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Optimal relay placement in multi-hop wireless networks

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ABSTRACT

Relay node placement in wireless environments is a research topic recurrently studied in the specialized literature. A variety of network performance goals, such as coverage, data rate and network lifetime, are considered as criteria to lead the placement of the nodes. In this work, a new relay placement approach to maximize network connectivity in a multi-hop wireless network is presented. Here, connectivity is defined as a combination of inter-node reachability and network throughput. The nodes are placed following a two-step procedure: (i) initial distribution, and (ii) solution selection. Additionally, a third stage for placement optimization is optionally proposed to maximize throughput. This tries to be a general approach for placement, and several initialization, selection and optimization algorithms can be used in each of the steps. For experimentation purposes, a leave-one-out selection procedure and a PSO related optimization algorithm are employed and evaluated for second and third stages, respectively. Other node placement solutions available in the literature are compared with the proposed one in realistic simulated scenarios. The results obtained through the properly devised experiments show the improvements achieved by the proposed approach.

1. Introduction

The topic of node placement in network environments has been recurrently addressed in the literature mainly aimed at defining the best communication infrastructure. Additionally, node placement is being increasingly used in fault-tolerant strategies for which the state of the network is monitored over the time and, in case of failure or misbehavior, the nodes are repositioned to recover the performance [1,2]. The repositioning process may be restricted to a subset of the nodes of the network that operate as relaying devices (i.e., relay nodes or RNs) to allow multi-hop origin-destination routes.

A number of proposals of node placement are based on the optimization of different performance goals [3]: coverage, data rate, load balancing, connectivity, cost, etc. This task becomes even more critical for wireless communications, since additional aspects such as propagation effects and interferences should be considered in deployments [4]. Besides, in wireless sensor networks (WSNs) new requirements appear [5,6], such as latency and lifetime, among others.

To find the best node positions some optimization algorithm has to be executed. There is a great variety of such algorithms, from graph or polynomial time-based techniques [7,8] to bio-inspired algorithms such as genetic algorithms [9], or those based on the *swarm intelligence* paradigm [10]. To the best of our knowledge, only a few works exist where network throughput and connectivity are jointly considered to optimize the placement of RNs [11].

Almost all relay node placement solutions can be grouped in two categories [12]: constrained- and unconstrained-based strategies. On the one hand, constrained-based strategies offer a solution restricted to certain parameters. As aforementioned, some examples of this are network lifetime preservation, coverage, delay or simply solutions restricting the location of the RNs to certain specific regions. On the other hand, unconstrained-based strategies are mainly intended to meet more general purposes like fault-tolerant and/or network connectivity without any precise constraint. The specific method should be previously studied, since both types of strategies have advantages and disadvantages.

The present paper introduces a new placement approach to maximize throughput and inter-node reachability in a multi-hop wireless network by providing and hybrid optimization approach that combines the advantages of constrained and unconstrained based approaches. The proposal relies on splitting the overall problem into a number of steps: (i) initial distribution of the RNs, and (ii) a solution selection. Additionally, a third step aimed at

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subsequently estimating the optimal locations, can be optionally launched. Leave-one-out (LOO) and particle swarm optimization (PSO) algorithms are implemented here at the solution selection and placement optimization stages, respectively. This multi-stage placement procedure provides more versatile and scalable solutions, as it will be shown through experimentation.

In summary, the main contributions of this work are:

- An efficient RN placement procedure for multi-hop wireless networks based on the joint optimization of inter-node reachability and network throughput.
- A novel optimization formulation to maximize this global two-criteria performance goal. This will result in the improvement of the overall connectivity of the network.
- A multi-stage procedure to divide the overall problem into more elemental subsequent steps.

The rest of the paper is organized as follows. Section 2 presents several principal works in the field of node placement in wireless networks. Section 3 outlines the general assumptions under which the RN placement approach is developed, while its details are presented in Section 4. After that, Section 5 is devoted to describe the experimental framework used to evaluate the proposal, from which the results obtained are compared with other solutions in the literature, and carefully analyzed afterwards in Section 6. The proposal is also briefly discussed from the perspective of some open challenges to be addressed in further work in Section 7. Finally, Section 8 presents the main conclusions of the work. We also include an Appendix to introduce the *swarm intelligence* fundamentals and describe the PSO algorithm.

2. Related work

Strategies developed to position nodes in a wireless network can be grouped in two categories: constrained- and unconstrained-based strategies. On the one hand, constrained-based strategies offer a solution restricted to certain parameters. Some examples of them are network lifetime preservation, coverage, delay or simply solutions restricting the location of the RNs to some specific regions. On the other hand, unconstrained-based strategies are mainly intended to meet more general purposes like fault-tolerant and/or network connectivity without any precise constraint.

Most of the unconstrained-based RN placement strategies present a common objective: to provide a k-connected network by using the minimum number of RNs. To accomplish with fault tolerance goals, the k parameter must be greater than or equal to 2. Otherwise, if $k = 1$ the network connectivity from the perspective of the inter-node reachability is contemplated. In this category a variety of works ([13–19], among others) can be found. For example, in [13] the authors address single- and two-tiered 1-connected solutions aimed at minimizing the number of RNs deployed. They provide 7-approximation and $(5+\epsilon)$-approximation algorithms for facing the previous purposes, respectively. The same authors in [14] extend this work by designing a 2-connected approximation algorithm also for single- and two-tiered approaches. K-connected networks are proposed in [15] for any desired k as well. The authors demonstrate that whatever the selected k parameter is, they can reach a polynomial based approximation solution. A similar approach is introduced in [17] where the authors are able to locate the minimum number of RNs getting a k-connected network. The proposed heuristic improves the previous one by applying a simple selection step to remove some RNs while the k-connectedness is preserved. In [16], the objective is to provide fault tolerance in heterogeneous WSNs, where sensors posse different transmission radii. They develop a $k \geq 1$ connected approximation solution taking into account the desired degree of fault tolerance (full- or partial-fault resiliency) and the communication flows (one- or two-ways).

Some of the most relevant placement solutions relying on constrained strategies are those in [12,20–30]. Some of them try to find (i) the number of relay nodes to minimize the network cost ([20–23]), (ii) the minimum number of relay nodes to achieve a fully connected network or a two-tiered network ([12,24,25,28–30]), or (iii) the minimum number of relay nodes to reduce the delay in the communications ([26] and [27]).

Authors in [20] determine the number and deployment of heterogeneous devices, so that the total network cost is minimized while constraints regarding lifetime, coverage and connectivity are satisfied. The work has been further extended in [21–23] to address the problem of deploying a second-tier of RNs to balance the traffic by using the least number of additional RNs.

A number of works propose placement approaches to maximize connectivity. In [24], the authors try to place the lowest number of RNs in the playing field of a sensor network in such a way that each sensor node can communicate with at least one RN, and the network of RNs is completely connected. This objective is achieved by means of two optimization problems: a connected relay node single cover (CRNSC) problem, and a 2-connected relay node double cover (2CRNDC) problem, and in both of them only certain available locations instead of the whole XY plane are considered. Authors in [28] try to place the minimum number of relay sensors to maintain global connectivity restricting the locations of the relay nodes using the minimum Steiner tree with minimum number of Steiner points. Similar idea is implemented in [29] for restoring the connectivity lost. They iteratively select those Steiner points connecting at least three network partitions until the Steiner tree has less than three points. After that, they locate the RNs on the line from each partitions to its closest Steiner point. A connectivity and energy constrained efficient approach for relay placement in WSNs is proposed in [30], where the relay nodes can only be placed at some pre-specified candidate locations. To provide survivability, the goal is to form a 2-connected network. References [12,25] discuss similar approaches.

Authors in [26] (an improved version of [27]) design a multi-hop wireless mesh network with minimum number of additional RNs to facilitate wireless-communication between each of the sensor nodes and the base station. The placement of the relays should ensure that the delay on the paths between the base station and the sensors meet a pre-specified delay bound. Authors study the structure of the projection polyhedron of the problem and develop node-cut inequalities. A branch-and-cut algorithm is defined based upon the projection formulation to solve delay constrained RN placement problem (DCRNPP) optimally.

Beyond the specific metrics chosen to be optimized, the optimization algorithm itself considered to determine the best position of nodes can vary. Some examples come from those based on graph- or polynomial time techniques [7,8] to others bio-inspired, among several others. A bi-objective (user coverage and network connectivity) genetic-based optimization algorithm is considered in [9] for node placement in wireless mesh networks. In [31], a PSO algorithm is proposed to determine the best placement of nodes in industrial environments in terms of network reliability, load uniformity, total cost and convergence speed. For sensing coverage purposes in WSNs, the authors in [32] propose a PSO-based solution for minimizing the existing coverage holes through the use of a fitness function based on the computation of Voronoi regions. A modified PSO-based proposal is also used in [10] to address the sink placement problem in WSNs by minimizing the worst case delay path in the network. A minimax scheme is developed in [33] to optimize coverage ratio and uniformity. On the other hand, authors in [34] propose an algorithm that emulates the attractive force (as in a stretched spring) and the repulsive force (as the electrostatic