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Novel relay node placement algorithms for establishing connected topologies

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ABSTRACT

This paper addresses the problem of placing the least number of fixed-range relay nodes (RNs) in order to establish multi-hop paths between every pair of terminals. We derive an optimal solution for the case of three terminals and for the cases of more than 3 terminals, we present three novel heuristics, namely, Optimized Triangle Selection based on Minimum Spanning Tree Triangulation (OTS-MST), Incremental Optimization based on Delaunay Triangulation (IO-DT) and hybrid approach. These heuristics take advantage of the optimal three-terminal based solution by forming connected sub-graphs for steinerized sets of three terminals and then connecting these sub-graphs via steinerized edges. OTS-MST considers triangles that have two mst edges and picks the subset of these triangles which provides the highest reduction in the total number of required RNs as compared to a solution that is based on steinerized mst edges. IO-DT calculates the Delaunay triangulation of terminals and iterates over the formed triangles. In each iteration, the algorithm steinerizes a triangle as part of the final topology if selecting such a triangle reduces the RN count. Finally we consider a hybrid approach, which combines the strengths of OTS-MST and IO-DT. The performance of the proposed algorithms is validated through simulation.

1. Introduction

There has been a massive growth in the use of networked devices in civil, scientific and military applications in recent years. In some of these applications need arises to interconnect a set of terminals to serve a certain mission while avoiding major infrastructure investment. An example is when multiple data sources or standalone networks need to be federated in order to aggregate their services and efficiently handle emerging events such as search and rescue, disaster management, and criminal hunting. The federation is often enabled by placing relays that form paths between these sources/networks. Another example is when a wireless sensor network (WSN) gets partitioned due to a breakdown or damage of a subset of its nodes. WSNs often serve in inhospitable environments which make nodes susceptible to failure, e.g., due to detonation of explosives in a battle field and natural calamities (Akyildiz et al., 2002). The failed nodes may cause the WSN to be split into disjoint segments. Restoring connectivity among these WSN segments would be necessary for the network to become operational again. Deploying relay nodes (RNs) is the most popular approach (Younis et al., 2012, 2014) for repairing the network topology. Given the limited accessibility, the least resources should be used/employed.

On the other hand, many applications serve in controlled setups in which deterministic positioning of nodes is pursued to meet the design requirements and provide the desired quality of service (Younis and Akkaya, 2008). Examples of these applications include security surveillance, habitat monitoring, safety assessment of factory floor, and hazard detection in urban area. The controlled nature of the application allows pre-planning and careful selection of where to place nodes and how they may communicate. Usually area or landmark coverage is the main criterion for determining where sensor nodes should be. For establishing connectivity, relay nodes (RNs) are deployed to ensure that data can be shared. Determining the number and the position of RNs in the aforementioned application scenarios is usually subject to optimization. The application designer often likes to employ the least RNs to achieve the desired connectivity goal. In addition, the positioning of these RNs should establish, possibly, a multi-hop path between the terminals, e.g., data sources or network segments, subject to communication range constraints. Our problem can be thus formally defined as follows: "Given n disjoint WSN segments what are minimum number and position of the relay nodes for establishing inter-segment connectivity?". This problem is equivalent to the Steiner Minimum Tree with Minimal Steiner Points and

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Bounded Edge-Length (SMT-MSPBEL), which is shown to be NP-Hard by Lin and Xue (1999).

A number of heuristics have been proposed in the literature for solving the SMT-MSPBEL problem. Some of these heuristics focus on reducing the number of RNs and form a minimum spanning tree (*mst*), where the node degree of the individual RNs is two (Cheng et al., 2008; Lloyd and Xue, 2007; Lin and Xue, 1999). Meanwhile, the focus of other work has been on the degree of connectivity of the formed WSN topology with less emphasis on the RN count (Lee and Younis, 2010; Senel et al., 2011). In this paper we present an algorithm which finds the least RN count for forming SMT-MSPBEL for the special case of three terminals (i.e., a triangle) by either (1) populating the RNs along *mst* edges, i.e. two sides of the triangle, with a distance of R units apart, where R is the communication range of RNs, or (2) finding a point x inside the triangle, which we call Discrete Fermat Point, and connecting the vertices of the triangle to x. Next we study the generalized problem for the case of n terminals and present three novel algorithms, namely Optimized Triangle Selection based on *mst* triangulation (OTS-MST), Incremental Optimization based on Delaunay Triangulation (IO-DT) and a hybrid heuristic. These algorithms opt to minimize the required RN count and vary in the solution quality and runtime complexities.

The main idea behind the proposed algorithms is to optimally solve the SMT-MSPBEL problem for the case of three terminals and try to find the minimal RN count for larger networks using subsets of three terminals. OTS-MST finds the *mst* of the terminals and identifies the set of triangles which contains two *mst* edges. The algorithm then finds adjacent triangles (i.e. the triangles sharing one *mst* edge) and forms a graph of triangles called Triangular Adjacency Graph (TAG) whose vertices represent triangles and edges denote adjacency relationships. Using TAG, the OTS-MST algorithm finds the best subset of non-adjacent triangles which provides the highest reduction in the total number of required relays as compared to an *mst*-based solution. The runtime complexity of OTS-MST is $O(n^2)$. Meanwhile, the IO-DT algorithm calculates the Delaunay triangulation (DT) of terminals and iterates over the formed triangles with the time complexity of $O(n^2)$. In each iteration, the algorithm steinerizes a triangle, i.e., form a Steiner tree of 3 vertices, as part of the final topology if selecting such a triangle provides a reduction in the total number of required relays as compared to an *mst*-based solution. Unlike OTS-MST, IO-DT does not restrict itself to triangles having two *mst* edges. The third algorithm is a hybrid heuristic that combines the strengths of both OTS-MST and IO-DT. The performance of all three heuristics is also validated through simulation and is shown to exceed contemporary heuristics in the literature.

The next section discusses related work. Section 3 describes the optimal solution for three terminals. Sections 5 and 6 describe the OTS-MST, IO-DT and hybrid approaches in detail, respectively. The runtime complexity and performance of the algorithms are analyzed in Section 7. Section 8 presents the simulation results. Finally, Section 9 concludes the paper.

2. Related work

The goal of the proposed algorithms is to place the minimum number of RNs in such a way that there exists a path between every pair of terminals and each hop in the path is less than or equal to the transmission range of the individual nodes. As we mentioned, this problem is shown to be NP-Hard by Lin and Xue (1999). They have further presented a polynomial time approximation algorithm that deploys RNs along the *mst* edges of terminals. The algorithm first constructs the complete graph of terminals and forms *mst* using Kruskal's algorithm. RNs are populated along the tree edges at a distance of at most R apart, where R is the communication range of RNs. In Chen et al. (2001), the authors proved that the algorithm yields a solution that is at most 4 times as much as the optimal value. In Cheng et al. (2008), the authors employ a three-step heuristic. In the first step, they connect the nodes where the distance between the nodes is less than or equal to R. In the second step, 3-stars are formed for each subset of three nodes u, v, w, for which there exists a point s such that s is at most R units away from u, v, and w. Assuming that $\overline{uv}$ and $\overline{uw}$ are *mst* edges, a 3-star modifies the *mst* by replacing $\overline{uv}$ and $\overline{uw}$ with $\overline{su}$, $\overline{sv}$ and $\overline{sw}$. In the last step the algorithm populates RNs along modified *mst* edges that are not substituted with 3-stars. In Cheng et al. (2008), the authors also presented a randomized algorithm that yields better results, yet it has 50% probability of convergence. A randomized algorithm does not necessarily guarantee the solution consistently. In this paper, we focus on the same problem studied in Lin and Xue (1999), Cheng et al. (2008), and Chen et al. (2001). Unlike these publications, the proposed algorithms strive to find a subset of triangles and form triangular Steiner trees by connecting the vertices of each triangle at a point inside the triangle which will be called as Discrete Fermat Point. As we validate through simulation, the proposed algorithms significantly outperform those of Lin and Xue (1999), Cheng et al. (2008), and Chen et al. (2001). In Senel and Younis (2011), we have studied the problem in the context of federating disjoint network segments and presented an algorithm called FeSTA with $O(n^4)$ runtime complexity. The algorithm iterates over all possible triangles and greedily selects triangles to apply Discrete Fermat Point optimization. The algorithms proposed in this paper, namely OTS-MST, IO-DT and Hybrid, are significantly less complex than FeSTA. A preliminary version of IO-DT algorithm was reported in Senel and Younis (2012). This paper presents an additional scheme and extend IO-DT.

The focus of Lee and Younis (2010) and Senel et al. (2011) is on a variant of the SMT-MSPBEL problem where additional metric is to be optimized. In Lee and Younis (2010), Lee and Younis strive to connect the terminals inward so that the inter-terminal topology has a high node degree. They have proposed an algorithm called CORP that models the deployment area as equal-sized grid cells. CORP has two phases. In the first phase, the algorithm iteratively identifies border terminals and determines the best cell for deploying an RN based on the distance between the farthest terminals (or RN) from the centroid. The cells connecting multiple terminals are called junction cells. In the second phase, after all terminals are connected, the algorithm prunes redundant RNs. In Senel et al. (2011) a bio-inspired heuristic called SpiderWeb has been proposed to form topologies that not only exhibit stronger connectivity but also achieve better sensor coverage and enable balanced distribution of traffic load on the employed relays. Unlike these algorithms, minimizing the number of RNs is the main objective in this paper.

In addition to establishing connected topologies, relay node placement has been studied for improving the performance in terms of other metrics (Younis and Akkaya, 2008). Network lifetime has received the most attention among them. Depending on the transmission media, energy consumption for transmitting data is directly proportional to d^j where d is the distance and $j \geq 2$ (Lloyd and Xue, 2007). Due to this fact, long distance data transmission is very costly and stabling multi-RN paths is advantageous. In Efrat et al. (2008) the authors have studied this problem for both single-tiered and two-tiered WSN architectures. In single-tiered architectures, sensors transmit their own messages and also forward messages from other nodes. Meanwhile in two-tiered architectures nodes transmit only their own messages to a relay node or the base-station. Distinct polynomial-time approximation RN placement algorithms for one- and two-tiered architectures have been developed by modeling the network as a unit disc graph