Application of Component-Based Localization in Sparse Wireless Networks

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Abstract—Localization is crucial for wireless ad hoc and sensor networks. As the distance-measurement ranges are often less than the communication ranges for many ranging systems, most communication-dense wireless networks are localization-sparse. Consequently, existing algorithms fail to provide accurate localization supports. In order to address this issue, by introducing the concept of component, we group nodes into components so that nodes are able to better share ranging and anchor knowledge. Operating on the granularity of components, our design, CALL, relaxes two essential restrictions in localization: the node ordering and the anchor distribution. Compared to previous designs, CALL is proven to be able to locate the same number of nodes using the least information. We evaluate the effectiveness of CALL through extensive simulations. The results show that CALL locates 90% nodes in a network with average degree 7.5 and 5% anchors, which outperforms the state-of-the-art design Sweeps by about 40%. Index Terms—Component-based, finite mergence, localization, node-based, ranging-model-based estimation (RMBE).

INTRODUCTION

LOCATION in wireless networks is critical for both network operation and data interpretation [1]. Practically, it is difficult to equip each node with a positioning device. Instead, only a few nodes, called anchors, know their locations. Other nodes estimate their locations through internode measurements from the anchors. Most existing localization algorithms require the network have a high density and sufficient number of anchors before computing node locations. Localization in sparse networks with a few anchors is not fully addressed [2]. Indeed, a sparse network for localization is often dense in communication, as the distance-measurement ranges are typically much less than that of communication range for many ranging systems [3]. Eren et al. [4], [5] investigate the theoretical conditions for localization in general networks. They show that a network can be uniquely localized if and only if its corresponding grounded graph [4] fulfills the following three conditions: 1) redundantly rigid; 2) triconnected; and 3) having three anchors embedded, denoted as RRT-3B [5]. For a partially localizable network, RRT-3B can identify most localizable nodes by recursively partitioning the network into globally rigid parts [5]. Thus, the RRT-3B becomes a criterion to evaluate the
performance of localization algorithms. To the best of our knowledge, there is no scheme that can explicitly achieve the amount of localizable nodes under RRT-3B conditions. The state-of-the-art algorithm of approaching to the capacity of RRT-3B is Sweeps [2]. Sweeps utilizes the concept of finite localization to relax the node participating conditions from trilateration to bilateration. Due to its dependence on each single node to estimate the localizability locally, however, Sweeps is subject to the restriction on the anchor distribution. If no node can find at least two anchors among its direct neighborhood, the algorithm cannot be initialized. Also, Sweeps requires that the network have a bilateration ordering, which is not always true in sparse networks. Indeed, a localizable network is not necessarily to be a bilateration network, thus Sweeps often fails in many actually localizable networks [2], [6]. Such limitations result in more serious consequences in localization-sparse networks. Major contributions of this work are as follows. 1) We introduce the concept of component and present a component-based algorithm, CALL, which improves the success ratio of localization in sparse networks. 2) We propose a mechanism called finite mergence to stitch components. Furthermore, we form the basic anchor requirement conditions to realize components. These mechanisms serve as the basis of this design. 3) By exploiting the ranging-model-based estimation (RMBE) schemes, we reduce the states maintained at each node and make more nodes localizable, i.e., 20% in average, even though some of them do not follow the RRT-3B condition. 4) We propose a new metric, least information requirement (LIR), to analyze the performance of existing localization algorithms. We show our CALL achieves the best result as yet under the LIR criterion.

RELATED WORK Many studies have focused on localization in wireless and ad hoc networks [7], mainly falling into two categories: range-based [2], [8] and range-free [1], [11]. Range-free designs do not rely on measurement hardware, but normally require high network density [1]. This work focuses more on range-based designs for sparse networks, so we discuss the classical range-based algorithms that address the network or anchor sparseness problem. Savarese et al. [12] propose a virtual-coordinate-based algorithm TERRAIN to address the sparse anchor problem. TERRAIN constructs a virtual coordinate system on each anchor and takes the advantage of the property that the virtual coordinate holds the distance information between each node pair. The essential principle used by TERRAIN is trilateration. By using virtual coordinates on each anchor, TERRAIN extends the ranging distance of anchors and makes each node triangulate to the enlarged anchors.

![Fig. 1. Example of component-based localization. (a) Distance graph (b) Component generation. (c) Component mergence. (d) Component realization.](image)

Before introducing the details of our component-based localization algorithm, we further explain the concept of components using an example. We show the distance graph of a network in Fig. 1(a), where the squares denote anchors and the circles represent nonanchor nodes. If we adopt node-based algorithms, we cannot localize any node in this network, as there is no single node that can obtain enough (at least two) distance measurements to the anchors.
CALL inserts an extra substep in each of the above operations to check the consistency of the potential position sets. During each mergence or realization, CALL enumerates all candidate positions of each node in its potential position set. Not all of the combinations of the candidate positions can generate valid results under the distance constraints. We say an item is incompatible if no result can be obtained by this candidate position. After mergence or realization, nodes will prune the incompatible items in the potential position sets. There are two steps to prune incompatible items. First, the reference nodes associated with the interconnected edges can identify their incompatible items after the mergence or realization. Second, if a node has pruned some incompatible items, it will broadcast an update message to its neighbors to inform the deleted items. The node that receives the update message will then check the consistency of the potential position set and prune their incompatible items. By iteratively pruning the incompatible items, the potential position sets of all nodes will eventually be consistent with each other. This mechanism guarantees that the consistency check can prune all the incompatible items of the nodes in the same component. We say a node or a node set is finalized if the size of its potential position set is reduced to one. Finally, all nodes belonging to the realized components are localized. By the items in the potential position set, we can directly determine whether a node is uniquely localized. In Section IV, we will show the rationale of the mergence and the realization. Unfortunately, this procedure cannot guarantee to terminate in polynomial time because the potential position set may grow exponentially in the worst case.

Theorem 4 (Realization for CALL): A component can be realized to finite states by fulfilling at least one of following conditions.

a) The component contains at least two anchors.

b) The component contains one anchor and a nonanchor node sharing an edge with a realized node.

c) There are at least three edges connecting the component with at least two distinct realized nodes, and there are at least two vertices associated with these edges in the component.

Corollary 1 (Realization for BCALL): A globally rigid component can be uniquely realized by containing three distinct vertices fulfilling one of the following conditions.

a) They are three anchors.

b) They are two anchors and a nonanchor node sharing an edge with a realized node.

c) They are one anchor and two distinct nonanchor nodes sharing two edges with two distinct realized nodes.

d) There are at least four independent edges connecting them with at least three distinct realized nodes.
CONCLUSION

We propose the concept of components as well as a component-based approach, CALL, to address the localization issue in sparse wireless ad hoc and sensor networks. We form basic rules for operations on components and design RMBE to further improve the performance of this approach. Theoretical analysis and simulation results show that this design significantly outperforms previous approaches. Future work leads into three directions. First, we will extend this design to generate robust results with noisy distance measurements. Second, we are going to investigate the theoretical bound of localizability using polynomial spatial-temporal cost. Lastly, we will apply our design in our ongoing system, GreenObs, and further examine its applicability in the real system.

REFERENCES


