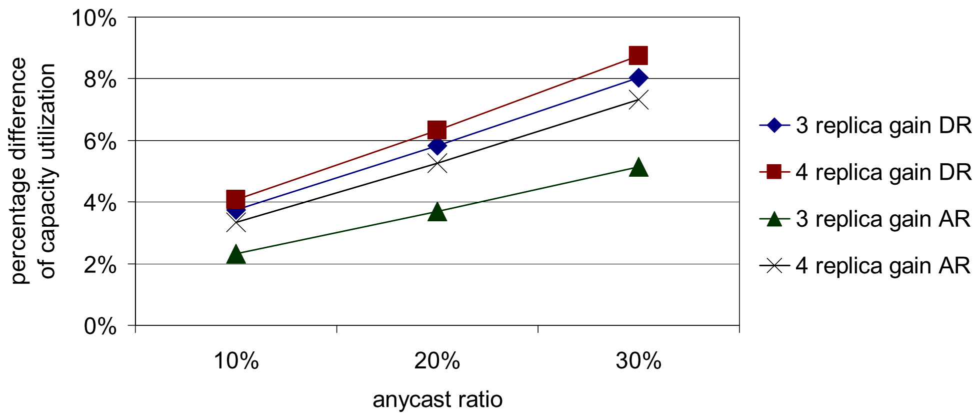


Fig. 12 Replica gain of capacity utilization as a function of anycast ratio for the NSF Network and UAFARL models

DR model in terms of the path length is a trade-off between performance (path length) and additional survivability requirements. Obtained results of path length in terms of the hop count are comparable to the ones for the path length computed according to ξ_h metric.

During experiments we also monitored the capacity utilization (CU) level, i.e. the ratio of link capacity occupied by working and backup paths of all demands, calculated as:

$$RCU = \frac{\sum_{h\in A}\sum_{r\in D}(x_{r,h} + y_{r,h})}{\sum_{h\in A} \Lambda}. \quad (26)$$

In Figs. 10–11, we present the 4 replica gain of capacity utilization obtained for AR and DR models, respectively. Figure 12 shows the results obtained for the NSF Network presenting 3 and 4 replica gain in the case of DR and AR models. We can notice that the increase of the replica gain is proportional to the ratio of anycast traffic in the network. It is in harmony with our previous observations related to the influence of the replica server count on network performance (see e.g. Figs. 7–8). In addition, in Fig. 12 we can observe that the replica gain of capacity utilization is larger for the DR model, compared to the AR model.

5 Concluding remarks

In this work we have explored issues related to simultaneous optimization of unicast and anycast flows and replica location in survivable networks. To assure protection against a single link failure, we have applied the single backup path approach for both kinds of demands. In the case of anycast traffic we have considered several possible strategies of working and backup replica server selection. Proposed ILP formulations have been verified using CPLEX 11.0 solver. Broad numerical experiments have been performed to examine our approach in various scenarios. Obtained results show that increasing the number of replica servers improves the network performance in terms of the overall cost, path length and resource utilization. Furthermore, the performance gain following from adding new replica servers to the network depends on the proportion of anycast traffic and network topology. Another finding is that the constraint to provide disjoint working and backup replicas leads to higher cost and consumption of network resources. As an ongoing work, we plan to deploy heuristic algorithms that enable solving the considered optimization problems for much larger network instances.

Acknowledgements The work of J. Rak was supported by the Polish Ministry of Science and Higher Education under the grant N N519 581038. The work of K. Walkowiak was supported by the Polish Ministry of Science and Higher Education under the grant N N516 070435.

References

1. Hofmann, M., & Beaumont, L. (2005). *Content networking: architecture, protocols, and practice*. San Francisco: Morgan Kaufmann.
2. Buford, J., Yu, H., & Lua, E. (2009). *P2P networking and applications*. San Francisco: Morgan Kaufmann.
3. Shen, X., Yu, H., Buford, J., & Akon, M. (2009). *Handbook of peer-to-peer networking*. Berlin: Springer.
4. Walkowiak, K. (2010). Anycasting in connection-oriented computer networks: models, algorithms and results. *International Journal of Applied Mathematics and Computer Science*, *20*(1), 207–220.
5. Walkowiak, K. (2007). Anycast communication—a new approach to survivability of connection-oriented networks. *Communications in Computer and Information Science*, *1*, 378–389.
6. Mukherjee, B. (2006). *Optical WDM networks*. Berlin: Springer.
7. Vasseur, J.-P., Pickavet, M., & Demeester, P. (2004). *Network recovery*. San Francisco: Morgan Kaufmann.
8. Pióro, M., & Medhi, D. (2004). *Routing, flow and capacity design in communication and computer networks*. San Francisco: Morgan Kaufmann.
9. Molisz, W., & Rak, J. (2005). Region protection/restoration scheme in survivable networks. In *Proceedings of 3rd MMM-ACNS*. *LNCS*, Vol. 3685 (pp. 442–447). Berlin: Springer.

10. (2011). www.akamai.com.
11. Perros, H. (2005). *Connection-oriented networks: SONET/SDH, ATM, MPLS and optical networks*. New York: Wiley.
12. ILOG AMPL/CPLEX software (2011). www.ilog.com/products/cplex/.
13. Walkowiak, K., & Rak, J. (2010). Joint optimization of anycast and unicast flows in survivable optical networks. In *Proceedings of 14th international telecommunications network strategy and planning symposium (Networks'10)* (pp. 54–59).
14. Awerbuch, B., Brinkmann, A., & Scheideler, C. (2003). Anycasting in adversarial systems: routing and admission control. In *LNCS*, Vol. 2719 (pp. 1153–1168). Berlin: Springer.
15. Din, D. (2005). Anycast routing and wavelength assignment problem on WDM network. *IEICE Transactions on Communications E88-B*(4), 3941–3951.
16. Krishnan, P., Raz, D., & Shavitt, Y. (2000). The cache location problem. *IEEE/ACM Transactions on Networking 8*(5), 568–582.
17. Qiu, L., Padmanabhan, V., & Voelker, G. (2001). On the placement of web server replicas. In *Proceedings of IEEE INFOCOM* (Vol. 3, pp. 1587–1596).
18. Li, B., Golin, M., Italiano, G., Deng, X., & Sohraby, K. (1999). On the optimal placement of web proxies in the Internet. In *Proceedings of IEEE INFOCOM* (Vol. 3, pp. 1282–1290).
19. Guha, S., Meyerson, A., & Munagala, K. (2001). Improved approximation algorithms for fault-tolerant facility location. In *Proceedings of ACM-SIAM symposium on discrete algorithms* (pp. 636–641).
20. Jain, K., Mahdin, M., & Saberi, A. (2002). A new greedy approach for facility location problems. In *Proceedings of 34th annual ACM symposium on theory of computing* (pp. 731–740).
21. Arya, V., Garg, N., Khandekar, R., & Meyerson, A. (2004). Local search heuristics for k-median and facility location problems. *SIAM Journal on Computing*, *33*(3), 544–562.
22. Charikar, M., & Guha, S. (1999). Improved combinatorial algorithms for the facility location and k-median problems. In *Proceedings of 40th annual symposium on foundations of computer science* (pp. 378–388).
23. Markowski, M., & Kasprzak, A. (2005). The Web replica allocation and topology assignment problem in wide area networks: algorithms and computational results. In *Proceedings of ICCSA. LNCS*, Vol. 3483 (pp. 772–781). Berlin: Springer.

Krzysztof Walkowiak was born in 1973. He received the Ph.D. degree and the D.Sc. (habilitation) degree in computer science from the Wroclaw University of Technology, Poland, in 2000 and 2008, respectively. Currently, he is an Associate Professor at the Chair of Systems and Computer Networks, Faculty of Electronics, Wroclaw University of Technology. His research interest is mainly focused on optimization of network distributed systems like P2P systems, multicasting systems, Grid systems; network survivability; optimization of connection-oriented networks (MPLS, DWDM); application of soft-optimization techniques for design of computer networks. Prof. Walkowiak was involved in many research projects related to optimization of computer networks. Moreover, he was consulting projects for the large companies including TP SA, PZU, PKO BP, Energia Pro, Ernst and Young. Prof. Walkowiak published more than 120 scientific papers. He serves as a reviewer for many international journals including: Computer Communications, Future Generation Computer Systems, Computational Optimization and Applications, International Journal of Applied Mathematics and Computer Science, Expert Systems, Pattern Analysis and Applications, International Journal of Computer Mathematics. He is/was actively involved in many international conferences. Prof. Walkowiak is a member of IEEE and ComSoc.

Jacek Rak holds M.Sc. and Ph.D. degrees in computer science (options: computer networks, and computer communications, accordingly) received with distinction in 2003 and 2009, respectively from Gdansk University of Technology (GUT), Poland. He is currently an assistant professor at the Department of Computer Communications of the Faculty of Electronics, Telecommunications and Informatics at GUT. His main research areas include: routing, design, dimensioning and analysis of high-speed wavelength routed backbone networks with focus on survivability.

Dr Rak was involved in many projects related to optimization of reliable computer networks. He was the TPC Co-Chair of NETWORKS 2010 Conference, Publication Chair of NETWORKS 2010 and BCFIC 2011 conferences. He also served as a TPC member/reviewer of important conferences on communications, e.g. IEEE ICC, IEEE GLOBECOM, DRCN, and journals, e.g. IEEE/ACM Transactions on Networking, or IEEE Communications Letters.

Dr Rak is a member of IEEE (and IEEE Communications Society), IFIP TC6 WG 6.10 (Photonic Networking Group), as well as Polish Information Society (PTI). He is also the founder and the General Chair of the International Workshop on Reliable Networks Design and Modeling (RNDM).