Faster Distributed Localization of Large Numbers of Nodes Using Clustering

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***Abstract*—Chirp Spread Spectrum (CSS) based localization techniques are becoming more attractive as they provide improved localization accuracy and robustness compared to WiFi or ZigBee based approaches. However, a remaining problem is the necessary update frequency: In existing CSS based localization systems, the positions of the objects are determined one by one via unicast with nearby anchors instead of using broadcasts. We propose a faster distributed localization scheme for CSS based systems. A portion of nodes are considered cluster heads; they determine the locations of un-localized nodes by dynamically increasing the transmission power. Our novel scheme not only fully utilizes the spatial redundancy, which is crucial for speeding up the localization process. By also allowing to establish new anchors in a two-hop range, we can further increase speed without significantly influencing localization error. The performance of the proposed method is demonstrated through simulation.**

I. Introduction

Although different types of localization systems have been designed and widely deployed in many civilian and military applications, many of them only provide *coarse grained* localization information in a reliable manner. For example, most GPS receivers have an accuracy of about 15 meters [1]. On the other hand, the Received Signal Strength (RSS) of radio transmissions, e.g., using WiFi [2], cellular [3], Zigbee [4], or FM radio [5], is quite sensitive to environmental variations. Thus, such RSS based approaches can achieve reliable accuracy only on room or floor level.

Today, we are facing an increasing number of applications that require *fine grained* localization information. For example, to prevent accidents in a construction site it is usually necessary to continuously monitor both workers and moving objects such as construction hoists and tower cranes ('falling from height' and 'striking against moving objects' are the top reasons for fatalities in constructions areas). In the literature, the tolerable localization error in such scenarios is given as approximately one meter [6].

To achieve fine grained localization results, it is generally a prerequisite to provide accurate and reliable ranging information. Many localization techniques have been proposed in the literature based on central controllers [7], [8] or based on site surveys and fingerprinting [9].

The drawbacks of such approaches are obvious: they require considerable time and resources for the setup and maintenance. Thus, they are infeasible in continuously changing environments. This motivated the development of new, fully distributed localization techniques [10]–[12]. Among others, Chirp Spread Spectrum (CSS) has been identified as a promising basis for ranging techniques [13]. Nanotron proposed and implemented CSS in their nanoLOC devices [14], which are used in academia and industry [15]. These CSS based nodes adopt an extended Time of Flight (ToF) ranging method called Symmetric Double Sided Two Way Ranging (SDS-TWR) [16], in which a chirp pulse is sent from one node followed by an acknowledgment sent back from another node.

CSS based nodes can achieve a reasonable accuracy for ranging measurements (better than 0.5 m in most cases [15]), even in challenging environments. In general, using CSS for localization has many advantages. First, due to the wide bandwidth of CSS, the ranging result of CSS based nodes is highly robust against obstacles, interferences, and multi-path effects and can achieve much higher ranging accuracy than the RSS based methods. Secondly, a site survey, which is typically the most time consuming and labor intensive task in localization systems using fingerprints, is no longer required.

However, one problem of using CSS based techniques for localization is their comparatively low update frequency. The main reason is that the ranging process (i.e., SDS-TWR) can only be accomplished by one-to-one communication between each pair of nodes. Unlike those using WiFi or Zigbee, it is not possible for multiple CSS based nodes to simultaneously determine their distances to another CSS based node if the latter broadcasts a signal. As a result, given a large number of CSS based nodes whose locations are to be determined, it may take a long period of time to complete one round of the localization process.

In this paper, we present our preliminary work on improving CSS based localization systems using clustering. In this scheme, a portion of nodes which have already been localized can be used to further help localizing other nodes. They determine the locations of the un-localized nodes by dynamically increasing the transmission power. This scheme not only can fully utilize the spatial redundancy, which is crucial for speeding

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up the localization process, but also control the localization error, which usually accumulates in the approaches where successfully localized nodes are used to localize other nodes. The performance of the proposed method is demonstrated through simulation.

II. Basic Localization & SDS-TWR

Classic Symmetric Double Sided Two Way Ranging (SDS-TWR) divides nodes into two classes: *anchors* (nodes with known position) and *tags* (nodes with yet unknown position). For a 2D coordinate system, three different measurements of three distinct anchors are necessary, to get an unique solution in the trilateration process [10]. The basic operation of SDS-TWR is that an anchor starts the measurement and sends the result (i.e., a distance) to the tag. After a tag received three distinct measurements, it performs the position calculation using trilateration. It has to be noted that every distance measurement produces some error caused by the characteristics of wireless transmissions; therefore the calculated position is not exact. To announce the presence of non-localized tags, Hello messages are broadcasted by every tag continuously with random time intervals. We name this default scheme, where every tag gets localized one by another, *one-by-one*.

Since each anchor can only perform one distance measurement at a time, the localization of a large amount of nodes does not scale well. Building up upon the fact that all nodes have the same capabilities, a more scalable concept has been proposed: Dynamically turning a successfully localized tag into a new anchor intuitively increases the localization speed, but this may substantially impact the positioning accuracy. We name this scheme *tag-tag*.

Our *clustering* approach is based on the mentioned concepts, but helps keeping accuracy high while speeding up the localization.

III. Cluster Based Localization Extension

In our *clustering* approach, we take advantage of variable transmission powers for the ranging process. This allows to create several clusters that, ideally, do not interfere with each other. These clusters can perform the ranging process in parallel and drastically speed up the overall localization time. To increase the localization accuracy compared to the *tag-tag* approach, each tag gets ranged over two hops at most.

In our system, we define an additional node type called *cluster heads*. Cluster heads use a reduced TX-Power, therefore increasing the spatial reuse of the wireless frequencies. This way packet collisions (and, thus, backoff times) are reduced, which further speeds up the overall localization. Our approach takes advantage of power ramping, which starts with a low transmission power, and increases it step-wise if every node within the communication range has been successfully localized. For the cluster head selection, we randomly select some nodes of all available tags according to some probability. Implementing this selection scheme on a sensor node corresponds to a simple dice roll, performed on power up. The model therefore introduces two new node types, *cluster heads* and *initial anchors*.

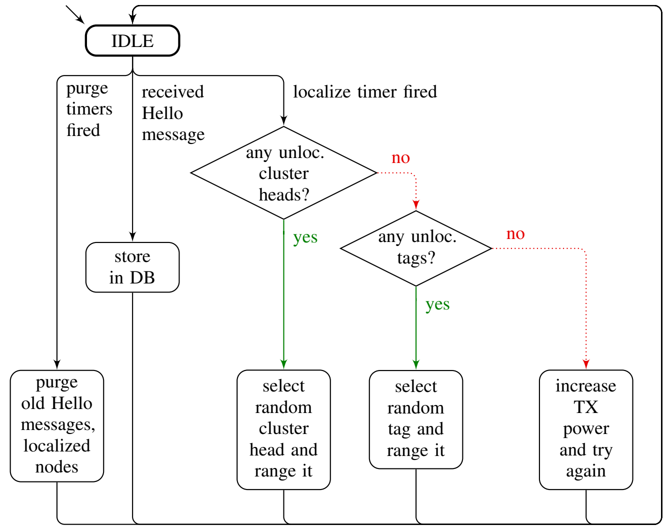

Fig. 1. Flow chart of initial anchors: these pre-configured anchors are responsible for locating first the cluster heads, then any tag.

Cluster heads are a hybrid version of tags and anchors: they start operation as tags and become anchors after they have been localized. Initial anchors, which are pre-configured, first range cluster heads, as shown in Figure 1. After all cluster heads have been localized, (i.e., the full transmission power has been reached), initial anchors can also range other tags. Hello messages are only sent by un-localized nodes, if triggered by initial anchors or cluster heads, respectively.

IV. Simulation Study

We evaluate all the three approaches using the network simulator OMNeT++ together with the MiXiM framework for modeling lower layer wireless communication. The underlying wireless communication consists of an IEEE 802.15.4a MAC and PHY layer, where CSMA/CA is used for channel access. The nanoLOC nodes use CSS, which is one of the two available modulation schemes in IEEE 802.15.4a. In our simulation model, we use an Ultra Wideband (UWB) PHY and adopted it to the requirements of the nanoLOC hardware. We have chosen a maximum TX-Power of 4000 mW in the 2.4 GHz ISM-band which allows all nodes to be within communication range.

Our simulation scenario (cf. Figure 2) consists of 3 anchor nodes, which we place in the top left corner and 301 tags, which are distributed randomly within a 2D area of 2 km $\times$ 2 km. For the localization process, we use a probability of 0.1 for a tag to be a cluster head, 400 power ramping steps, and one-way ranging only.

We investigate each of the three approaches *one-by-one*, *tag-tag*, and *clustering*, reporting on three metrics:

- localization time (i.e., the time from the beginning of the simulation until the node has been successfully localized);
- localization hop count, to model position inaccuracies;
- backoff time of each node, as an indicator for the wireless channel utilization.

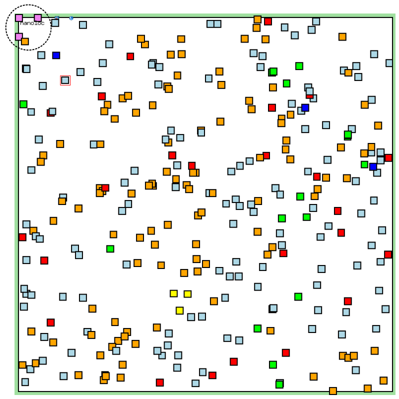

Fig. 2. Screenshot of a running simulation. Three anchor nodes are located in the top left corner, 100 m apart. Selected cluster heads are shown in red.

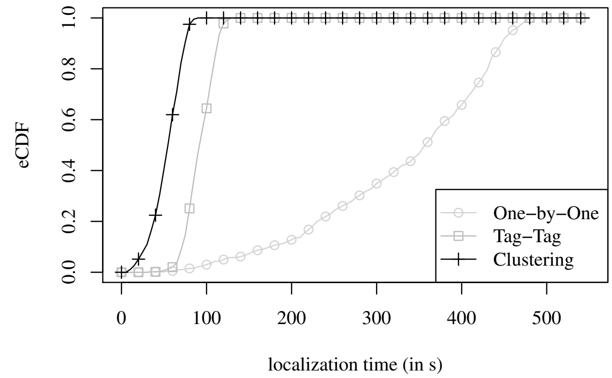

Fig. 3. Comparison of the localization speed of all three approaches. *clustering* outperforms both *one-by-one* and *tag-tag*.

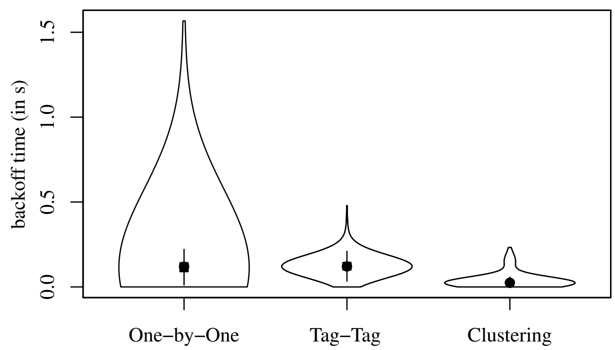

Fig. 4. Backoff time as an indicator for the wireless channel utilization. A wider envelope indicates more nodes using the desired backoff time.

Note, that in each simulation run, every node has been localized, i.e., at the end, there are no non-localized nodes available anymore.

A. Benefit in Terms of Localization Time

In Figure 3 we see the localization time needed to successfully calculate the position of all nodes. Results are shown as eCDF plots, clearly demonstrating that the *clustering* approach outperforms both *tag-tag* and *one-by-one*. We see that nodes get localized more quickly at the beginning when doing clustering. Furthermore, it is faster in the overall localization time, which is caused by the fact that the position of the first nodes gets determined earlier than in the *tag-tag* approach. The reason is that the amount of nodes broadcasting Hello messages at the beginning of the simulation is smaller, causing lower channel utilization and fewer packet collisions in the *clustering* approach.

A strongly correlated metric to that is shown in Figure 4, where the backoff time of packets queued in the MAC layer is measured. Results are shown in the form of violin plots: Boxes are drawn from the first to the third quartile of all recorded values, with whiskers extending to 1.5 times the inter-quartile range; a kernel density plot is overlaid to show the distribution of values. We can see that due to the distribution of the cluster heads and the lower TX power, the *clustering* approach has a significantly lower value than the other two versions. A higher backoff time raises the possibility for nodes to get an timeout of the localization process, which then triggers a new ranging process increasing the overall localization time.

In our distributed localization approach which supports lower transmission powers, the wireless channel is less utilized, which decreases the possibility of packet collisions. This also drastically reduces interference between nodes of different clusters, allowing them to perform the ranging in parallel.

B. Benefit in Terms of Positioning Accuracy

Measuring the localization accuracy, again *clustering* outperforms both *one-by-one* and *tag-tag* as shown in Figure 5. Results are shown in the form of box plots: Median values are marked as a thick line; boxes are drawn from the first to the third quartile of all recorded values, with whiskers extending to 1.5 times the inter-quartile range; outliers, observations outside this range, are drawn as points. The localization hop count shows the relative position inaccuracy; therefore the lowest possible value is one, which is measured on all tags at the *one-by-one* approach.

For the *clustering* approach, the maximum value is two, but since some nodes also get localized by initial anchors, the value can drop to one for several tags.

The *tag-tag* approach shows high values, which is due to the fact that successfully localized tags became anchors locating remaining tags. Thus, the positioning error gets accumulated.

C. Clusterhead Probability

To get reasonable good values for our system model, we designed a parameter study to determine a good *cluster head probability*. In Figure 6, the localization time of the *clustering* approach with several different cluster head probabilities is shown. With very low cluster head probabilities, the system behaves like the *one-by-one* approach, since in an extreme case no cluster heads are available at all. On the other hand, when using very high probabilities, e.g., all nodes are cluster heads, the system also behaves like *one-by-one*.

Like illustrated in the figure, a probability of 0.1 shows the lowest localization time, but this is dependent on the used node number and the other system models parameters.

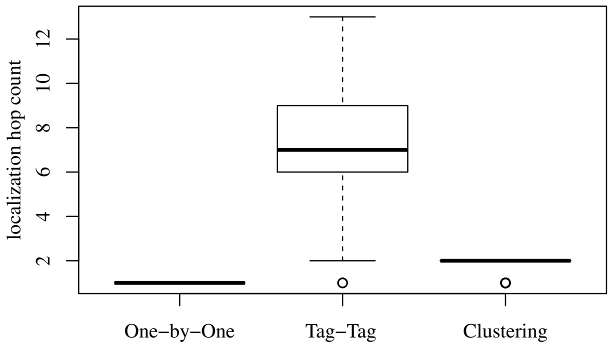

Fig. 5. Localization hop count as a measure of the relative position inaccuracy.

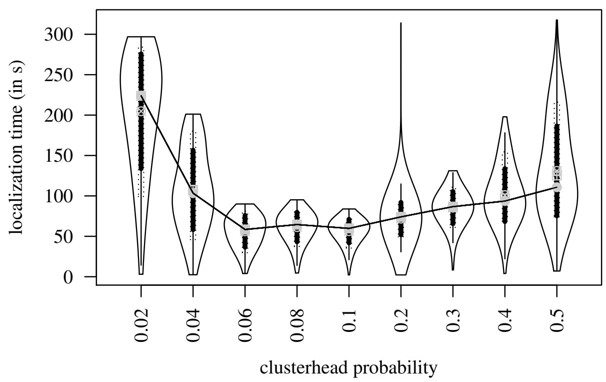

Fig. 6. Localization time for different cluster head probabilities. For very low and very high probabilities the *clustering* approach behaves like the *one-by-one* approach. Each violin shows the density of different localization times.

V. Conclusion and Future Work

In this paper we presented a simulation model for ranging and locating nodes by using nanoLOC's Symmetric Double Sided Two Way Ranging (SDS-TWR). We propose a distributed approach to perform the localization of a large amount of tags by minimizing the localization time and keeping the localization inaccuracy below a reasonable threshold. We compared our *clustering* approach with two standard localization techniques, which either use the best available localization accuracy by determining the position of each tag *one-by-one*, or do it in a flooded way when successfully localized tags become anchors to localize other tags, called *tag-tag*. Using a dynamic usage of transmission powers, our approach outperforms both schemes in terms of localization time.

In future work, we aim to further increase the localization speed by using an adaptive approach for nodes sending Hello messages to announce their presence. Similar concepts have successfully been introduced in other application domains for wireless networking such as vehicular networks [17]. Another step would be to improve the cluster head selection, changing the randomized approach with predefined probabilities to an adaptive one, which also recruits new cluster heads during the localization process. Moreover, we plan to implement the presented *clustering* approach in hardware (i.e., deploy it on nanoLoc nodes) and evaluate the performance in a real world scenario.

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