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Models and Solvers for Coverage Optimisation in Cellular Networks: Review and Analysis

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***Abstract*—Cellular phone networks are one of the most widely-used means of communication whose design is a quality-determining task. During the former step many engineering problems must be solved and where coverage optimisation is one of the most critical ones. The latter was proven to be NP-hard which has led to proposing several scattered and non-unified mathematical models to solve it. This models' heterogeneity hinders comparing or linking works to accelerate advances in this field and it also hardens choosing the adequate model for a given case study. In order to cope with these issues, this work presents a systematic survey on coverage optimisation models. It analyses 80 works done from 1995 to 2021. The comparison considers 6 comparison metrics and 3 classes of coverage models. Our work's contributions aim at (I) coping with the lack of models' standardisation, (II) providing practitioners with a repository of coverage models, (III) sketching guidelines of a unified model, and (IV) opening future research perspectives in this axis.**

***Keywords*— Cellular Networks and Coverage Optimisation.**

I. Introduction

Cellular phone networks (2G-6G) are one of the most popular communication networks. Their growth has motivated a rising interest and concurrence at both the economic and scientific levels, where operators and customers are expecting a high level of reliability, robustness and service quality. Considering this, the design of such networks became a success/failure-key task that regroups the most influential issues in the cellular network life cycle [1], [2]. The coverage optimisation problem remains one of the most critical and quality-determining ones. Indeed, a good (or bad) coverage optimisation may lead to overlapping that might ease (or harden) the capacity optimisation and, thus, facilitates (or jeopardises) the rest of the design phase [3], [2].

The coverage optimisation is an NP-hard combinatorial problem [4], [5], [6]. Actually, it is so difficult to model that even a simple formulation treating only the area's coverage has been shown to be NP-complete [7]. This fuzziness encouraged the appearance of several *scattered* and *non-unified* models, formulations and algorithms to solve it. This models' heterogeneity and lack of benchmarking considerably slows-down the advances made on this problem considering that it is hard to link and compare works/algorithms to build thoughtful knowledge. This raises several important questions such as: *What model should one use when solving the coverage problem*? *Are the current models correct/complete*? *If "no", how should one correct them*? *What should be the features of a standard model*?, etc.

This paper copes with the above-mentioned pitfalls by conducting a survey on the coverage optimisation models. Overall, 80 works treating three classes of coverage models are analysed by conducting a comparison based on 6 metrics. The former are the wave propagation, problems' formulation/standardisation/interdependency/modelling and lastly reliability and extensibility. This work's contributions stand in (I) dealing with the coverage models' standardisation shortfalls, (II) providing a clear and encompassing repository of coverage models, (III) introducing a blueprint of a unified model and (IV) drawing new research lines to be explored.

The rest of the paper is structured as follows. Section II enumerates the sources, inclusion/exclusion criteria and also the comparison metrics considered in this work. Next, Section III reviews the terms referring to the coverage problem in the literature, while Section IV introduces the related works and the technicality of the three models being considered here. In Section V, an analysis and comparison of these models is done. Section VI presents the future research trends in coverage optimisation. Finally, Section VII concludes the work.

II. Inclusion, Exclusion and Comparison Criteria

This paper considers works that have been officially published (e.g. Springer, IEEE, Elsevier, ACM, etc.) as well as theses (e.g. bachelor, master, PhD, etc.) or other types of publications (e.g. journal, conferences, etc.). The content of the selected works must be specific to cellular network independently from the generation of the former. Nonetheless, these works can treat the coverage problem individually or jointly with other problems (e.g. frequency assignment problem). This literature review led to consider 80 works tackling the STORMS, ARNO and isolated coverage models. The conducted survey has also identified 16 terms referring to coverage optimisation, where 8 are widely-used while the others have rarely been employed (see Fig. 1).

This review is done by considering 6 comparison metrics: (I) "*wave propagation*" analyses how signal dispersion has

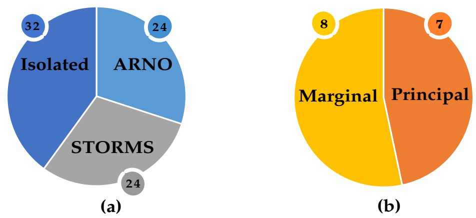

Fig. 1. Statistics of coverage literature: (a) models and (b) naming

been modeled. (II) "*problem formulation*" sketches the main objectives and constraints considered in the model. (III) "*problems' interdependency*" focuses on whether coverage optimisation is tackled jointly with another problem. (IV) "*standardisation*" analyses the issues raised by the lack of normalisation of the models (e.g. data). (V) "*reliability and extensibility*" exposes the limitations/applicability of the studied models to other generations of cellular networks. (VI) "*problem modelling*" reviews the main modelling differences between the studied models (e.g. landscape, area, etc.).

III. Coverage Optimisation in the Literature

The coverage optimisation in cellular networks stands mainly in adequately locating the transmission devices (e.g. Transceiver Base Station (BTS), node-B or enode-B). This problem has been researched under several non-unified names. Based on a preliminary analysis, this work regroups the coverage problem's nomenclature in two principal categories: the *principal* ones that are statistically most used, and the *marginal* ones containing isolated names that have been used only once.

A. Principal Naming

The coverage optimisation problem [8], [9] is also known in the literature as the Antenna Positioning Problem (APP) [2], [10], [11], [12], [13], the Radio Network Design (RND) [4], [6], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], the Antenna Placement Problem (APP) [14], [24], [25], [26], [27], [28], [29], [30], the Automatic Cell Planning (ACP) [31], [32], [33] or the Radio Network Optimisation (RNO) [34], [35], [36], [37], [38]. It is also called the Base Station Placement (BSP) [39], [40], [41], [42], [43], [44], [45], [46] or finally the Base Station Location (BSL) [47], [48], [49], [50], [51], [52] .

B. Marginal Naming

Besides the frequently-used nomenclature presented above, the coverage problem is also found to be sometimes called as the optimisation of area coverage [53], the mobile antenna location identification [54], the GSM mobile station location [55], or the automatic base station deployment [56], the global optimisation of transmitter placement [57], the site placement and site selection [58], the network resources optimisation [59], the design of cellular network [60] or finally the mobile station positioning [61]. Although, it is worth noting that the *Antenna Positioning Problem* (APP) is used in the rest of the paper as principal name and stand for all the others.

IV. The Case Study

The APP's fuzziness made that it is hard to model it. This fact gave birth to several models. In this section, the main ones, their origin, modelling and the solvers devised to deal with them are investigated (see Fig. 2).

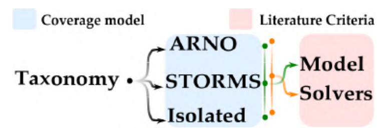

Fig. 2. The case study: ARNO, STORMS and Isolated

A. The ARNO Project

This section introduces both a bird's eye view of the ARNO model and the solvers devised to tackle it.

1) The Model: Many works were conducted on this model [2], [5], [30]. It is based on the formulation proposed within the EU project ARNO [1] [62]. It seeks to treat a real-life and complex model that regroups the major aspects, objectives and constraints related to the radio network design such as the number of used sites, the number of used antennas, the coverage amount, traffic hold, handover constraint, the interference constraint and the cells' shape constraint. For this reason, it is formulated as a multi-objective constrained optimisation problem. The mathematical model used within the ARNO project is based on Reininger's earlier works [63], [64], [65], which consider the covered area as a discrete grid. The grid is a set of points: Service Test Points (STP), Traffic Test Points (TTP), Reception Test Points (RTP) and Candidate Sites (CS). Radio transmission is simulated by a propagation loss matrix. Generally, Okumura-Hata [66] and Walfish-Ikagami models [67], or combination of complex propagation wave models [5], [22], [60] are used. The objective of this model is to find a set of optimal parameters such as the antenna type, the transmission power, the vertical and horizontal deviations (tilt and azimuth) to ensure and fulfil the above-mentioned objectives and constraints.

2) The Solvers: The first works were mainly dedicated to the mathematical formulation of the APP. Reininger's earlier works [63], [64], [65] were the principal basis of the formulation used later within the ARNO Project [62]. Then, the authors in [33] proposed a hill climbing search coupled with problem-dependent procedures of initialisation and post-processing of the population to solve the APP. Then, a multi-objective genetic algorithm was proposed in [38] with problem-dependent operators to solve the APP. The authors in [2] proposed a heuristic for the APP, including a pre- and post-processing procedures and an optimisation process based on tabu search algorithm. A framework based on Simulated Annealing algorithm (SA) for the APP solving was proposed in [68]. In [53], the authors used a simple

[1] ARNO: Algorithms for Radio Network Optimisation, IT Project 23243

steady-state evolutionary algorithm. Later, the authors in [29] proposed several evolutionary algorithms, whereas in [30], they proposed an evolutionary algorithm (ENCON) for solving the APP. A Non-Dominated Sorting Genetic Algorithm II (NSGA-II) was used in [69]. Then, in [52] a two phase strategy algorithm mixing between a sequential greedy algorithm and NSGA-II against a random search method.

The authors in [70] used four multi-objective genetic algorithms which are: the NSGA-II, the Strength Pareto Evolutionary Algorithm II (SPEA-II), the pareto envelope-based selection algorithm and the simple evolutionary algorithm for multi-objective optimisation. Then, in [71] authors studied the properties of evolutionary algorithms when dealing with the APP. Later, the authors in [72] devised an evolutionary multi-objective algorithm for solving the APP. A parallel asynchronous steady-state evolutionary algorithm was proposed in [60], then three complementary hierarchical parallel models for solving the APP using a multi-objective steady-state genetic algorithm were proposed in [22]. Later, in [5] the authors presented a parallel hybrid metaheuristic for the antenna positioning problem. Then, in [73] a Particle Swarm Optimisation algorithm (PSO) was used to solve the APP. In [74], the authors proposed a new multi-objective permutation-coded evolutionary strategy for the APP. In [54], the authors used the NSGA-II and also proposed a modified version of it. Later, the NSGA-II and another evolutionary algorithm designated as the modified NSGA-II were proposed in [49]. The authors in [75] used the PSO to solve the APP. Finally, in [76], a solving of the APP under a dynamic load of traffic was studied.

B. The STORMS Project

This section introduces an overview of the STORMS model and the optimisers that have been designed to solve it.

1) The Model: Several works have been also conducted on this model [4], [10], [44]. It was born from the works done in the STORMS project [2] [37]. It is based on a graph formulation introduced by Calegari [16], [34], [35], [36], [37] that seeks to treat a more canonical and simplified model of the APP. It regroups only the fundamental objectives of this task such as the amount of covered area and the number of used antennas. For this reason, it is formulated as a mono-objective optimisation problem. The mathematical formulation used within the STORMS project model is also based on Calegari's earlier works. It considers the treated area as a discrete grid. The grid is a set of points. Unlike the ARNO model, there is no distinction between the type of points and no complex propagation loss matrix is used to simulate the wave propagation. Simple isotropic or directive wave propagation models are used [24], where cells coverage can be computed and returned by an ad-hoc function [35]. Each point is represented with Cartesian coordinates. The objective is to find the most optimal sites among a set of potential candidates to place base stations and ensure the largest coverage.

[2]STORMS: Software Tools for the Optimisation of Resources in Mobile Systems

2) The Solvers: The first works related to the positioning of antennas within cellular phone networks were mainly done within the STORMS project and were dedicated mostly to the formulation and the modelling of the APP. The first general formal definition of the APP was introduced in [37], then a more detailed formulation of the problem recalling the minimum dominating set problem, and at the same time the first mathematical formulation of the APP were introduced in [35], [77]. The authors used a parallel island-based version of the genetic algorithm to solve the APP. Later, another detailed formulation of the APP recalling the unicast set cover problem was given in [16]. These authors used a standard steady state genetic algorithm and a parallel island-based genetic algorithm. The two previous formulations were grouped in the same work [78]. The authors used first a simple greedy algorithm and then a Genetic Algorithm (GA).

A simple greedy algorithm, a weighted set GA and a parallel island-based GA were used in [34] to solve the APP. Then, a sequential and a parallel steady-state GA were proposed in [14]. A parallel GA for the base station placement was introduced in [15]. After, authors in [19] proposed a differential evolution algorithm with problem-dependent operators. Afterwards, a faster differential evolution algorithm with more suitable differential operators for the APP was proposed in [18], then the SA and the population-based incremental learning, the canonical Differential Evolution (DE) and an evolutionary-based algorithm (CHC) were used in [6] to solve the APP. The SA, the steady-state, the generational genetic algorithm and the CHC were used later in [24]. Hence, a multi-objective evolutionary-based algorithm was proposed in [28] to solve the APP. Several evolutionary algorithms were also presented in [6], [23].

Three evolutionary computation techniques which are the GA, the memetic algorithm, and the chromosome appearance probability matrix algorithm were used in [21]. Later, the authors of [4], [17] used several algorithms for benchmarking the APP's solvers. Several multi-objective algorithms such as the NSGA-II, the SPEA-II and the adaptive and non-adaptive indicator-based evolutionary algorithm were used also in [11] to tackle a multi-objective formulation of the APP. Then, a parallel hyper-heuristic was designed in [12] to solve the APP. The authors in [13] proposed a multi-objective formulation of the APP. Then, various parallel island-based algorithms were designed in [10]. Finally, a differential evolution algorithm and a bat algorithm were proposed for solving the APP in [20], [79], respectively.

C. Other Isolated Models and Solvers

This last section regroups several marginal and isolated models and formulations of the APP. Some of them were based on a more or less exact combination of the two previous models, while others were based on enhanced versions of one of the previous models. Finally, other models were based on totally different concepts.

In [59], the authors developed a hierarchical optimisation planning method based on the SA. A dynamic programming was used in [48]. Later, in [80], a combination algorithm for total optimisation was proposed. Then, the authors in [51] used the SA to tackle the APP. Artificial Neural Network (ANN) for base station location was used in [61]. After, the authors in [42] proposed a hierarchical approach for solving the APP. Then, different genetic approaches to tackle the antenna placement were also devised in [81]. The authors in [82] developed an efficient algorithm for the APP in CDMA systems.

The authors in [55] used ANN. Then, a new parallel multi-objective GA was also designed in [83] to tackle the base transceiver placement. Later, a genetic approach was used in [40]. In [84], the authors proposed a genetic-based algorithm for solving the APP. A branch and cut algorithm was proposed in [85]. The authors in [43] proposed a new problem-dependent GA. Later, an efficient pattern search algorithm (Dividing Rectangles) was presented in [57]. Authors in [86] considered the frequency assignment problem and the APP simultaneously using a multi-objective evolutionary algorithm. Then, heuristic and stochastic optimisation techniques were considered in [87]. In [45], the authors used the PSO for solving the APP. Then, in [26] the GA, the SA, a random-walks algorithm were used. Later, authors in [50] proposed a parallel GA for the APP in 3G networks.

In [47], the authors developed a Lagrangian heuristic technique to solve adequately the antenna placement problem. Then, an artificial immune system for solving the APP was used in [41]. Later, in [27] a problem-dependent GA to tackle the antenna positioning problem in third-generation networks was designed. A GA was also devised in [88]. Then, the authors in [58] proposed an algorithm using pattern search techniques for solving the antenna placement problem in third-generation networks. Recently, the authors in [89] proposed a combination between the greedy algorithm and the SA for tackling the APP. In [56], an automatic cellular network design algorithm was presented. Then, the authors in [90] developed an integer linear program for the antenna placement. After that, in [91] the authors treated the antenna positioning problem through K-means clustering. An optimisation method containing jointly a ray tracing engine and the GA was designed in [92]. Authors in [39] introduced a summary on the Nigerian experience in radio network planning. In [93], an asynchronous PSO for the antenna positioning was presented. Then, a combination of the GA and the learning automata was designed in [94]. Finally, the authors in [25] proposed a problem-dependent algorithm for the APP.

V. Critical Analysis And Comparative Study

Since ARNO and STORMS are the two principal models, in the following, a comparative study is conducted on these two models by highlighting the principal advantages and drawbacks of each one with an emphasis on ARNO. Fig. 3 illustrates the comparison criteria used.

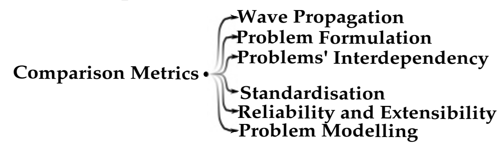

Fig. 3. Comparison metrics

A. Wave Propagation

Considering this comparison aspect, the first shortfall stands in using a complex *wave propagation model*. Generally, doing so aims at treating a more realistic version of the APP by simulating the phenomenon of electromagnetic wave propagation in a specific environment (e.g. urban, countryside, sea, etc.). But, the propagation model used in most of the works only took into consideration one kind of environment (e.g. dense urban areas), while a more realistic coverage formulation might use several models to reflect each type of the environments being in the studied area (e.g. buildings, leafs, water, air, ect.), or more complex models like 3D ray tracing. Secondly, measuring the interference for each potential location using a complex model of wave propagation is very time and computationally-consuming [11], [86]. Therefore, it cannot be used during a real-time optimisation process [2]. Thirdly, the computation of the radio field is based on non-trivial mathematical functions (e.g. arctang, sorting algorithms, etc.) and also depends on the wave propagation model. Likewise, the needs in terms of memory are huge [60], [38]. Finally, the constrained multi-objective formulation with its high computational cost required for the function evaluation and constraints tests hardens the radio network design [38]. Unlike the ARNO model, the STORMS' one does not use such heavy propagation models, since it employs a simplified representation of the radiation pattern of realistic antennas (e.g. directive and isotropic) [24].

B. Problem Formulation

The second pitfall is the *formulation* of the problem itself (i.e. objectives and constraints). The ARNO model tried to encompass too many objectives, aspects and constraints of the APP. Some of them are directly related to it such as the maximisation of the coverage, minimisation of the number of base stations and the handover constraint. Other objectives are weakly related to it, like the interference, which is more linked to the FAP than to the APP. Others such as the traffic hold and some additional objectives and constraints should be formulated as independent optimisation problems. All of these facts made the APP complex and unsolvable in real-time. For many non-experts in communication, a rich model means a better solution, but in reality, it is not always true. Nonetheless, the fact is that a real-life deployment of a cellular network relies on the same model used within the STORMS project and not the one within the ARNO project. For this reason, unlike the first model, the second one gives a canonical and feasible formulation workable for the real-world optimisation, since it tackles only the basic objectives of the APP which are the maximisation of the coverage and the minimisation of the number of base stations used.

C. Problems' Interdependency

The third misconception is the *modelling* of the APP. The FAP is inevitably relying on the APP. So, any results of the optimisation of the base station position must be workable on the next phase, which is the FAP (for the 2G networks). For this reason, any modelling of the APP has to be built in a way it can be seen as an extension of the FAP formulation (or other problems depending on the cellular network generation). The ARNO model gives a hardly-workable optimisation result on some variants of the FAP. Unlike the first model, The STORMS' one gives more flexibility when treating the FAP and the APP by allowing the use of optimised antennas' positions with the FAP, since both APP and FAP are formulated as graph problems. Finally, it allows treating the two problems simultaneously within a more general graph formulation.

D. Standardisation

Considering that the ARNO model is weakly unified, the fourth drawback is the *benchmarking*. Actually, every work addressing ARNO has its problem instances used to assess the efficiency of the proposed algorithms. Some of them use randomly-generated, synthetic, realistic data or a combination of one or two or all of these data types. Knowing that the behaviour of an algorithm is strongly bonded to the kind of data it is designed to tackle makes the reliability of these algorithms very poor and unworkable from one work to another. Secondly, every work within the ARNO model has its vision of the objectives and constraints (mathematically speaking), which makes those works look like they are treating a common problem (i.e. the APP) but in reality any change in a constraint, a parameter or an objective makes that they are treating problems of different complexities. Sometimes these formulations are conflicting, slightly different or even independent.

Thirdly, the cellular networks are strongly based on radio transmission, which makes any change in the technical (mathematical formulations and models) used to reflect this aspect of the problem influences the resolving of the problem itself. Regarding this aspect, the works within the ARNO model are generally non-unified since they include special properties of radio wave propagation when computing the strength field, like the vertical and horizontal patterns' radiation. In real life, these kinds of patterns are provided by manufacturers and computed through complex equations. Thus, no two antennas are having the same pattern of radiation. For this reason, it is impossible to find two works treating the ARNO model and using the same type of antennas.

Apparently, a major lack of benchmarking (e.g. problem's instance, mathematical formulation of the problem, vertical and horizontal radiation patterns, type of antenna, radio wave propagation model, etc.) is noticed within the ARNO model. All of these facts make the comparison between the proposed algorithms very difficult. Unlike the first model, the STORMS' one has a unified formulation of the objectives (mathematically speaking) which makes the comparison between the devised algorithms easier and more constructive than the first one.

E. Reliability and Extensibility

The fifth shortfall of the ARNO model is that it was specifically formulated and modelled (e.g. objectives, constraints, etc.) for the second generation of cellular networks. So, any use of this model for optimising the antennas' positions in advanced networks (e.g. 3G, LTE, 5G, 6G and beyond) can be hard or even incorrect. This is because next-generation networks have different objectives and constraints to fulfil. Unlike the ARNO model, the STORMS one is high-level-designed. Indeed, it considers objectives that are generation-independent, which facilitates its use in other advanced networks. Like the first model, the second one has some drawbacks too, which are explained in the following section.

F. Problem Modelling

The main drawback of STORMS model is the lack of modelling. In fact, even though it is still practical, it remains not rich as the ARNO model. This is because it encompasses few objectives and no constraints. Indeed, unlike the ARNO model that includes a very large set of objectives and constraints that made it closer to the reality. Table I summarises the main differences and similarities between STORMS and ARNO models.

TABLE I
PROBLEM MODELLING: STORMS VS ARNO MODELS

Metrics \ Models	STORMS Project	ARNO Project
Type of Formulation	Mono-objective	Constrained multi-objective
Objectives	Coverage	Coverage
		Handover
		Interference
	Number of used sites	Number of used sites
		Traffic
		One component
		Cell shape factor
		Cost
Constraints	None	Same as the objectives
Working Area	Discretised grid	Discretised grid
Area Entity	Candidate Sites (CS)	Candidate Sites (CS)
		Receiving Test Points (RTP)
		Service Test Points (STP)
		Traffic Test Points (TTP)
Wave Propagation	Squared antenna	Okumura-Hata propagation model
	Omnidirectional antenna	Walfish-Ikagami propagation model
	Directive antenna	Free-space propagation model
Mathematical Formulation	Unified	Not-unified
Technical Formulation	Unified	Not-unified
Complexity	2^n	see: [72, 73]
Computational Cost	Acceptable	Highly computational
Benchmark Instances	Unified	Not-unified

VI. Towards a New Coverage Optimisation Model

Based on the above-stated analysis and the comparisons of the APP's existing models, this section sketches the main features of what could be a more *correct*, *realistic* and *encompassing* model for solving the APP. First, the new model has to find a *balance between simplicity and complexity*. Indeed, the model has to be enough simple to be solved in real-time considering the technological advances and enough sophisticated to encompass real-life constraints and objectives. Secondly, the new model has to be *generation-independent* to include even 6G and beyond. Actually, several technologies and generations of cellular networks are cohabiting to create the current highly-heterogeneous worldwide coverage. So, to increase the use of the proposed model, it has to be applicable to any cellular network technology or generation. For example, frequency assignment constraints in 2G and cell breathing issues in 3G can be simplified or neglected. Finally, the new APP's model needs to be formulated as a *dynamic* problem. Indeed, cellular networks are very dynamic environments where the communications' traffic load changes constantly. Thus, modelling the coverage problem without considering this constraint will lead to proposing methods able to solve it at period t but not at period (t+1) when the load changes. This will result in designing 3G networks suffering from cell breathing [95] or non-self-organised LTE networks unable to manage load balancing (see Fig. 4).

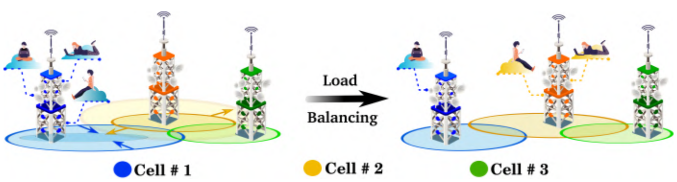

Fig. 4. Load balancing in APP's dynamic model

VII. Conclusion and Research Perspectives

Cellular networks' design is a highly challenging and quality-determining task where the coverage optimisation is one of the most critical problems. The latter is proved to be NP-hard which led to proposing several scattered and non-unified models and algorithms to solve it. This models' heterogeneity makes it difficult to link or compare works and algorithms to one another to build thoughtful knowledge. To cope with these pitfalls, in this paper, a survey on the coverage problem has been conducted for the first time. This work analyses 80 works using 6 comparison metrics to (I) create a clear and exhaustive repository for coverage optimisation models, (II) deal with the models' normalisation issues that exist, (III) draw the main features of a new unified coverage optimisation model and (IV) open new research perspectives in this axis.

As perspectives, it is planned to extend this survey by including more mathematical details of the formulations of both ARNO and STORMS models. Also, it is intended to provide complete mathematical details of the new APP's model as well as thoroughly evaluating it.

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