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# Metaheuristics in Telecommunication Systems: Network Design, Routing, and Allocation Problems

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***Abstract*—Recent advances in the telecommunication industry offer great opportunities to citizens and organizations in a globally connected world, but they also arise a vast number of complex challenges that decision makers must face. Some of these challenges can be modeled as combinatorial optimization problems (COPs). Frequently, these COPs are large-size, NP-hard, and must be solved in "real time," which makes necessary the use of metaheuristics. The first goal of this paper is to provide a review on how metaheuristics have been used so far to deal with COPs associated with telecommunication systems, detecting the main trends and challenges. Particularly, the analysis focuses on the network design, routing, and allocation problems. In addition, due to the nature of these challenges, the paper discusses how the hybridization of metaheuristics with methodologies such as simulation and machine learning can be employed to extend the capabilities of metaheuristics when solving stochastic and dynamic COPs in the telecommunication industry.**

***Index Terms*—Channel allocation, metaheuristics, network design, routing, telecommunication systems.**

## I. Introduction

IN TODAY'S world, optimization methods allow managers and engineers to make smarter decisions in order to improve the systems they design and operate. Combinatorial optimization problems (COPs) can be found anywhere, from logistics and transportation to health care, production, finance, smart cities, and telecommunication systems. When solving these problems, the typical goal is to find the best possible solution among a usually vast set of feasible combinations. Thus, for instance, we might be interested in: 1) minimizing the cost or energy consumption of some activity or system [1] or 2) maximizing the profit, output, performance, or efficiency of some activity or system [2].

Real-life COPs are usually NP-hard and large scale, which means that they cannot be solved using exact methods unless a considerable amount of computing time and efforts are invested. In those frequent cases, metaheuristics reveal themselves as good alternatives to exact methods, since they can find high-quality or even near-optimal solutions in low computing times [3]. Metaheuristics are high-level algorithms that coordinate simple heuristics and rules to find near-optimal solutions to COPs, typically after some seconds. Being general approaches, the same metaheuristic framework can be employed in solving very different types of COPs.

In the information era, telecommunication systems are all around us. Showing an increasing number of users, telecommunication services raise many challenges to the optimization research community [4]. In effect, some of these challenges can be formulated as COPs, as in the case of the frequency-assignment problem in radio networks, the network design problem, the routing problem, or the optimization of allocation channels [5]. Since most of these problems are NP-hard and large scale, heuristics and metaheuristics have been increasingly used to deal with them. Often, these metaheuristic approaches have been combined with other soft computing methods, thus, generating hybrid algorithms [3]. Thus, for instance, the network design problem represents one of the most challenging COPs in the telecommunication industry. This problem is related to strategic or tactical planning of network resources [6]. Designing an efficient network is a challenging task frequently found in many real-world applications. Network design decisions also affect other managerial decisions, such as repository (or hub) location and routing paths. In recent years, a large number of routing and network design technologies have been developed and updated [7]. The diversity of deployed networks and the rapid pace of technological change rise the need for new optimization approaches that support smart decision making. Some of the major driving forces behind these requirements are the need for quality of service (QoS) guarantees and the explosive growth in network size and usage. Likewise, the demand for mobile communication has increased. However, there is a finite spectrum allocated to such services, which arises the channel allocation problem in mobile radio systems [5].

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TABLE I
OVERVIEW OVER OPTIMIZATION PROBLEMS CHALLENGES IN TELECOMMUNICATIONS

| Optimization Problem | Challenges and Requirements |
|---|---|
| Network design | 1) Location of hosts, servers, terminals, and other end nodes<br>2) Projected traffic for the network<br>3) Projected costs for delivering different service levels<br>4) Limitation of hardware resources<br>5) Security<br>6) QoS requirements<br>7) Reliability and availability |
| Routing | 1) Efficient routing with mesh infrastructure<br>2) Scalability<br>3) Robustness<br>4) Guarantee security<br>5) Overloaded situations |
| Channel allocation | 1) Adaptability<br>2) Channel utilization<br>3) QoS support<br>4) Fault tolerance<br>5) Self-configurability<br>6) Packet flow assignments |

The related optimization problems found in the literature cover many types of networks. A generic network design infrastructure and a routing method must ensure that data can travel through the network between arbitrary end points. The resulting network should be able to support many scenarios, among others: heavily and loaded networks, traffic patterns, multicast, or point-to-point traffic. The rapid growth of telecommunication capacity—driven in part by the wide ranging deployment of optic fiber as well as the expansion of wireless technologies—has led to an increasing concern regarding traffic characteristics and different QoS demands. Also, the design of communication networks and routing schemes should guarantee some subset of the following requirements:

1) all-time connectivity, providing at the same time the required robustness, high reliability, and availability;
2) efficient energy management and other issues at the lowest possible cost;
3) QoS guarantees or, at least, a high probability of good service;
4) prevention of routing oscillations, loops, and overloaded network situations.

Table I gives a general overview of the discussed application fields. Since architectural redesign efforts are time consuming and hence expensive, there is a critical need for efficient approaches to support the proper design decisions. Thus, the use of metaheuristic algorithms is required in solving COPs in the telecommunication area. Furthermore, notice that a number of processes in the telecommunications field are subject to uncertainty, which makes them even more challenging to optimize. The remaining of this paper is structured as follows: Section II presents the research methodology and an overview of recent publications. Section III provides a summary of the main metaheuristics that will be cited in this paper.

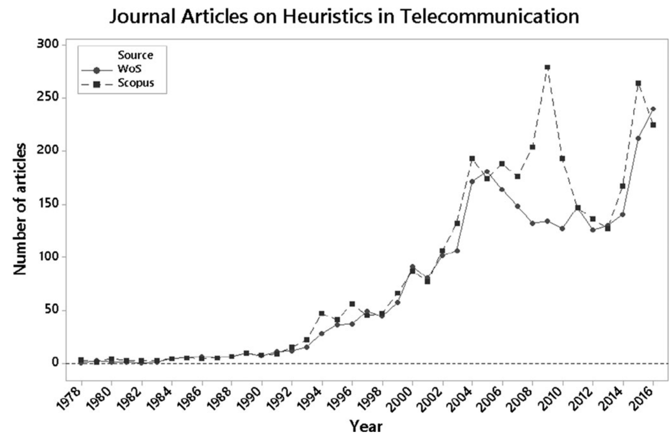


Fig. 1. Time series of journal articles indexed in Scopus and Web of science.

Section IV introduces a series of challenges related to the design of telecommunication networks. The more relevant challenges associated with routing and other miscellaneous applications are reviewed in Sections V and VI. Future trends in the application of metaheuristics in telecommunication systems are analyzed in Section VII. Finally, the main findings of this paper are highlighted in Section VIII.

## II. SURVEY METHODOLOGY

Real-life telecommunication systems are subject to a large set of environmental conditions, and many factors and parameters may affect the performance of these systems. Usually, processes in telecommunication systems can be slow and expensive. Thus, any savings in terms of time and resources will make network designs more sustainable. One important issue to be addressed while selecting the right optimization algorithm for solving a COP in the telecommunication field is the balance between the algorithm's performance and the computation time it requires. Since there are so many optimization problems in the field of telecommunication systems, it is not surprising that the use of metaheurisics has been gaining attention over the last years. This is evidenced in Fig. 1, which shows a time series chart of the number of indexed journal articles (both in Scopus and in Web of Science) during the last decades. Notice the increase in the number of published articles since the early 2000s.

The data for the previous time series were obtained by running a search procedure including the following logical condition: ((*heuristic) OR ("genetic algorithm") AND telecommunication). This condition was applied to the title, abstract, or keywords of the searched papers.

## III. BRIEF OVERVIEW ON METAHEURISTICS

Over the last years, a large number of metaheuristic approaches have become increasingly popular for addressing NP-hard COPs. Metaheuristics are particularly suited for solving highly complex optimization problems including many decision variables with nonlinear interactions among them, multiple objectives and/or constraints, and ill-understood structures. Metaheuristics can be classified into single-solution

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metaheuristics,which maintain a single solution; population-based metaheuristics, which work with a set of individual solutions; and hybrid metaheuristics.

### *A. Single-Solution Metaheuristics*

In the area of telecommunication systems, the most frequently used single-solution metaheuristics are Tabu Search (TS), greedy randomized adaptive search procedure (GRASP), and simulated annealing (SA). TS is a local search procedure that also includes a "tabu" list of recently visited solutions to increase efficiency [8]. Contrary to memoryless metaheuristics, TS makes use of flexible and adaptive memory designs. This procedure uses a selection rule based on the concept of *best improvement*, where the best solution in the neighborhood is chosen to replace the current reference solution. This acceptance criterion allows the search to avoid getting trapped into a local optimum, although a cyclic search could happen. To avoid this undesirable behavior, recently visited solutions are forbidden from being visited during a certain number of iterations, thus, avoiding cyclical paths in the neighborhood set. The GRASP [9] is another single-location metaheuristic currently employed in the optimization of telecommunication systems. GRASP is an iterative procedure. Each iteration consists of two phases: construction and local search. The objective of GRASP is to repeatedly sample stochastically greedy solutions, and then use a local search to refine them to a local optimum. The strategy of the procedure is centered on a stochastic and greedy stepwise construction mechanism, which drives the selection of the components of a solution based on a given sorting criteria. SA represents another single-solution metaheuristic [10]. SA is a stochastic algorithm that enables, under some conditions, the degradation of a base solution with the goal of avoiding local minima.

In addition to the aforementioned metaheuristics, the iterated local search [11] is another possible approach for solving COPs in the area of telecommunications. First, a local search is applied to an initial solution. Then, at each iteration, a perturbation of the obtained local optima is carried out. Finally, a local search is applied to the perturbed solution.

### *B. Population-Based Metaheuristics*

Most of the population-based algorithms are nature-inspired. In this context, the theory for the origin and diversity of life resulted in the development of one of the most popular natural-computing approaches, the Evolutionary Algorithms (EAs). EAs work on populations of individuals and model the natural evolution, which is an adaptation process with the aim of improving survival capabilities through natural selection, reproduction, competition, mutation, and symbiosis. In other words, given a population of individuals, the environmental pressure causes natural selection (survival-of-the-fittest) and, therefore, the objective (fitness) function of the population—which we seek to optimize over the generations—is improved. Based on this fitness, some of the better candidates are chosen to seed the next generation by applying recombination and/or mutation to them. The recombination and mutation leads to a set of new candidates (the offspring) that compete with the old ones for a place in the next generation. The process is repeated until either a fit-enough solution is found or a previously set computational limit is reached. The most common EAs implementations are genetic algorithms (GAs), which model genetic evolution [12]. Another computing approach motivated by biology is swarm intelligence (SI). The term is used to describe any attempt to design algorithms or problem-solving devices inspired by the collective behavior of social organisms, from insect colonies to human societies. SI has two main areas: algorithms based on the collective behavior of social insects—such as ant colony (ACO) or bee colony (BCO) optimization—and algorithms based on cultures of sociocognition as the particle swarm optimization (PSO) [13].

Nature-inspired algorithms are usually well-suited for applications like planning, design, control, classification and clustering, time series modeling, music composing, etc. Unlike most optimization techniques, these algorithms maintain a population of tentative solutions that are manipulated competitively by applying some variation operators to find a global optimum [14].

### *C. Hybrid Metaheuristics*

Many other alternatives exist, especially through hybridization of metaheuristics with other methodologies. The motivation behind implementing hybrid algorithms is usually to obtain better performance approaches that take advantages of each of the single strategies [15]. In fact, choosing an adequate combination of multiple algorithmic concepts is often the key for achieving state-of-the-art performance in solving most difficult COPs. One can distinguish three types of hybridization [16]. The first possibility consists of introducing concepts or strategies from either class of algorithms into the other. For example, some population-based metaheuristics make use of this kind of hybridization by incorporating local search procedures. The second form of hybridization is based on the exchange of information of two or more algorithms that are typically run in parallel, helping each other to cover the space research. Finally, the last approach integrates metaheuristics with exact methods [17], simulation [18], and even machine-learning techniques [19].

## IV. Network Design

Telecommunication network-design problems have gained attention over the last decades. The classical version of this problem consists in finding a network design that minimizes total costs while satisfying users' demands, providing a minimum QoS, and respecting the capacity constraints of each link. In the past, the design of communication networks was solved as a single objective optimization problem, using the cost of the network as the objective to be minimized and considering constraints, such as reliability, maximum delay, etc [20]. However, there is a clear trend to consider the design of a telecommunication network as a multiobjective optimization problem. A typical architecture for such a network consists of tributary networks—which connect nodes to hubs—and a backbone network—which interconnects the hubs. Depending on the application, hub nodes are called by various names, including

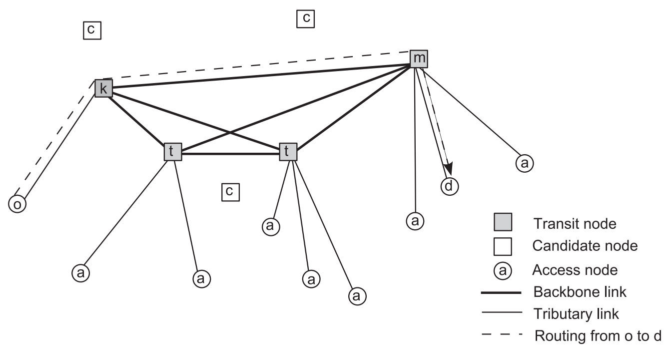


Fig. 2. Example of a backbone/tributary network problem, in which the backbone network is fully connected while the tributary networks are star networks [25].

gates, concentrators, switches, control points, or even access points [21]. Similarly, tributary networks are also called local or access networks, while backbone networks may be referred sometimes as hub-level networks. Frequently, due to the size of the problem, the design of the backbone network is considered independently from that of the tributary networks. Thus, a solution approach proposed in [22] for the integrated design was based on a TS algorithm. The authors dealt with the problem of how to expand a metropolitan area networks in a cost effective way. The proposed model considered the update of the access network with a star topology and the expansion of the backbone network with various types of topologies. Results demonstrated that the TS approach presents relatively stable behavior in terms of closeness to the optimal solution. The results were obtained on instances up to 500 users in a reasonable amount of time. Another COP that arises in the design of telecommunication networks is the star ring problem. In this problem, the aim is to locate a simple cycle through a subset of vertices of a graph with the objective of minimizing the total cost of all connections in a ring star topology. A new hybrid metaheuristic approach to solve this problem was proposed in [23]. The approach combined a variable neighborhood search with a GRASP algorithm. The hybrid metaheuristic was tested on the traveling salesman problem library, with instances involving between 50 and 300 vertices. Even though the star topology is a distinct choice for many types of access networks, there are situations where other layouts might be more appropriate, as the tree topology. In [24], Girard *et al.* presented a fast TS algorithm for the design of access tree networks. They described in detail the parameters used for the data structure and indicated how that could lead to substantial improvements of the overall computational time while providing costs lower than those obtained using traditional methods. The work presented by [25] dealt with a hub location problem in which the topologies of the backbone and the tributary networks are given. The locations of the hubs must be chosen among the terminal nodes, and each terminal node must be assigned to exactly one hub. The authors addressed the problem of planning a two-level network as illustrated in Fig. 2, i.e., a network in which the traffic collected by the access nodes must be routed through a backbone network, whose nodes are called transit nodes. In order to solve the problem, the authors proposed a TS-based algorithm.

The importance of telecommunication networks has dramatically increased over the past few years. Today's networks require a significant amount of investment in order to guarantee QoS and performance. Network design and planning in engineering systems requires policy decisions, analysis of investment strategies, and technical development plans. The multilevel network optimization problem is a network design model that raises optimization aspects of dimension, topological design, and facility location. Multilevel network optimization problems appear in many contexts, such as telecommunication, logistics, transportation, and electric power systems. Flores *et al.* in [26] proposed parallel asynchronous versions of promising multiobjective EAs, with the aim of designing an optimal telecommunication network in the presence of multiple conflicting objectives as cost and performance.

The topological design problem is NP-hard, and thus, it becomes intractable using exact methods as the number of nodes increases. With the emergence of some applications—such as teleconferencing, interactive simulation, or distributed content systems and multigames—the number of people demanding multicast services is growing. Multicast communication refers to the delivery of information to many receivers simultaneously. This information may come just from one source (one-to-many multicast) or many sources as well (many-to-many multicast). There are several potential applications of multicast, e.g., news delivery, stock quotes distribution, software updates, audio and video streaming, etc. In [27], Li and Pan formulated this problem and then solve it using a parallel GA. In their computational experiments the algorithm was tested in a network with 25 nodes. The GA-based solution could generate a lower link cost to achieve multicast. An issue regarding multicast is how to provide a reliable service. The provisioning of reliable multicast service deals with how to handle packet retransmissions. In [28], Santos *et al.* focused on the server replication method, wherein data are replicated over a subset of the multi-cast-capable relaying hosts and retransmission request from receivers that are handled by the nearest replicated server. They proposed a hybrid metaheuristic to find near-optimal solutions to this problem. Experiments were conducted on multicast scenarios.

As an alternative of connecting each pair of demand nodes with a direct connection, a hub-and-spoke topology is used in a number of networks. In this type of networks, direct communication between pairs of demand nodes is usually pricey. The flow of information, goods, or passengers from different origins can be obtained at hub nodes before transmission to their destination. The design of hub-and-spoke networks is also known to be a NP-hard problem, and it has recently been tackled by approaches based on metaheuristics. Thus, in [29] a hybrid GA with TS is proposed. The GA determines the number and location of the hubs while the TS allocates nonhub nodes to the installed hubs. Likewise, [30] proposed an efficient GA for the design of hub-and-spoke with single allocation, where the creation of the initial population is based on a GRASP metaheuristic. In [31], a capacitated asymmetric allocation hub problem was considered. The approach determined the number of hubs, their location, and the asymmetric allocation of nonhubs nodes to hub with the objective of minimizing total transportation costs while satisfying the required service level. The proposed solution method is based on combining ACO with a GA.

In addition, networks may become partially disconnected due to catastrophic component failures, and it is important for network users to be able to access some network services even under such circumstances. Availability of network services can be increased by strategically allocating servers over a network. In that sense, [32] developed a novel simulation–optimization approach combining Monte Carlo simulation with PSO to solve the reliable server assignment problem. The proposed approach was tested using random problems ranging from 30 to 100 nodes. Then, the same authors defined this problem as determining a deployment of identical servers to maximize a measure of service availability, and solved it using nature-inspired metaheuristic approaches, such as ACO and PSO [33]. The reliable server assignment problem in networks has been addressed by a limited number of works presented in the literature. This is closely related to the $p-$ median problem [34], and is concerned with locating $p$ identical servers at $p$ distinct nodes of a network to minimize the total weighted distance between the nodes and the closest servers. Most network reliability problems are NP-hard and, because of its difficulty, the $p-$ median problem has been usually studied under simplifying assumptions. Recently, [35] introduced the reliable server assignment problem considering attacks, which seeks to choose the locations of servers on a network in order to maximize the network reliability that results from a worst-case attack on the edges of the network. They introduced a GA that embeds the game-theoretic structure of the problem into the algorithm.

Moreover, telecommunication service operators are increasing their investment in solving the network design problem in order to deal with any traffic requirement under certain bounds and physical network conditions. In [36], Diaz-Baez *et al.* proposed a GA to design robust networks with optimal capacity of links, considering a stable routing with uncertain traffic that can be divided into $k$ subroutes. However, raising the $k$ value implies an increase in the number of viable solutions. Thus, a tradeoff between $k$ and the quality of the solutions obtained by the proposed algorithm was detected. Likewise, given the importance and complexity of the problem of robust network design, Arteta and Pinto-Roa in [37] studied the robust network design subject to guarantee certain QoS level. By reserving an adjustable bandwidth for each node, the network is not negatively influenced by traffic from the rest of the network. Hence, a multiobjective EA was proposed to solve and find a robust network design, which also minimizes the cost of the network, minimizes the inequity of traffic, and maximizes the traffic service in the worst-case scenario.

Pressure to reduce costs is also adding new urgency to the search of practical communication network design and optimization algorithms that can pack traffic into fewer or less expensive facilities without requiring new technology or capital purchases. Thus, Cox and Sanchez [38] presented in their work a new metaheuristic algorithm based on a short-term TS approach for designing least-cost telecommunication networks that carry cell site traffic to wireless switches while meeting survivability, capacity, and technical compatibility constraints. Also, many research works have been done for optimizing average network delay and, thereby, designing either minimal-cost reliable networks or maximal-reliable economic networks. A hybrid PSO algorithm was implemented in [39] to design a network infrastructure including decisions concerning the locations and sizes of the links. The results indicated an improvement in the optimization process in comparison to GAs. In [40], Dasgupta *et al.* proposed a modeling of data networks with delay and packet loss ratio. They minimized network cost using a GA. For that, three objective functions were defined.

TABLE II
METAHEURISTICS APPLIED TO NETWORK DESIGN OPTIMIZATION PROBLEMS

| Article | Optimization Problem | Single-Solution | Population-Based |
|---|---|---|---|
| [22] | Topology design | TS | |
| [23] | Topology design | GRASP | |
| [24] | Topology design | TS | |
| [25] | Hub location problem | TS | |
| [26] | Optimal network design | | EA |
| [27] | Coding topology design | | GA |
| [28] | Reliable multicast network | GRASP | |
| [30] | Hub location problem | | GA |
| [31] | Hub location problem | | GA |
| [32] | Reliable server assignment | | PSO |
| [33] | Reliable server assignment | | PSO |
| [35] | Reliable server assignment | | GA |
| [36] | Robust design | | GA |
| [37] | Robust design | | EA |
| [38] | Design least-cost network | TS | |
| [39] | Topology design | | PSO |
| [40] | Topology design | | GA |

Table II summarizes the main articles that have proposed metaheuristics applied to network design problems in telecommunications. Notice that TS is the most popular single-solution search metaheuristic to approach network design problems. In general, however, population-based metaheuristics, especially GAs, are the most employed methodologies.

## V. ROUTING

In the last decades, we have seen dramatic changes in the telecommunication industry that have far-reaching implications for our life-styles. There are many drivers for those changes: There is a continuing and relentless need for more capacity in the network and, at the same time, business today rely on high-speed networks to conduct their business. Not too many years ago, wire and radio technologies were the choices to send messages effectively. Today, optical fiber has been displacing wire in many applications and, with wireless, is emerging as one of the dominant transmission technologies. The aforementioned factors have driven the development of high-capacity optical-fiber networks and their remarkably rapid transition from the research laboratories into commercial deployment. Optical-fiber networks offer the promise to solve many of the problems we have mentioned. In addition to providing enormous capacities in the network, an optical-fiber network provides a common infrastructure over which a variety of services can be delivered. In the first generation of these networks, optical fiber was essentially used for transmission, and simply to provide capacity.

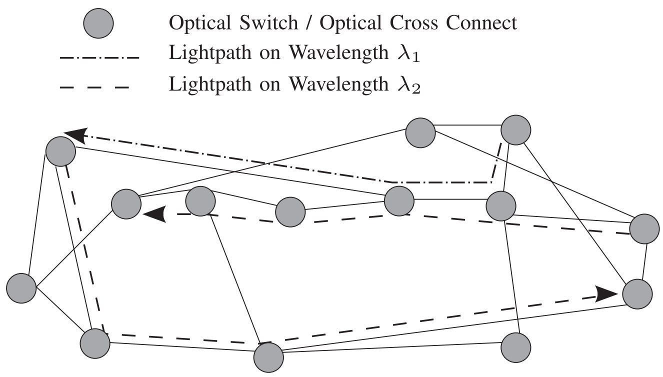


Fig. 3. Wavelength-routed optical WDM network with light-path connections [45].

The second-generation of optical-fiber networks has also routing and switching capabilities, as well as intelligence in the optical layer [41]. In both generations, multiplexing techniques provide an increase in transmission capacity. The need for multiplexing is driven by the fact that, in most applications, it is much less expensive to transmit data at higher rates over a single fiber than to transmit at lower rates over multiple fibers. There are basically two ways of increasing the capacity transmission on a fiber: the wavelegth division multiplexing (WDM) and the time division multiplexing. The idea of WDM is to transmit data simultaneously at multiple carrier wavelength (or equivalently, frequencies, or colors) over a fiber. In a wavelength-routed WDM network, end users communicate with one another via all-optical WDM channels, which are referred to as light-paths [42]. A light-path is viewed as a point-to-point light connection from a source to its destination. The concept of light-path can be extended to a light-tree, where a point-to-multipoint connection is set up using a single or multiple wavelengths [43]. In [44], Siregar *et al.* considered the multicast routing problem in large-scale WDM optical-fiber networks, where transmission requests are established by point-to-multipoint connections. The authors proposed a GA that exploits the combination of alternative shortest paths for the given multicast requests in order to minimize the number of required split-capable nodes.

Given a set of connections, the problem of setting up light-paths by routing and assigning a wavelength to each connection is called the routing and wavelength assignment problem (RWAP) (see Fig. 3). An algorithm to solve the dynamic RWAP in a distributed manner was proposed in [46]. It uses the ACO metaheuristic to obtain updated information about the network state, which is then employed to find the routes and wavelength that allow to establish new connections through an adaptive process able to deal with dynamic changes in the network state. In [45], a PSO metaheuristic approach is proposed for solving the static RWAP. To help the particles to converge toward an optimal solution quickly, a novel scheme is devised for route selection during the particles search. In [47], Hassan and Phillips addressed the dynamic RWAP in WDM optical networks. For solving this variant, they proposed a chaotic PSO. The static RWAP is often referred to as the virtual topology design problem [48]. In [49], Ghose *et al.* considered the problem of designing virtual topologies for multihop optical WDM networks. To analyze this problem, two metaheuristic algorithms were introduced: GRASP and EA. An ACO routing algorithm was proposed in [50] for transparent optical-fiber networks. It took into consideration the bit error rate of the connections that is derived from amplified spontaneous emission noise accumulated along the light-path.

In order to maximize the usage of the light-paths, telecommunication carriers adopt a technique that consists in grooming low speed traffic streams into high capacity channels [51]. This technique is referred to as the RWAP with traffic grooming. In [51], Wu *et al.* proposed a GRASP algorithm for solving the traffic grooming and routing problem with simple path constraints in WDM mesh networks, and introduced a mechanism to tackle the interaction between the grooming problem and the routing problem. Traffic demands in WDM optical-fiber networks can be classified into three categories [52]: permanent or static lightpath demands, scheduled lightpath demands (SLDs), and random lightpath demands (RLDs). SLDs are known in advance, and are supposed to be active only for a limited period of time (hours, days, or weeks). In [53], Marković *et al.* studied the RWAP of SLDs in all-optical wavelength division multiplexing networks with no wavelength conversion capability. They proposed a novel algorithm based on the BCO metaheuristic. It was shown that, by applying the proposed algorithm, significant improvements in terms of the number of established light-paths could be achieved by taking into account temporal information of light-path demands compared to the case when this information is not considered. Optimizing information exchange and routing is a challenging problem with implications of many aspects of the network: determining the required paths while minimizing the cost, minimizing the delay, or maximizing the reliability, etc. A commodity represents a certain demand of telecommunication traffic between two nodes. If multiple pairs of source and destinations have to be managed, the problem is defined as a multicommodity flow problem (MCFP). Masri *et al.* in [54] extended the MCFP by considering multiple sources for each flow, and a solving ACO metaheuristic was proposed.

Orthogonal frequency division multiplexing (OFDM) has been recently proposed as a modulation technique for optical networks due to its good spectral efficiency. Optical OFDM is more flexible compared to traditional WDM systems, enabling elastic bandwidth transmissions. In [55], Christodoulopoulos *et al.* introduce the routing and spectrum allocation problem in OFDM-based optical networks, as opposed to the typical RWAP in traditional WDM networks. The objective is to serve the connections through adequate spectrum allocation, with the constraint that no spectrum overlapping is allowed among those connections, and minimize the utilized spectrum. These authors proposed an SA metaheuristic to find good orderings that yield near optimal performance.

In addition, many researches have proposed metaheuristics for solving different variants of network routing problems. Thus, [56] introduced an algorithm based on ACO for solving various types of routing and congestion problems in computer networking. Likewise, [57] addressed the joint channel and routing problem for multicast applications. In their work, a technique based on a multiobjective GAs was proposed to build a delay-constrained multicast tree with minimum interference. Similarly, in [58] a GA and a PSO metaheuristic algorithms were proposed to maximize utilization and improve QoS in expanding networks.

In a data communication network, nodes and arcs represent routers and transmission links, respectively. Intradomain traffic engineering aims at making a more efficient use of network resources within autonomous systems [59]. Interior gateway protocols, such as the open shortest path first (OSPF) and the intermediate system–intermediate system are commonly used to select the paths along which traffic is routed within an autonomous system. Given a set of traffic demands between origin-destination pairs, the OSPF weight-setting problem consists on determining weights to be assigned to the links so as to optimize a cost function, typically associated with a network congestion measure. One of the first works considering even traffic splitting in OSPF weight setting is [60]. Later, Buriol *et al.* in [59] propose a GA with a local search procedure for the OSPF weight-setting problem.

Ad hoc networks are a type of wireless networks that do not require any infrastructure, such as a backbone or configured access points. The great advantage of ad hoc networks is the high flexibility they offer, even when there is no fixed communication infrastructure, there are high installation costs, or the reliability levels are lower than used to be in other networks. Other advantage of ad hoc networks is their robustness. Due to these characteristics, there are several applications of ad hoc networks: they can be used in places where rapid installation is required. A mobile ad hoc network (MANET) is a collection of mobile nodes that communicate over radio. In a MANET, no infrastructure is required to allow the exchange of information between mobile device users. Since the nodes are mobile, the network topology may change rapidly and in an unpredictable way over time. The major challenge found in this kind of networks is to find a path between the communication end points satisfying QoS requirements. The difficulty of this challenge is increased due to the mobility of the nodes. In [61], an ACO metaheuristic is introduced to handle the routing problem in a multihop MANET. This approach consisted of three phases: route discovery, route maintenance, and handling of route failures. Likewise, in [62] an ACO-based routing protocol was proposed for a MANET supporting multimedia communications. In fact, Multicasting plays and important role in the ad hoc wireless networks. In [63], an ACO metaheuristic was introduced for multicast routing in ad hoc wireless networks. A vehicular ad hoc network (VANET) is a subclass of a MANET, frequently employed in intelligent transportation systems. Multicasting provides different traffic information to a limited number of vehicle drivers by a parallel transmission. However, it represents a very important challenge in the application of VANETs, especially in the case of the network scalability. In [64], Bitam and Mellouk proposed a novel BCO algorithm to solve the QoS multicast routing problem for VANETs with multiple constraints. More recently, [65] proposed a hybrid routing intelligent algorithm that combines a PSO approach and an ACO approach with the goal of improving various performance metrics in MANET routing, including: end-to-end delay, power consumption, and communication costs. Also, in [66] a multipath routing scheme employing SA was introduced to deal with a hostile dynamic real-world situation into the conflict MANET routing problem.

TABLE III
METAHEURISTICS APPLIED TO ROUTING NETWORK DESIGN OPTIMIZATION PROBLEMS

| Article | Optimization Problem | Single-Solution | Population-Based |
|---|---|---|---|
| [44] | Multicast routing | | GA |
| [46] | Distributed RWA | | ACO |
| [45] | Static RWA | | PSO |
| [47] | Dynamic RWA | | PSO |
| [49] | Virtual routing | GRASP | EA |
| [50] | Adaptive RWA | | ACO |
| [51] | Traffic groaming | GRASP | |
| [53] | RWA of SLDs | | BCO |
| [54] | MCFP | | ACO |
| [55] | MCFP | SA | |
| [56] | Network routing | | ACO |
| [57] | Multicast routing | | GA |
| [58] | MANET routing | | Hybrid |
| [60] | OSPF weight setting | LS | |
| [59] | Weight setting | | GA |
| [61] | MANET routing | | ACO |
| [62] | MANET routing | | ACO |
| [63] | Multicast routing | | ACO |
| [64] | QoS-MRP VANET | | BCO |
| [65] | MANET routing | | Hybrid |
| [66] | MANET routing | SA | |

Table III summarizes the articles that have proposed metaheuristics applied to routing network design problems. Up to now, population-based metaheuristics like GAs and ACOs are the most employed ones in these routing problems.

## VI. CHANNEL ALLOCATION AND OTHER PROBLEMS

Another relevant problem is the channel allocation in mobile radio system. The rapid growth of cellphone users brought the need for efficient reuse of the limited frequency spectrum allocated to cellular mobile communications [67]. The efficient reuse of this spectrum is also important from the financial point of view, since less spectrum required to offer services to the same number of users means a lower cost. In the current scenario of cellular mobile services, the transmission frequencies are grouped into bands that are usually codified in a set of channels. Thus, each base station receives a portion of the total number of channels available to the entire system. Therefore, it is important to establish a strategy in order to reduce the total use of the available frequencies. Unfortunately, when it comes to wireless communication there is the interference problem—a phenomenon that represents the superposition of two or more electromagnetic waves at the same point. Some approaches have been developed in order to solve it. In [68], a channel allocation problem is considered. The goal is to minimize the weighted average blocking probability subject to cochannel interference constraints in a cellular mobile system. These authors simplified the problem using the concept of pattern, and applied an SA procedure to deal with it. Likewise, in [69] a GA is

TABLE IV
METAHEURISTICS APPLIED TO OTHER TELECOMMUNICATION OPTIMIZATION PROBLEMS

| Article | Optimization Problem | Single-Solution | Population-Based |
|---|---|---|---|
| [2] | Allocation resource | | Hybrid |
| [68] | Allocation resource | SA | |
| [69] | Allocation resource | | GA |
| [71] | Positioning problem | | ACO |
| [72] | Positioning problem | | ACO |
| [73] | IP networks | TS | GA |
| [74] | Allocation resource | | Hybrid |

introduced for hybrid channel allocation. It focuses on reducing the interference in cellular networks.

Along with the fast-increasing in mobile cellular networks, wireless sensor networks (WSN) have been evolving. A WSN is usually described as a network of nodes that track physical or environmental conditions, enabling interactions between persons or computers and the enclosing environment [70]. During the deployment of a WSN, one key objective is the full coverage of the monitoring region with a minimal number of sensors and a minimal energy-consumption of the network. In [71], a multiobjective ACO is used to solve this problem. Later, in [72], a similar algorithm is proposed to minimize the number of required sensors while covering a maximum area. Due to spectrum scarcity and the high demand for services, the same problem that is presented in mobile networks is also a problem in satellite communication networks. The challenge of assigning telecommunication services to satellite spectrum resources have been modeled as a packing problem. Thus, in [73], a packet network design methodology was introduced to assign flow and capacities under end-to-end QoS constraints. The solving approach is based on the use of a GA and a TS.

With the development of new technologies, Internet-distributed computing has become increasingly popular, which has brought new emergent paradigms. However, the scarce availability level of nondedicated resources constitutes an important challenge to the range of possible applications of these systems. In [74], a simulation-optimization approach was proposed for cost-effective and availability-aware service deployment. Likewise, in [2], Mazza *et al.* dealt with the resource allocation problem for supporting fast access of mobile devices. They presented a biased-randomized heuristic [75] to support efficient and fast link selection.

Table IV summarizes the information reviewed in this section. Notice the diversity of metaheuristics that have been used to deal with these problems, including hybrid ones.

## VII. EMERGING TRENDS AND CHALLENGES

The use of metaheuristics has increased during the last two decades to address many telecommunication problems, such as hub location, topology design, reliable server assignment, frequency assignment and wavelength allocation, routing, etc. Through an extensive analysis of the literature, different trends can be identified regarding the solution of these problems. One trend in the area of telecommunication networks is the search for more effective designs. According to the available traffic information, the type of network design can be classified as deterministic design, stochastic design, and robust design. In the latter, only information on traffic dimensions is assumed. In the resource allocation problem for robust network design, a misallocation of capacities could have two side effects: 1) significant data loss for certain traffic—i.e., a nonrobust design and 2) over-sizing of installed capacities—i.e., a robust design at a high investment cost. Both undesirable effects justify the need for metaheuristic algorithms in order to achieve an efficient allocation of resources.

Another observed trend is the current predominance of population-based metaheuristics over single-solution ones. In our view, both are valid approaches and, therefore, much research can be done yet regarding the use of single-solution metaheuristics in the telecommunication field. In fact, single-solution metaheuristics might offer some advantages over population-based approaches, since the former typically employ less parameters and might be easier to implement in practical applications. Regarding the test cases and performance evaluation of the proposed algorithms found in the literature review, one can notice the predominance of small- and medium-sized instances. This is probably due to the computing time required to solve large-sized instances. However, in most real-life telecommunication systems a solution might be required after a few seconds or milliseconds. These applications justify the need for developing faster heuristic and metaheuristic algorithms, which might be able to provide good solutions in almost real time for large-sized instances with thousands or even millions of nodes.

Also, due the growing developments in metering and digital technologies, the amount of different electronic mobile devices around us is increasing. This mobile technology is massively being used today in smart cities, which arises several challenges related to the use of 5G communication technologies, cloud computing services, security, trust and privacy, etc. In this context, the use of fast metaheuristic algorithms becomes necessary to deal with the associated design communication problems. During the next years, new challenging problems will emerge in the telecommunication industry. For instance, we observe an expansion of the wireless technologies, an increasing demand for higher QoS, a continuous raising in traffic flow, and a strong growth in the use of mobile ad hoc and peer-to-peer networks. These emerging challenges raise new COPs characterized by uncertainty and dynamic conditions. Despite the fact that metaheuristics constitute a powerful tool to tackle complex optimization problems in the field of telecommunication systems, most of the existing approaches in the scientific literature have been developed assuming deterministic and static inputs and constraints, which represents an oversimplification of the real-world conditions that characterize telecommunication systems. In order to include uncertainty in optimization models, simheuristic algorithms integrate metaheuristics with simulation. This hybridization allows us to tackle stochastic COPs in a natural and efficient way [18]. Likewise, in order to include dynamic inputs in the optimization models, learnheuristic algorithms combining metaheuristics with machine-learning techniques have been recently proposed as a novel and promising approach yet to be explored in detail [19]. In effect, some problems in the telecommunication field are characterized by inputs that are not fixed in advance (e.g., the performance of transmission devices). Instead, these inputs might vary according to the solution properties (e.g., the number of users assigned to them). Thus, during the generation of each new solution, a machine-learning technique—such as a neural network—can be iteratively employed to estimate and update the values of these inputs after each step of the constructive heuristic (e.g., as new users are assigned to each available channel).

## VIII. Conclusion and Future Work

Due to the increasing amount of new optimization challenges in the telecommunication industry, metaheuristic algorithms have received an increasing attention during the last two decades. This paper offers a review of recent works proposing different metaheuristic approaches to efficiently deal with the aforementioned challenges. Three main telecommunication fields have been the focus of this paper: networks design, routing, and allocation. Inside these fields, several subproblems have been identified, since the design of telecommunication systems comprises many different aspects, including: topologies, location of resources in links and nodes, unicast versus multicast routing, reliability and availability of networks, etc. From the literature review, it can be concluded that, so far, population-based metaheuristics—such as GAs, ACO Optimization, and PSO—have been more popular than single-solution ones—such as TS, GRASP, or SA. This is probably due to the fact that most authors belong to computer science departments, where the use of population-based metaheuristics is widely extended. However, this also offers a good chance to researchers in other fields—e.g., operations research or industrial engineering—to propose new single-solution approaches that typically require less parameters and might be easier to implement in real-life scenarios.

With the emergence of new mobile and decentralized telecommunication systems, aspects such as uncertainty and dynamism are more relevant than ever. For this reason, it is expected that during the next years new challenges related to the use mobile and wireless communications in complex environments such as smart cities or cloud computing will appear. To solve these challenges, a new generation of hybrid optimization methods combining metaheuristics with simulation and machine-learning techniques will become the topic of study of many researchers and practitioners.

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