Evolutionary Computing in Telecommunication Network Design: A Survey

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Over the past few decades the use of telecommunication services has been growing dramatically, and many new and advanced services will be brought to the market in the years to come. Information and communication (IC) infrastructures are becoming increasingly complex, but at the same time are expected to handle strongly increasing amounts of data transactions in a cost-effective manner, while meeting strict requirements on the Quality of Service (QoS). This raises the critical need for system architects to properly design their IC infrastructures, since in practice architectural redesign efforts are extremely time consuming and hence expensive. This leads to a variety of highly complex design optimization problems, with complicating factors and side constraints that can not be effectively solved by the classical solution techniques. Evolutionary Algorithms (EAs) constitute a promising class of solution techniques to effectively treat large and complex optimization problems. EAs have been successfully applied to telecommunication design problems over the past decade, covering a variety of problem areas. In this paper, we give an extensive literature survey, listing over 350 references on the use of EA techniques for solving telecommunication design problems.

Keywords: Evolutionary Computing, telecommunications, design, survey, genetic algorithms, overview

1 Introduction

The emergence of the Internet, the popularity of PCs and the advances in networking technology have boosted the use of telecommunications services dramatically. Nowadays, communication infrastructures must process huge amounts of data transactions, while the ability to deliver high and predictable Quality of Service (QoS) levels is becoming increasingly important. In the competitive market of telecommunication services, the ability to meet QoS requirements in a cost-effective manner has become crucial for the business of telecommunication service providers and network operators. Since architectural redesign efforts are extremely time consuming and thus expensive, there is a critical need for efficient techniques to support the proper design decisions. Typical examples of such problems areas are node location problems, topology design problems, routing and restoration problems, the development of efficient admission control mechanisms, frequency assignment and wavelength allocation problems, to name a few. Due to the increasing complexity of communication infrastructures, many design problems have become extremely complex, and have to deal with a variety of complicating side constraints (e.g., the presence of multiple objectives, noise, dynamically changing parameters, large solution space), that in many cases cannot be handled effectively by the existing optimization techniques. On the other hand, an important and convenient aspect of IC system design problems is that there is no critical need for real-time split-second decision making.

A promising means to deal with this type of complex optimization problems is Evolutionary Computing (EC).

Evolutionary algorithms (EAs) are particularly suited for solving highly complex optimization and design problems having many variables with nonlinear interactions among them, multiple objectives and/or constraints and ill-understood problem structure. There are many such problems in the field of telecommunication, so it is not surprising that the use of EC techniques to tackle complex telecommunication design problems has been gaining momentum over the past decade, evidenced by the growth of the number of papers that appeared in the open literature. However, a systematic overview of the use of EC for telecommunication design problems is currently lacking. Motivated by this, in this paper, we provide a comprehensive survey of the current state-of-the-art in the use of EC in telecommunication design and planning, listing over 350 references.

The remainder of the paper is organized as follows. In Section 2 we give a brief to introduction to the main ideas of EAs, describe for which type of problems EA are suitable and discuss several alternative approaches. In Section 3 we provide an extensive and comprehensive overview of the use of EC for solving telecommunication design problems. Finally, Section 4 contains several concluding remarks and address the challenges ahead.

2 General introduction to Evolutionary Computing

In the early days of evolutionary computing developments took place rather independently from each other [104]. This led to what is now seen as different "dialects" or subareas within EC. The contemporary terminology denotes the whole field by EC and considers evolutionary programming, evolution strategies, genetic algorithms, and genetic programming as subareas (see [95]). The common underlying idea, in other words: the natural inspiration, behind all these techniques is the same: given a population of individuals the environmental pressure causes natural selection (survival of the fittest) and hereby the fitness of the population is growing. It is easy to see such a process as optimization. Given an objective function to be maximized we can randomly create a set of candidate solutions, that is, elements of the domain of the objective function, and apply the objective function as an abstract fitness measure - the higher the better. Based on this fitness, some of the better candidates are chosen to seed the next generation by applying recombination and mutation to them. Recombination is a binary operator applied to two selected candidates (the so-called parents) and results one or two new candidates (the children). Mutation is a unary operator, it is applied to one candidate and results in one new candidate. Executing recombination and mutation leads to a set of new candidates (the offspring) that compete – based on their fitness – with the old ones for a place in the next generation. This process can be iterated until a solution is found or a previously set computational limit is reached. In this process there are two major forces driving progress: *selection* that acts as a force pushing quality, and *variation* operators (recombination and mutation) that create the necessary diversity, thereby pushing novelty. Their combined application leads to improving fitness values in consecutive populations, that is, the evolution is optimizing. (Actually, evolution is not 'optimizing' as there are no general guarantees for finding an optimum, it is rather 'approximating', by approaching optimal values closer and closer over its course.)

Many components of an evolutionary process are stochastic. Variation operators are normally stochastic, since the choice on which pieces of information will be exchanged during recombination, as well as the changes in a candidate solution during mutation, are random. Selection operators can be either deterministic, or stochastic. In the latter case fitter individuals have a higher chance to be selected than less fit ones, but typically even the weakest individuals have a chance to become a parent or to survive. The general scheme of an evolutionary algorithm can be given as follows. The words in CAPITALS can change from algorithm to algorithm and are explained in the example found below.

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INITIALIZE population with random individuals (candidate solutions)
EVALUATE (compute fitness of) all individuals
WHILE not TERMINATION CONDITION DO
    SELECT parents
    RECOMBINE pairs of selected parents
    MUTATE the resulting offspring
    EVALUATE the offspring
    SELECT new population from last population and offspring
OD
```

It is easy to see that this scheme falls into the category of generate-and-test, or trial-and-error, algorithms. The fitness function represents a heuristic estimation of solution quality and the search process is driven by the selection operators and the variation operators (recombination and mutation producing new candidate solutions). Evolutionary algorithms (EAs) are distinguished within in the family of generate-and-test methods by the use of recombination to mix information of two candidate solutions and by being population based, i.e., by processing a whole set of candidate solutions.

The previously mentioned dialects of EC follow the above general outlines and differ only in technical details. For more information, the reader is referred to the book by Eiben & Smith [95].

One domain that generates increasing attention is that of multi-objective optimization. Specific selection methods allow one to spread the population of an EA over the Pareto front of a multi-objective problem (the set of the best compromises between the objectives). This requires only a fraction of extra computation time than the optimization of a single objective.

2.1 Example: Antenna placement

Let us look at the problem of selecting antenna sites for a new radio network. Given 10 possible locations we want to select the best sites, with the lowest costs, while giving us the coverage needed. A good representation can be 10 bits, a bit for each site, that determines whether the site is used or not. This gives us a solution (or genotype) space of 2^{10}.

We initialize our algorithm with a random bit-string. A population, of size 4, can look like:

Individual	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
1	1	0	0	0	1	1	0	0	1	1
2	1	0	1	1	0	0	1	1	1	1
3	0	0	0	1	1	0	1	1	0	1
4	1	1	0	0	0	1	0	0	1	0

Each individual will be evaluated and given a certain fitness value, for example individual 1 might get value 321.95. We assume the fitness function is given and based on the radio coverage and the costs (rental, placing). This fitness will be used to determine whether an individual is better or worse than another individual.

After we evaluated the individuals, the next step is to select parents. We might simply randomly pick enough pairs of parents to create all the children, allowing one individual to become parent more than once. Then we recombine those parents into children. We can take two individuals, and randomly take values from the first individual or from the second individual. We can make a second child at the same time that just has the other values. Based on the individuals above, if we select individuals 1 and 3 as parents, we might generate the following children (grey indicates bits from individual 3):

Individual	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
Child 1	0	0	0	0	1	0	0	1	0	1
Child 2	1	0	0	1	1	1	1	0	1	1

Next, we also use some mutation on the children. For example, with a certain probability (e.g. 1/10) we invert the value of a site.

Finally, some selection will have to take place, to give better individuals an advantage. For example, we start with a population of 10 individuals. Then we might generate 60 children, and then throw away all parents. Of these 60 children we select the best 10 and have a new, and hopefully better, population. We repeat this process until we see no new best solutions for 25 subsequent populations. The complete algorithm can be specified as in Table 1:

Representation	binary strings of length 10
Recombination	Uniform crossover
Recombination probability	100%
Mutation	each value inverted with independent probability p_m per position
Mutation probability p_m	10%
Parent selection	random pairs
Survival selection	generational, best 10
Population size	10
Number of offspring	60
Initialization	random
Termination condition	no improvement in last 25 generations

Table 1: Tableau describing the EA for the Antenna placement problem

2.2 When to use EC

EC is used for hard optimization and design problems. It is usually well-suited under the following conditions:

1. *Large solution space*
   If the solution space is not too large, exhaustive search is probably to be preferred. EC is able to tackle really large problems and it is simple to use in combination with parallel computing.

2. *Complex objective function (utility function)*
   If the problem includes an objective function (utility function) that is highly complex, e.g., non-linear, non-derivable, discontinuous. EC also works in cases where there is no closed formula for the utility function, but the quality/utility of candidate solutions has to be calculated by simulations.

3. *No exact solution methods or good heuristics are available*
   EC is well suited for ill-understood problems, since evolution works without problem-specific knowledge, simply driven by the fitness/utility values of the candidate solutions. However, if good problem-specific heuristics are available, they can be used in combination with an evolutionary algorithm (cf. hybrid algorithms, memetic algorithms).

4. *No need to find the best solution*
   EC usually finds a good solution, but it is not guaranteed that this solution is the best solution possible. It also does not provide information on how far away the found solution is from the global optimum.

5. *No need for very fast results*
   The computational effort required for running EC algorithms may be significant.

6. *Presence of complex constraints or multiple objectives*
   EC is well able to handle difficult problems with complex constraints and multiple objectives.

7. *Robust solutions are needed*
   EC can be used in combination with noise and dynamic environments. The algorithm usually adapts well to a new environment.

2.3 Alternatives to EC

There are some well-known alternatives to EC. The most commonly found ones are briefly described below.

Simulated Annealing
Simulated annealing [157] is quite similar to local search. Technically, simulated annealing can be seen as an evolutionary algorithm with population size 1, but it is normally seen as another class of algorithms.

The main difference between local search is that neighbors are inspected in a random fashion and that sometimes worse neighbor solutions are accepted. By accepting worse solutions, hopefully local optima are left, so that the global optimum is found. Over the time, the probability of accepting a worse solution goes down to zero. The probability is also related to the difference in the value of the new solution. The probability of picking a slightly worse solution is higher than the chance of picking a much worse solution. As the last solution seen certainly does not have to be the best solution seen, the best solution is always kept.

Tabu Search
Tabu search [116] is another general combinatorial optimization technique. The basis idea is the same as with local search, but usually by disallowing points previously visited (hence 'tabu'), the exploration process does not have to stop at a local optimum.

Other nature-inspired algorithms
A well-known algorithm is Ant colony optimization [40], which is derived from the structured behavior of ants. It works especially well for routing. Other nature-inspired algorithms are for example based on the behavior of bees and the working of the immune system.

Others
Many other alternatives exist, like Greedy Algorithms, Hill climbers, scatter search, path relinking methods, grasp algorithms, problem-specific algorithms, and so on.

2.4 Memetic algorithms

Mixing EC with other heuristics leads to memetic algorithms (or hybrid evolutionary algorithms). For example, initialization can be done by using well-known solutions. During evolution, some problem-specific local search might be used after crossover and mutation to improve newborn solutions. Very often, such algorithms offer the best of both words, a combination of the explorative power and robustness of evolutionary search and the greedy search of a problem-specific heuristic.

3 Literature survey

In this section we give an extensive survey of the use of EC techniques that have been applied to telecommunication design problems. A part of the survey is based on a review by Sinclair [303], providing an overview of the state-of-the-art until 1998. This review was never published as an article, except for a summary [295]. The survey provided in this section extends this survey to include the main references up until 2005.

Telecommunication network design problems can be classified in different ways. To structure the broad range of design problems, we consider the following classification of problems: (1) node location, (2) topology design, (3) tree design, (4) routing, (5) restoration, (6) network dimensioning, (7) admission control problems, and (8) frequency assignment and wavelength allocation. Note that the classification is not unique, and that a number of papers may be classified in different classes. In these cases, we have classified the papers in the most natural class.

The state-of-the-art of the literature on each of the classes is outlined below. To structure the wealth of references, a table listing the key per-class references is given in the Appendix.

3.1 Node location

Node location problems occur in many application areas. In 1992, Potter et al. [250] studied the design of military networks, using a hybrid genetic algorithm with several representations and problem-specific operators. Their work included battlefield location and network element selection. Later, in [56, 249, 57] the results in

[250] were improved upon with enhancements to the objective function, efficiency gains and additional heuristics.

Local access networks
In the context of local access network design Routen [276] showed that genetic algorithms could be used to place concentrators in the network, used problem-specific operators and an integer representation. Chardaire [58] studied similar location problems for concentrators for computer terminals, among others. Celli et al. [51] studied the positioning of concentrators for metropolitan area networks (MANs) with a genetic algorithm to demonstrate that parallelization and a proper choice of variables speed up the algorithm used. Webb et al. [334, 333] employed a genetic algorithm with heuristic repair for the selection of backbone nodes in a ring/star transport network. They showed the topologies resulting from true economic cost models, instead of the classical distance-cost models. Levitin [184] considered the optimal positioning of retransmitters in a transmission network with vulnerable nodes by using genetic algorithms. Livramento et al. [195] studied the partitioning of a city network into service sections that can be controlled by a single standard communication switch. They also studied positioning of the switches. Tests of their genetic algorithm with real model instances showed promising results.

Radio networks
For radio networks, a key problem is the proper positioning of locations for antennas and receivers. In 1997, Calégari et al. [47, 46, 48] showed that their parallel genetic algorithm with multiple populations strongly outperformed a single population algorithm for this problem. Moreover, in [49] they also found some other heuristics to be less well performing. Gondim [117] tackled the problem of associating cells to switching centers with a genetic algorithm. Zimmermann et al. [356, 357] used EC techniques to address the antenna placement problem. Tang et al. [312, 314] used a multi-objective genetic algorithm for determining the number of locations and their places in a wireless local area network (WLAN). Lieska et al. [190] used three different approaches to locate base stations, and showed that the behavior of genetic algorithms may differ significantly depending on the approach. Krzanowski & Raper [169] used hybrid genetic algorithms for the proper selction of base stations. Jedidi et al. [144] used genetic algorithms to tackle node location problems using geometric criteria, rather than radiographic criteria, to enable theories on these geometric structures to be used by network designers. Raisanen et al. [268, 267], Meunier et al. [217], Watanabe et al. [332] and Ozugur et al. [233] used multi-objective genetic algorithms to address base station location problems, which led to a multitude of good solutions on a Pareto front. Reininger et al. [271] investigated base station placement taking into account multiple periods of use. Chan and et al. [54] and Li et al. [185] investigated base station placement in CDMA-based personal communication networks. Alba et al. [14] used a parallel evolutionary algorithm to select base stations. Maple et al. [208] also used a parallel multi-objective evolutionary algorithm to select base stations for third generation networks. Hei et al. [129], Siregar et al. [305], Chan et al. [55] and Vijayanand et al. [328] studied wavelength converter placement and routing in optical networks using genetic algorithms.

3.2 Topology design

Computer networks
To develop topologies for computer networks, Kumar et al. [172, 173] used a genetic algorithm, with some problem-specific repair and crossover function, mainly focusing on reliabilty. Michalewicz [218] also developed tree topologies for computer networks, also using a problem-specific crossover and mutation operator. Later,

Kumar et al. [171] developed a genetic algorithm to tackle computer network expansion. Their genetic algorithm selects new nodes to be added and determines their link to the existing network. Srivastava et al. [308] revised that work to demonstrate their distributed genetic algorithm. Hewitt et al. [131] studied minimum cost network design, using connectivity and delay constraints. They used a hybrid genetic algorithm. Later, Ko et al. [162] used hybrid genetic algorithms in three stages, to create after each other a topology, routing and link capacities. Pierre & Legault [244, 245] also studied minimum cost network design with genetic algorithms, using connectivity and delay constraints. They select network links, but the fitness function used also allocates link capacities. Qin et al. [254] designed ISDN networks using a genetic algorithm. Their fitness function used also allocates link capacities, but network delay is not calculated. Habib et al. [119] created a computer program for designing hierarchical intranets using genetic algorithms. Berryman et al. [38, 39] used EC to explore the tradeoffs between network redundancy and pleiotropy ('server duplication') in computer networks. Combining both created robust networks. Gen & Cheng [110, 113] studied network design on various topics including LAN design, and found genetic algorithms quite effective. Altiparmak et al. [17, 19, 18] compared various meta-heuristics for computer network design and found that memetic algorithms were favorable.

Communication networks

Many papers are focused on communication network design. Sobotka [306] studied survivable military communication networks, assuming a fixed number of satellite links. He also used a problem-specific recombination and tried to reduce the impact of damages. Deeter & Smith [80] studied reliable topology design with genetic algorithms for small networks, while minimizing costs. Later, a variety of authors with Deeter, Smith & Konak [81, 164, 163, 165] designed backbone network topologies with capacities taking into account both economics and reliability. Dengiz et al. [83] also studied this subject with a genetic algorithm, but their links all had the same reliability and fixed, known costs. In order to study even larger networks, they refined their fitness function to give a more accurate assessment for the fitter individuals [85, 84]. With a hybrid genetic algorithm, they [87, 86] obtained much better results by using local search optimization and repair, among other things. Bayan et al. [28] used a team of solvers including genetic algorithms to create reliable networks. Sayoud et al. [288] also found that genetic algorithms were able to create better network designs faster for small test networks. Reichelt et al. [270] created topologies under a reliability constraint using a genetic heuristic with intelligent repair operator. Liu & Iwamura [192] solved network reliability models by a simulation-based genetic algorithm. Ghosh et al. [114] used genetic algorithms for backbone network design under a costs constraint. Ljubic, Raidl et al. [155, 266, 197, 198, 196] used EC to create bi-connectivity graphs, where there are at least two connections between two nodes. Tang et al. [313] showed that asynchronous transfer mode (ATM) network design was solved better using genetic algorithms. Thompson [320] compared the performance of genetic algorithms and simulated annealing for topology design of ATM networks. On average, the genetic algorithm solution was better. Tanaka & Berlage [311] studied video-on-demand network design with genetic algorithms, by designing a topology and specifying storage nodes for the videos. McMahon et al. [214, 215] and Berry et al. [36] had success with using genetic algorithms for network design. In 2003, Tsuji et al. [322] investigated the construction of metropolitan area networks using genetic algorithms, using a special operator for keeping created 'building blocks'.

Saha & Chakraborty [281] studied ways to add new links to a network with a genetic algorithm. They assumed that both the cost and the profit for a link were known in advance. Nakamura & Oda [229] also studied this problem, but then over multiple planning periods. They used a genetic algorithm combined with a heuristic routing and restoration algorithm. Rothlauf & Grasser [275] used a genetic approach to support network topology planning over multiple use periods. Montana et al. [220] studied adaptive reconfiguration of data networks. Hedible [127], Quintero & Pierre [259, 256, 255, 257, 258] and Din et al. [89, 88, 90, 91] assigned cells to switches in mobile networks using (hybrid) genetic algorithms. Sahhbaz [290] and Krishnamachari & Wicker [168] obtained good result with using a genetic algorithm for the design of a fixed network. Chamberland [53] investigated the expansion of an UMTS network considering the existing network.

Multi-objective optimization problems
Another interesting sub-area of topology design is optimization under multiple criteria. Flores et al. [102] used parallel multi-objective evolutionary algorithms to generate Pareto front of solutions for a telecommunication network design problem. Kim et al. [156] used genetic algorithms to generate network topologies, using bi-criteria optimization, considering both cost and reliability to generate a Pareto front. Gen et al. [111, 112, 20] considered bi-criteria optimization for network topologies using genetic algorithms with the aid of fuzzy logic. Kumar et al. [177, 176] extended their work, using genetic algorithms considering multiple objectives, and generated solutions on a Pareto front. Later, they [174, 175] extended their work even further, including to distributed evolutionary algorithms. Duarte et al. [94] selected links using parallel genetic algorithms to generate a Pareto front considering multiple objectives for network design.

Terminal assignment
Another application area is how assign terminals to concentrators. Abuali et al. [5] used a genetic algorithm to assign terminals to concentrators with a permutation encoding. They found the genetic algorithm to work better than a greedy algorithm. Later, they [9] solved the subset interconnection problem and produced superior results to some previous known algorithms. The subset interconnection problem is a topology design problem where all nodes in a subset have to be internally connected, as well as the subsets themselves. Salcedo & Yao [283] combined genetic algorithms and neural networks to assign terminals to switches.

Optical networks
Genetic Algorithms have also been widely applied for disigning optical network topologies. Sinclair et al. tried to figure out which links to include in the network topology, minimizing costs. They applied a simple genetic algorithm [297], a hybrid algorithm [300] and other genetic programming approaches [13, 301] to this problem. Mikac & Inkret [219] extended Sinclair's work with genetic algorithms by also taking minimizing unavailability into account. They used two different fitness functions: In odd generations, the fitness focused on minimum costs, while in even generations it focused on availability. White et al. [337] not only determined ring structures, but also determined dimensioning and routing to avoid global sub-optimization. Armory et al. [23] developed reliable ring structures for optical networks using genetic algorithms. Karunanithi & Carpenter [153] used a genetic algorithm for determining the size of SONET ring structures. Pickavet & Demeester [243] determined SONET topologies and capacities too, using a special zoom-in heuristic. Cortes [67] did global optical topology design using genetic algorithms that explored optimality conditions. Liu et al. [194] also optimized logical topologies in optical networks. He et al. [126] determined optical ring structures and showed better results with an evolutionary algorithm than a genetic one. Xin et al. [341] used genetic algorithms combined with heuristics to design large optical networks. Paul et al. [241, 242] studied tree topologies for optical networks. They minimized costs for local access networks and used some problem-specific operators. Brittain et al. [41] extended this work to non-tree topologies.

3.3 Tree design

Steiner tree problems

Hesser et al. [130] applied a simple genetic algorithm with some heuristics for decoding to determine arbitrary Steiner points. Steiner points are points that are added to a graph, to make the total length of a network covering all points smaller. Later, Kapsalis et al. [150, 58] used a genetic algorithm to select Steiner points from a given set of nodes. Julstrom [147] covered the rectilinear Steiner tree problem, where only horizontal and vertical lines are allowed. He used a hybrid genetic algorithm, but previous heuristics seemed to give better results. Later, Esbensen & Mazumder [99] returned to the selection of Steiner points from a given set of nodes. Their hybrid genetic algorithm uses a bit-string encoding and some repair routines. Later they [100] demonstrated that the algorithm performed better than the one Kapsalis made. In [101] the algorithm was improved further. Chu et al. [64] found that for the Steiner tree problem genetic algorithms performed comparable to their tabu search algorithm. Kulturel et al. [170], Saltouros et al. [284], Panadero & Fernández [239] and Presti et al. [251] also studied the Steiner tree problem and found good results. Galiasso & Wainwright [106] tackled the Steiner routing tree problem with single split paths.

Minimum spanning tree problems

A classical tree-related problem is the minila spanning tree problem, which has received a lot of attention in the literature. Abuali et al. [6] investigated minimal spanning trees using several genetic algorithms. Their permutation-encoded genetic algorithms outperformed some heuristics for this problem, especially for large networks. Routen [276] also studied this problem, but had

disappointing results with an integer-based encoding. Zhao et al. [351] had more success with a hybrid genetic algorithm, using an object-oriented representation. Abuali et al. [4] considered the stochastic version of the problem, where nodes only need to be connected with a certain probability. They used a so-called Prüfer encoding. Palmer & Kershenbaum [235, 234] argued against that encoding, and obtained better results than some existing algorithms using a genetic algorithm with a new encoding called node-cost bias encoding. Gottlieb et al. [118] argued again against Prüfer numbers. Abuali et al. [7] later designed the so-called determinant-factorization encoding for the stochastic minimum spanning tree problem. They [10] compared Prüfer encoding, node-cost bias encoding and determinant-factorization, and found that determinant-factorization and node-cost bias encoding performed well, but node-cost bias encoding performed better for larger networks. Abuali et al. [8] studied the more constrained three-star tree problem, where all branches have a chain of three nodes to the root. They also concluded that the determinant-factorization and node-cost bias encoding performed well, but that node-cost bias encoding performed better for larger networks. Berry et al. [37] also studied the minimum spanning tree problem, and used predecessor-vector encoding (also deprecated by Palemer & Kershenbaum [235]) with some heuristic mutation and recombination. Walter & Smith [329] also independently developed a hybrid genetic algorithm for directed minimum spanning trees. Soper & McKenzie [307] and Chou et al. [62] also studied minimal spanning trees. Li & Bouchebaba [188] solved the problem of finding an optimal spanning tree by working directly on the tree itself without an intermediate encoding. Hsinghua et al. [134] tested the effect of various properties of a genetic algorithm for the constrained minimal spanning tree problem. Despite being argued against, in 2002 Haghighat et al. [122] still used Prüfer numbers for constrained tree optimization. Zhou & Gen [354, 353] showed that their genetic algorithm for generating tree-like networks was highly effective compared to other heuristics.

Raidl et al. [265, 264, 145, 260, 263, 262] looked at the constrained minimum spanning tree problem. Zeng & Wang [349] & Knowles[159] also looked at constrained minimum spanning trees. Gaube & Rothlauf [108] revised the link and node biased encoding for trees. Raidl et al. [261, 146] proposed the edge set encoding for trees. Later, Tzschoppe et al. [324] revised this encoding. Rothlauf et al. [274] proposed a new encoding for trees: Network Random Keys. Delbem [82] proposed Node-depth encoding. Elbaum & Sidi [96, 97] studied the design of local area networks (LANs). Here, the LAN is seen as a tree, and encoded with a hybrid chromosome encoding.

3.4 Routing

Routing in switched networks
Cox et al. [69] used a permutation-based genetic algorithm for the bandwidth-packing component of a heuristic for routing in a switched network. The same year, Pan & Wang [237] used a genetic algorithm for link capacity assignment and routing in an asynchronous transfer mode (ATM) network. Munakata & Hashier [225] used a hybrid genetic algorithm for the maximum flow problem in a capacitated graph and got good results. However, they were unable to get better results than existing conventional heuristics. Sinclair [302] used a bit-string encoding for the design of static-routing tables for an unreliable circuit-switched network. However, his work also performed worse than some existing heuristics. His genetic algorithm in a 1999 paper [222] for reliable military communication networks also had worse results than another heuristic. Shimamoto et al. [294] studied dynamic routing in switched networks. They used a steady-state genetic algorithm to exploit the relatively slow changes in traffic distribution, and obtained a grade-of-service that compared well to a fixed routing algorithm. Mann et al. [205] tackled static routing to minimize costs while balancing the traffic load. Later, they [203] made a detailed comparison with different algorithms, both genetic algorithms and simulated annealing. The results where similar, but simulated annealing took less computation effort. Mann & Smith [204] later studied routing in optic ring networks, again minimizing costs while balancing the load. This time, they found a genetic algorithm to be more robust than some simulated annealing algorithms.

Munetomo et al. [226] used genetic algorithms to discover multiple shortest paths in a network. In 1999, Inagaki [142] tackled the same problem using genetic algorithms. Ahn & Ramakrishna [11] improved on these genetic algorithms even further, needing less fitness evaluations. Knowles et al. [160] researched static routing for backbone networks. They introduced a new operator that can be used for incremental evaluation to improve the performance of a genetic algorithm. They [161] also researched off-line routing and generated a Pareto front using cost and reliability criteria. Luckschandl [200] made a framework in Java to use genetic algorithms for routing optimization. Kwong et al. [179] used genetic algorithms for use in networks using the virtual path routing concept. Their approach worked for both normal and broadcast traffic. Liang et al. [189] investigated a distributed genetic algorithm for dynamic routing. It made good decisions without the need of global information (such as the number of nodes in the network). They improved on an ant colony based algorithm for this problem, called AntNet. Bendtsen & Krink [34] also improved upon AntNet by extending a genetic algorithm with a memory.

Point-to-multipoint routing
Hoelting et al. [133] studied the problem of finding an investigator tour in a network. This is the problem of finding a tour for fault detecting in a point-to-point telecommunication network. Their genetic algorithm

outperformed a deterministic heuristic. Hoelting et al. [132] studied broadcasting a message through a network to all nodes in minimum time. Their genetic algorithm with a permutation based encoding outperformed a recent heuristic found in the literature. Almost the same group studied [63] studying point-to-multipoint routing. The work of Cox et al. [69] was extended and a permutation-based genetic algorithm was combined with a heuristic Steiner tree algorithm. Compared to previous results, the results appeared to be superior. Zhu et al. [355] extended that work to also consider subsets of requests handled, if handling all requests is unfeasible.

Servet et al. [289] used genetic algorithms to estimate the size of traffic streams between nodes, starting from the offered traffic on the links. Huang et al. [137] evolved two routes between (pairs) of nodes in a network, guiding topology selection and link dimensioning. They used heuristic recombination and mutation. Later they [138, 136] investigated parallel computing to speed up the process.

Adaptive routing
For computer networks, Carse et al. [50, 103] evolved multi-agent systems for adaptive routing. They had good results with a small network. Munetomo et al. [227] studied approximately the same problem, but for larger networks. They employed path-based genetic operators to manipulate the routing tables directly. In comparison with existing Internet routing algorithms, their algorithm showed better performance (especially with heavy traffic). He [124] researched static routing and link capacity allocation in large computer networks, and used a genetic algorithm that accidentally used the same representation as Pan & Wang [237]. Tanterdtid et al. [316, 317] applied Shimamoto's [294] genetic algorithm for reliable circuit-switched networks to the problem of virtual routing in ATM networks. They were able to find some optimal solution to this problem. Later, Pitsillides et al. [247, 246] compared a genetic algorithm to a classical algorithm for this problem, and concluded that the genetic algorithm produced better results. Swaminathan et al. [309] also had good results with genetic algorithms. Shazli et al. [292] used fuzzy logic with a genetic algorithm to tackle this problem and got reasonable results. Medhi & Tipper [216] selected virtual paths for broadband routing. For larger networks, their hybrid approach worked better. Lin et al. [191] determined link capacities and routing for large-scale computer networks. Markaki et al. [209] researched a two-dimensional binary genetic algorithm combined with a hill-climbing algorithm for connection-oriented channel selection in a LAN/MAN. They got better results than a graph-coloring based solution. Loh & Shaw [199] used genetic algorithms to do fault-tolerant routing in multiprocessor networks.

Shortest path routing
Shortest path routing, OSPF, is a routing protocol frequently used for Internet connections between Internet Service Providers (ISPs), requiring weights to be set for the connections. Resende et al. [43, 98, 42, 44] examined a hybrid genetic algorithm for this task. They showed good or better results than other algorithms in terms of efficiency and robustness. Riedl [273] investigated different service metrics (bandwidth and delay) on this subject. Mulyana & Killat [224] also studied setting OSPF weights using hybrid genetic algorithms, minimizing utilization as an objective function. Kang et al. [315] evaluated the Quality of Service (QoS) of their algorithm using simulation. For optical networks, Pan et al. [238] investigated genetic algorithms for message scheduling. They reduced the number of passes required to send messages.

Routing in ad-hoc networks
Ad-hoc networks are communication networks with a dynamically changing topology. In sich networks the

development of effective routing schemes is important. Barolli et al. [29, 32] used genetic algorithms to incorporation quality of service requirements into ad hoc routing. Mao et al. [207, 206] investigated multicast routing for video. Turgut et al. [323] optimized the clustering of nodes in an ad hoc network. Marwaha et al. [210] and Liu et al. [193] did routing in ad hoc networks using fuzzy logic considering multiple objectives. Montana & Redi [221] optimized parameters for an ad hoc routing protocol using genetic algorithms.

QoS routing and multicast routing
Recently, QoS routing and multicast routing have gained interest. Leung et al. [183] and Xiang et al. [339] proposed a routing algorithm for multicast routing using genetic algorithms. Simulations showed that the algorithm provided reliable high-quality solutions. Ravikumar & Bajpai [269] tackled the same problem taking into account a maximum delay. Zhang et al. [350] used genetic algorithms using an experimental orthogonal crossover operation to design multicast trees for routing. Within a moderate number of generations, near-optimal solutions were found. Xiawei et al. [340] used a bit string genetic algorithm to develop tree schemas for multicast routing. Wu et al. [338] researched QoS multicast routing in asynchronous transmission (ATM) networks. Hwang et al. [141] also investigated multicast routing. Wang et al. [331] tackled multicast routing while looking at delay and bandwidth constraints. Roy et al. [277, 279, 278] investigated multicast QoS routing to mobile phones for multimedia applications using a genetic algorithm. Simulation showed that the algorithm worked even with imprecise information. Banerjee et al. [25] researched multicast route discovery in wireless networks. Thilakawardana et al. [319] investigated QoS packet scheduling in mobile networks. Chen & Dong [59] used a genetic algorithm with fuzzy logic to compensate for inaccurate global information and also showed good results in simulation. Haghighat et al. [120] and Xingwei et al. [342, 330] researched multicast routing with QoS requirements using genetic algorithms. Gelenbe et al. [109] discussed the use of a genetic algorithm for path finding and maintaining as an extension for their QoS routing protocol called CPN. Cornellas & Dalfo [65] investigated broadcast algorithms for Manhattan street networks using a genetic algorithm. Barolli et al. [166, 31, 30] also analyzed QoS-routing schems using genetic algorithms. Zhengying et al. [352] and Haghighat et al. [121] investigated least-cost multicast routing with bandwidth constraints using genetic algorithms and multicast trees. Li et al. [186], Araujo et al. [22], Tsai et al. [321], Pan et al. [236], Cui et al. [75] and Layuan et al. [181] also investigated QoS multicast routing with genetic algorithms under various circumstances. Siregar et al. [304] and Din et al. [92] investigated multicast routing in optical (WDM) networks.

Intelligent agents
Another interesting development is the use of intelligent agents for routing. Nonas & Poulovassilis [232] investigated network routing adaptation by intelligent agents using genetic algorithms. They showed that link failures could be recovered in a dynamic situation.

3.5 Dimensioning

Computer and communication networks
Davis & Coombs [78, 77, 66] chose link capacities for packet-switched wide-area networks using an integer genetic algorithm with problem-specific operators. They also tackled the problem of incorporating constraints into their model. IDavis et al. [79] minimized cost under a reliability constraint in a network. They used an integer genetic algorithm to select link capacities and traffic routes in a network, using problem-specific operators and local repair. Ahuja [12] dimensioned computer networks to optimize reliability. Garcia et al.

[107] tackled network expansions over multiple periods. They tried to determine when to increase link sizes to meet forecasted demand. They used a steady-state integer genetic algorithm combined with local search. Heegaard et al. [128] used genetic algorithms for dimensioning full service access networks, including both unicast and multicast traffic. In 2000, Mostafa & Eid [223] used a genetic algorithm combined shortest path routing to determine link capacities in a packet-switched network. A 3.17% reduction in costs was made over a previous method. Al-Rumaih et al. [16] determined spare capacities for survivable mesh networks. In 2001, Arabas and Kozdrowski [21] used an evolutionary algorithm to find good backbone capacities. Runggeratigul [280] showed a memetic algorithm for the link capacity problem in packet-switched networks, while taking into consideration the existing network facilities. Podnar & Skorin [248] used genetic algorithms to solve a problem of minimizing link costs, for the case that the costs for link usage are discounted if the usage exceeds a certain threshold. Atzori et al. [24] used genetic algorithms to determine network capacities for multicast traffic.

Optical networks
For optical networks, Chen & Zheng [60] studied the capacity allocation for optical ring structures. Chong & Kwong [61] had very favorable results with using genetic algorithms to allocate spare capacities. Mutafungwa [228] designed link redundancy enhancements for optical cross-connected nodes.

3.6 Restoration

Bentall et al. [35] used a genetic algorithm to find restoration paths for a heavily loaded network (where not all connections could be restored). They used the results as a benchmark, not for real-time computation. Kozdrowski et al. [167] used a hybrid genetic algorithm to assign link capacities and traffic streams in a network with link failures. Kirkwood et al. [158, 291] used genetic programming to obtain primary and restoration paths in a network with single link failures. Their approach however did not scale well to larger networks. He & Mort [125] developed backup-routing tables (i.e., restoration paths) with a hybrid genetic algorithm, while developing primary tables using shortest path routing. They found solutions that led to less congested nodes and links and a better utilization of network resources.

3.7 Admission control

Call admission, for radio networks, was studied by Yener & Rose. In 1994, they [347] studied a bit-string genetic algorithm to create admission policies for a small network. This leaded to results comparable to a simple 'admit if possible' heuristic. Later they [346, 345] studied admission policies based on local instead of global information, to be able to tackle larger networks. By examining the results, a novel heuristic local admission policy was suggested. Sherif et al. [293] studied call admission in wireless networks, considering the Quality of Service(QoS) of various multimedia services. Karabudak et al. [152] studied call admission for next generation wireless networks, including for multimedia QoS 'calls'. Abedi & Vadgama [3], Chakraborty [52], Huang & Cheng [135] and Ngo & Li [230] studied the scheduling of wireless broadcasting.

3.8 Frequency assignment and wavelength allocation problems

Frequency assignment problems
A lot of work in this area has been done by Crompton and co-workers. In [74] they used a parallel genetic

algorithm to minimize interference for frequency assignment for air to ground to air problems using an integer representation. Later [72] they improved this algorithm using heuristics and another representation. In [73] they compared their results with a backtracking heuristic. The genetic algorithm turned out to be better when using the same execution time. However, Hurley & Smith [139] demonstrated that simulated annealing, using incremental fitness evaluation, showed even better results. Tabu search [140] was also shown to outperform the genetic algorithm (but worse than simulated annealing). Valenzuela et al. [326] studied the same problem, but minimized the number of frequencies required if no interference is allowed. They [325] however showed that their genetic algorithm was better than simulated annealing or tabu search. Cuppini [76] used a bit-string genetic algorithm with no crossover for small frequency assignment problems. Kapsalis et al. [58, 151] also used a bit-string genetic algorithm. They tested a wide range of operators and fitness functions and tried to minimize both interference and the number of frequencies required. Later, Kapsalis and Smith [149] used a meta-genetic algorithm to select an even larger number of operators and tweak the parameters for their algorithm. In 1997, Ngo and Li [231] used a bit-string genetic algorithm with heuristic operators and local search to minimize interference. Kaminsky [148] studied the hourly assignment of military frequencies using a genetic algorithm. Sandalidis et al. [285] used bit-string evolutionary strategies for dynamic frequency assignment for cellular mobile radio. Their algorithm showed better results than four other (problem-specific) algorithms, but was not tested for real-time operations. Hao & Dorne [93, 123] tackled the frequency assignment problem (FAP) with a hybrid genetic algorithm and showed that their hybrid approach is promising compared to other global search methods. In 1997, Renaud & Caminada [272] tested various methods and operators for the frequency assignment problem. In 1998, Crisan & Mühlenbein [70] used a so-called breeder genetic algorithm for the frequency assignment in digital cellular networks, to minimize interference. Their problem formulation is more complex than the others. Later they [71] study the fitness landscape of the function that is optimized to explain the performance of previous evolutionary algorithms. Valenzuela [327] improved on the previous methods by exploring different operators and hybridization with a greedy algorithm. Weinberg et al. [336] combined multiple local search methods and introduced two new operators to tackle larger problems. Also in 2001, Cotta & Troya [68] compared different evolutionary algorithms and operators. Mabed et al. [201] dynamically allocated frequencies. In 2004, Matsui et al. [213] studied fixed frequency assignment with a bandwidth constraint.
Aardal et al. [1] evaluate global search methods for frequency assignment problems. The algorithm with the best results is best described as a hybrid genetic algorithm. Weicker et al. [335] studied station placement and frequency assignment together, using a multi-objective genetic algorithm.

Beckmann et al. [33], Ghosh et al. [115], Funabiki et al. [105], Li et al. [187], Yoshino & Ohtomo[348], Lau & Coghill [180], Jaimes-Romero et al. [143], Zomaya [358] and Sandalidis et al. [286, 287] tested various evolutionary algorithms for channel assignment problems. Kwok [178] used a Linux cluster to solve channel assignment problems using genetic algorithms. Kassotakis et al. [154] studied channel re-allocation using genetic algorithms. Matsui et al. [212] [211] researched channel assignment in case of limited bandwidth. Mabed et al. [202] tackled the channel assignment problem considering multiple periods.

Wavelength allocation
The earliest paper, by Tan & Sinclair [310] in 1995, uses a genetic algorithm for route selection between nodes in the network. The number of wavelengths needed to route traffic from node A to B is assumed to be an integer. A gene describes how this traffic is routed. The number of wavelength required between neighboring nodes C and D is simply the sum of all routes that go through it and the maximum wavelength count is minimized.

Sinclair [296, 299, 298] later extended his research with hybridization and considering cost models. At the same time, Abed & Ghanta [2] used a genetic algorithm for determining the topology of an optical network or Lightwave Network Architecture (LNA), using wavelength allocation on single optical fiber. Ali & Ramamurthy [15] used genetic algorithms to tackle the wavelength assignment and routing problem taking into account power considerations. Additional time taken by the genetic algorithm seemed to pay off. Saha et al. [282] also determined routing and wavelengths for optical networks taking into account reliability. Qin et al. [253, 252] solved the routing and wavelength assignment problem with limited range wavelength conversions. In 2003, Banjeree et al. [26, 27, 240] investigated the routing and wavelength assignment problem using multi-objective genetic algorithms, for presenting a number of combinations to network operators. The objectives used were things like average flow, average delay and expected blocking. Better results than with simulated annealing were seen. Cagatay Talay & Oktug [45] independently tackled this problem using a hybrid genetic algorithm to minimize costs. Their results looked promising compared to recent heuristics.

Recently, the area of it traffic grooming is starting to gain attention. Traffic grooming is the art of combining multiple low-bandwidth traffic streams into one waveband, in order to minimize the number of waveband stoppers needed. Lee & Park [182] and Xu et al. [343, 344] used genetic algorithms on this problem for some specific topologies.

3.9 Other design problems

There are many other design-related problems that can be tackled by EC, including for example node configuration problems, power management problem, protocol validation and design, the design of distributed databases and caching algorithms, the design of error-correcting codes, data equalization, multi-user detection, satellite communication design problem, provider selection problems, and registration area planning for cellular networks, amongst many others. To provide a literature survey of these problems is beyond the scope of this paper.

4 Concluding Remarks and Outlook

EC is used in a wide variety of telecommunication problems. Over 350 scientific papers on this area have been identified, covering all sorts of design-related problems. Problems tackled can be classified into node location, topology design, tree design, dimensioning, routing, restoration, admission control, frequency assignment and wavelength allocation, amongst many others.

In summary, it turns out that hybrid EAs (memetic algorithms) are very well suited for solving combinatorial optimization problems in telecommunications. When comparisons are made, almost for every problem considered, hybrid evolutionary algorithms do best, compared to problem-specific heuristics, simulated annealing, tabu search, and the like. As heuristics can be incorporated into EC resulting in memetic algorithms, even if a heuristic produces better results than an EC algorithm, combining both might be very worthwhile.

It should be pointed out that EC also has its limitations. For example, finding the global optimum is not guaranteed, the "distance" to the optimum remains generally unknown and the computational effort may be significant for large model instances (e.g., dyas of computing time). It is hard to estimate the exact added value of EC in telecommunications. The ECTELNET report [318] mentions that "an estimated operation cost reduction of 5-15% can be made by using EC instead of classic heuristics."

During the next few years, many new and challenging design problems in telecommunications will emerge. For example, we will observe a strong growth of infrastructures that support ambient information (i.e., information that depends on time and location) to be accessible anywhere and at any time. This leads to new design problems regarding how and where to store the ambient information. Also, we will observe a strong growth in the use of ad-hoc and peer-to-peer networks, whose topologies are inherently dynamic. This raises new issues related to dynamic capacity planning and routing. Additionally, we will observe a tremendous growth in the demand for strongly bandwidth-consuming interactive multimedia applications, which poses strict requirements on the performance of the network, leading to new design problems. We will observe a strong growth in the use Service Oriented Architectures (SOAs), where services are composed of sub-services owned by third parties, hence crossing multiple organizational borders. This development inevitably leads to a variety of challenges regarding the design and management of SOAs. Moreover, we will observe a strong growth of the use of computational grids, where huge numbers of jobs compete for access to computational resources, which leads to strongly fluctuating consumption of limited resources. The optimal dynamic control and resource scheduling of large-scale grids is another class of new and challenging tremendous design problems with its specific features and side constraints.

In the context of these new and upcoming technologies, EC provides a strong means to tackle complex design problems, as a viable alternative to the existing methodologies.

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A Articles by subject

	Network type			
Problem	General	Optical	Radio	Computer
Node location	[51] [276] [308] [334] [333] [250] [56] [249] [57] [195] [184]	[241] [242] [41] [129] [305] [328] [55]	[47] [49] [117] [312] [314] [250] [56] [249] [57] [144] [190] [268] [267] [217] [332] [233] [356] [357] [54] [185] [271] [14] [169] [46] [48] [53] [208] [335]	[58] [171]
Topology design	[163] [165] [28] [114] [214] [215] [36] [102] [9] [80] [83] [85] [84] [87] [86] [229] [281] [311] [5] [276] [334] [138] [308] [137] [136] [333] [306] [195] [322] [353] [354] [110] [113] [320] [81] [164] [177] [176] [174] [175] [156] [94] [270] [275] [192] [288] [313] [111] [112] [20] [155] [266] [197] [198] [196]	[13] [297] [300] [41] [219] [153] [243] [67] [301] [194] [337] [126] [341] [23]	[127] [256] [255] [259] [257] [258] [89] [88] [90] [91] [290] [168] [53]	[162] [172] [173] [244] [254] [245] [218] [171] [131] [283] [220] [119] [38] [39] [17] [19] [18]
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	Network type			
Problem	General	Optical	Radio	Computer
Tree design	[130] [150] [58] [147] [99] [100] [101] [6] [276] [351] [4] [7] [10] [8] [37] [170] [235] [234] [329] [63] [355] [307] [62] [274] [64] [265] [264] [145] [118] [349] [159] [260] [263] [262] [108] [261] [146] [324] [188] [106] [82] [284] [251] [239] [122] [134]	[241] [242]		[96] [97]
Routing, restoration & call admission	[69] [225] [302] [294] [205] [203] [133] [132] [63] [355] [289] [137] [138] [136] [35] [167] [158] [291] [79] [189] [160] [109] [232] [65] [183] [340] [350] [59] [200] [339] [166] [31] [30] [120] [342] [352] [121] [338] [330] [141] [236] [269] [331] [161] [216] [179] [222] [186] [22] [321] [125] [75] [11] [181] [34] [226] [142]	[310] [296] [299] [298] [182] [343] [204] [26] [27] [240] [45] [15] [92] [304] [129] [282] [238] [253] [252] [337]	[346] [345] [347] [277] [279] [25] [278] [52] [230] [293] [3] [135] [152] [319] [207] [206] [210] [193] [221] [29] [32] [323]	[237] [50] [103] [227] [124] [316] [317] [209] [162] [189] [247] [246] [292] [43] [98] [42] [44] [315] [273] [224] [199] [191] [309]
Dimensioning	[80] [137] [136] [138] [167] [225] [235] [234] [311] [329] [250] [56] [249] [57] [79] [107] [223] [16] [81] [164] [24] [128] [288] [248] [21]	[300] [13] [204] [219] [241] [242] [297] [60] [243] [61] [337] [228]	[250] [56] [249] [57]	[124] [131] [162] [244] [254] [245] [78] [77] [66] [237] [280] [191] [12]

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	Network type			
Problem	General	Optical	Radio	Computer
Frequency assignment & wavelength allocation		[310] [2] [296] [299] [298] [343] [344] [182] [26] [27] [240] [45] [15] [282] [253][252]	[74] [73] [72] [139] [140] [326] [325] [76] [58] [151] [149] [70] [231] [148] [285] [93] [123] [336] [71] [327] [68] [105] [33] [115] [178] [154] [202] [187] [348] [212] [211] [286] [287] [180] [143] [358] [201] [272] [1] [213] [335]	