3-D Optical Wireless Localization

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***Abstract*—In this paper, we explore the possibility of using directionality of free-space-optical (a.k.a. optical wireless) communications for solving the 3-D localization problem in ad-hoc networking environments. Range-based localization methods either require a higher node density (i.e., at least three other localized neighbours must exist) than required for assuring connectedness or a high-accuracy power-intensive ranging device such as a sonar or laser range finder which exceeds the form factor and power capabilities of a typical ad-hoc node. Our approach exploits the readily available directionality information provided by a physical layer using *optical wireless* and uses a limited number of GPS-enabled nodes, requiring a very low node density (2-connectedness, independent of the dimension of space) and no ranging technique. We investigate the extent and accuracy of localization with respect to varying node designs (e.g., increased number of transceivers with better directionality) and density of GPS-enabled and ordinary nodes as well as messaging overhead per re-localization. We conclude that although denser deployments are desirable for higher accuracy, our method still works well with sparse networks with little message overhead and small number of anchor nodes (as little as 2).**

***Index Terms*—Free-space-optics, ad-hoc networks, spherical FSO structures, localization**

I. Introduction

Providing contextual location information for the application-level data is a vital enhancement for ad-hoc networks.Localization capabilities are also important for network-level functionalities such as routing. Geographical routing protocols such as GPSR [1] are known to reduce the forwarding table sizes substantially, however, they need to know the location of nodes to do a successful ID-to-location mapping. Despite the strong need for localization, the task of localizing an ad-hoc node given its power capabilities, mobility, and other network parameters (e.g., node density, anchor density) is not trivial. Traditional approach of sensing the signal strength from 3 neighbors and triangulating using the derived distances requires a high neighbor density (3 localized neighbors) and is not accurate due to the multi-path loss in RF propagation. The issue becomes even more severe if the problem is considered in 3-D space, since then, it takes 4 nodes (reaching up to 2 times the normal node density) to triangulate and even more samples (preferably from different neighbors) for calibration and better accuracy [2]. Sonar and laser range finder devices are not suitable for the power capabilities and form factors of ad-hoc nodes and explicit bearing devices are space consuming. Alternatively,

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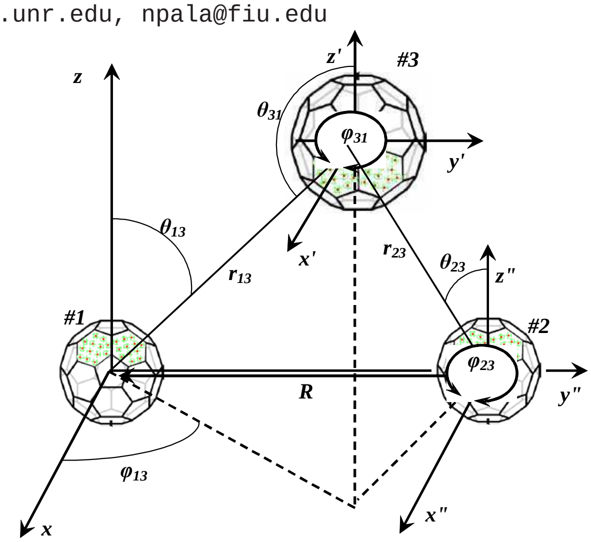


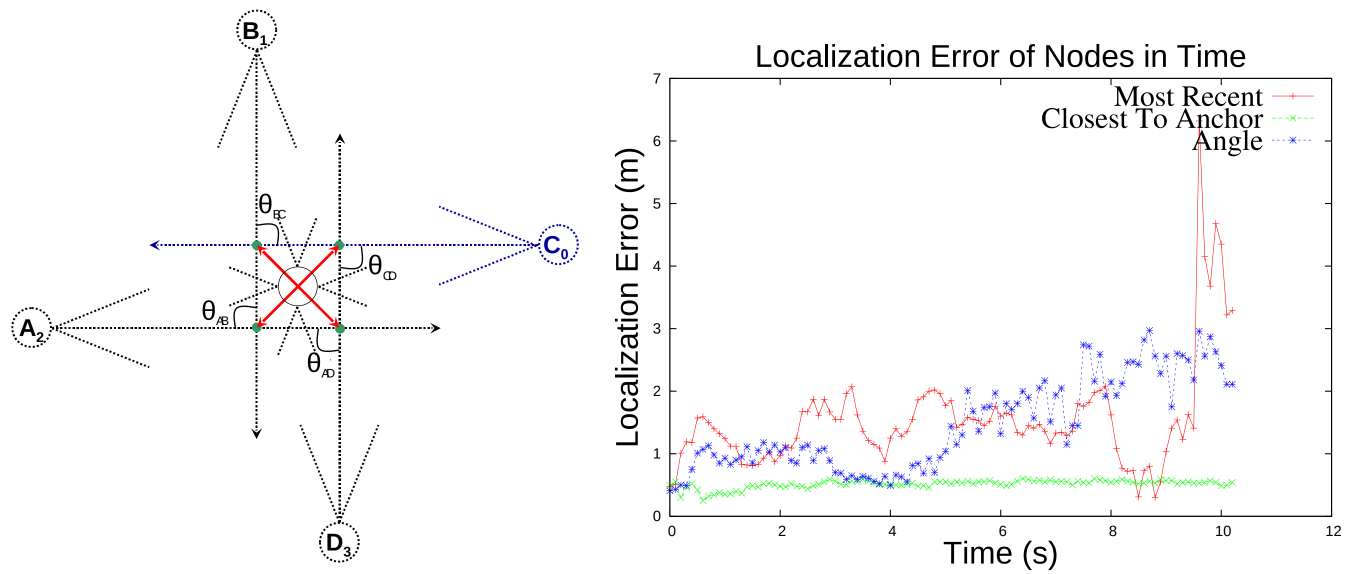
Fig. 1. A third node triangulating using the advertised normals received from two other localized or GPS-enabled nodes.

we propose to use the *directionality that is inherent in FSO communication* which does not impose any additional hardware requirements. In our approach, a node can calculate its location given that it has 2 neighbors that know their own location, and advertise their location and interface normals in the packets that they transmit. Our method is lightweight in comparison to range-based methods since it *only requires 2 localized neighbors* and it *does not involve a complex tuning phase*.

We considered FSO as a complementary communication mechanism to aid in increasing the overall network throughput in [3]. Previous studies revealed that FSO-only mobile ad hoc networks are viable and using *auto-alignment* circuitry and protocol, line-of-sight issues can be remedied significantly [4]–[7]. However, FSO communication technologies has not been used to solve the ad-hoc localization problem and they provide a substantial amount of potential as it is quite efficient to run triangulation algorithms using *direction of reception* (i.e., angle of arrival). We use directionality of FSO beams to identify the angle of arrival (Figure 1). By using *advertised normals* in packet headers, we can then calculate the relative angular orientation of neighbors with respect to each other. Since a node can receive packets (with advertised normal information in them) from more than 2 neighbors, we need to choose which information sets to use while triangulating. We suggest and compare three different heuristics to make this selection.

Key characteristics of our FSO-based solution are:

- capability of localization in 3-D,
- much less power consumption in comparison to techniques requiring RF hardware,



(a) A simplified triangulation in 2D using two GPS-enabled nodes and error in default LOS model.

(b) Localization errors are being amplified during the simulation when two latest received information sets are used for triangulation.

Fig. 2. Amplification of localization error in time and error in different heuristic models.

- only two localized neighbors are needed, which reduces the node density requirements, and
- fast heuristics to select a subset of neighbors to use for localization.

The rest of the paper is organized as follows: we present a background for the related work in localization in ad-hoc networks in Section II. Section III presents our implementation of a basic triangulation algorithm in NS-2 network simulator [8]. In Section IV, we discuss the heuristics in detail. We present the simulation results for different scenario setups in Section V and finally summarize our work.

II. Background: Ad-Hoc Localization

Problem of node localization has been tackled by various methods: using ranging techniques [9]–[11], bearing techniques [12], and combination of the two [2], [13]. Robotics and image community has been working on the localization problem using landmark detection techniques and laser range finders [**?**], [**?**], [14]. However those methodologies are less practical for ad-hoc network localization due to either power requirements or lack of a camera in an ad-hoc node.

Range-based methods require at least 3 localized nodes (4 in a 3-D setting) to enable localization of a fourth node with varying degrees of quality. Major limitation of range-only methods is that they require high density of nodes to achieve high localization coverage. SpotON [9] and Calamari [10] systems build on the assumption of a simple path propagation model with known parameters for RF whereas this does not hold in practical environments where multi-path propagation is the norm especially in indoor settings to score a 10% error in ranging even after an intense calibration process.

Niculescu considers angle-of-arrival as the approach for triangulation without the need for any ranging measurements [12]. Their approach requires additional hardware for detecting the angular placement of neighbor nodes (such as an antenna array or a sonar device). They conclude that angle-of-arrival (AOA) methods can have accuracy that is comparable to range-based methods. However, requirement for additional RF hardware results in large structures with potentially high power consumption and is impractical for many ad-hoc networking settings.

Algorithm 1 Relative Localization

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UPON Reception Of Packets With Localization Header:
if This Node Has At Least 2 Neighbors' Advertised Normals AND It Is Not A GPS-Enabled Node then
    if Using Most Recent Sets To Triangulate then
        FIND 2 Latest Received Localization Packets
    end if
    if Using Angular Priority then
        FIND 2 Localization Packets That Make An Angle Closest To 90°
    end if
    if Using Localization Rank then
        FIND 2 Localization Packets With Minimum Ranks
    end if
    CALCULATE Closest-Point-Of-Approach Of The 2 Rays
    UPDATE This Node's Location
    UPDATE This Node's Localization Rank
    UPDATE This Node's State Flag As "Triangulated"
    START Stamping Outgoing Packets
end if
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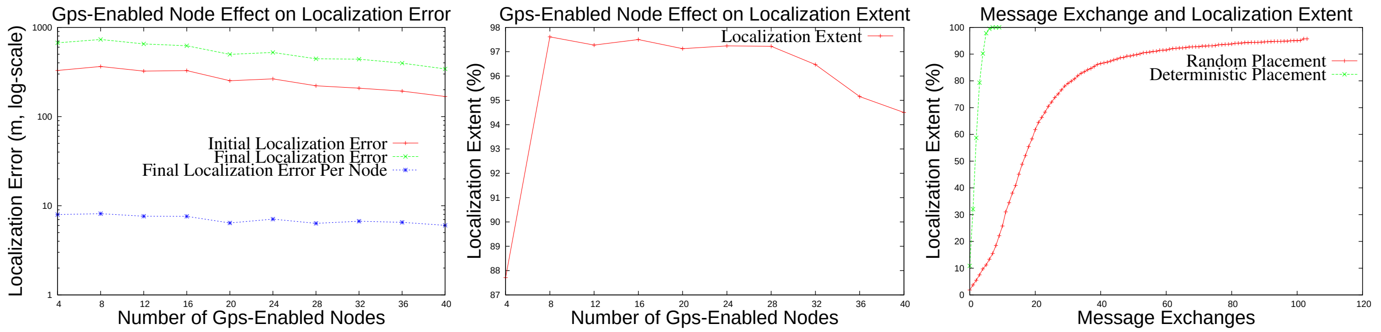
Akella proposed a hybrid technique [15] that uses optical wireless (FSO) combined with ranging techniques. They require only one localized neighbor relazing the node density requirement considerably. The method is appropriate especially for low-density and intermittently connected networks with accuracy trade-offs. However, their need for range measurement is, although achievable using signal strength measurements,



(a) GPS-enabled node effect on localization error. (b) GPS-enabled node effect on localization extent. (c) Localization extent with respect to message exchange for 200 nodes.

Fig. 3. Effect of number of GPS-enabled node on localization error and localization extent and message exchange overhead.

requires extra computational complexity and it is prone to measurement errors.

A key characteristic of our solution is to use *optical-only techniques* to achieve localization. Our method requires much less power availability than RF-based methods, and is particularly useful for ad hoc networking settings where line-of-sight exists among low-power nodes. Our proposition provides high localization extent with as little as only 2 localized or GPS-enabled nodes with acceptable accuracy through the use of narrow transceivers when 2-connectedness requirement is satisfied.

III. System Model

The 2 types of nodes are: anchor nodes with GPS devices and ordinary nodes that do not know their locations initially. Network nodes with a GPS device send control packets including their location and direction information so that the immediate neighbors without a GPS device can use the transferred information to find their own locations. These control packets convey the *advertised normals*, which include sender node's ID, if sender has a GPS device, if sender has previously triangulated, hop distance of sender from the nearest anchor node (localization rank), if the sender node has previously triangulated, and transmit antenna's global location and its direction (normal). The receiver of such a packet stores this information in a table (mapping from node ID to localization information) with the arrival time of the packet as presented in Algorithm 1.

One can derive simple algebraic equations:

$$r_{31} = \frac{R}{\sin\theta_{31}(\tan\varphi_{31} + \tan\varphi_{32})}\sqrt{1+\tan^2\varphi_{31}} \tag{1}$$

$$r_{32} = \frac{R}{\sin\theta_{32}(\tan\varphi_{31} + \tan\varphi_{32})}\sqrt{1+\tan^2\varphi_{32}} \tag{2}$$

$$X_3 = X_1 + r_{13}\sin\theta_{13}\cos\varphi_{13}$$

$$Y_3 = Y_1 + r_{13}\sin\theta_{13}\sin\varphi_{13}$$

$$Z_3 = Z_1 + r_{13}\cos\theta_{13} \tag{3}$$

that give the location of a third node. The distance between two GPS-enabled nodes is R (Nodes 1 and 2). From this distance and θ and φ angles that are derived from the transmitter normal advertisements in packet headers, we can calculate r_{31} and r_{32} (Equations 1 and 2). Lastly, we need to conduct simple vector additions to find the coordinates of Node 1.

Localization rank of a node is the hop distance of that node from the nearest anchor node. As depicted in Figure 2(a), node C has rank 0 indicated as a subscript. When a node without a GPS device triangulates, it's rank is the maximum of the ranks of sender nodes added by 1. Hence if a node is next to 2 GPS-enabled nodes (each with rank 0) and it triangulates using the information that it received from these two nodes, it will have rank 1. Such a ranking mechanism helps us prioritize the available information while triangulating. Intuitively, if we consider a network with uniform geographical distribution of nodes and anchor nodes placed at the center, nodes that are in the skirt of the network will have the highest ranks. Moreover, nodes with higher ranks are subject to larger localization errors.

A node is"ill-connected" when the number of directly reachable neighbors is less than 2. Hence, we require a node to be in transmission proximity of at least 2 direct neighbors even though it may not be able to transmit and receive from those neighbors because of line-of-sight issues. Thus, upon starting to place ordinary nodes (without GPS devices), we place the anchor nodes at arbitrary locations. For example, if number of GPS-enabled nodes in X axis is 2 and in Y axis is 3, we divide the X edge of the determined area into 3 and Y edge into 4 equal lengths and place one anchor node at the end of each X-Y edge with another corresponding anchor node placed on the same point with a given Z value. Hence a pair of GPS-enabled nodes are placed on top of each other with some distance in Z axis. We acknowledge that such a requirement on the placement of anchor nodes can limit the applicability of our approach. However, one can come up with placement methodologies that relax such strict placement requirements and ensure that a subset of surrounding non-anchor nodes have 2 connections to separate GPS-enabled nodes.

While placing non-anchor nodes, we consider a candidate location drawn from 3 uniform randoms for X, Y, and Z coordinates. We check if there are at least 2 nodes within the communication range of the candidate location. If so, we accept the candidate location and move to the next node. If we assume that there is only one pair of GPS-enabled nodes in the network, rest of the nodes form a sphere-like cluster in 3-D space. Moreover, when we increase the number of GPS-enabled node pairs to 2, we introduce the possibility of creating two disconnected clusters and enable the nodes to be placed in a larger volume, which in turn may decrease localization extent in the network because of line-of-sight issues involved. The only strict requirement while placing anchor nodes is that they are *placed as pairs*, on top of each other, which ensures that a third node that is able to see both nodes can localize itself.

IV. Heuristics

In our study, we found that it is possible to employ a number of *simple heuristics* while deciding which two information sets to use for triangulation from a given number of information sets. Possible number of different ways to localize is $\binom{n}{2}$ where n is the number of information sets available to a given node.

A. Stale Info Gets Forgotten

Possibly the simplest heuristic is to use the information that became available the latest. Assuming a node can use 4 different localization information sets as depicted in Figure 2(a), the triangulating node will select the latest two arrivals. Observe that localization error is amplified throughout the network with this heuristic. Since each node re-triangulates as it receives a packet using the most up-to-date information, node will consider the latest information no matter how far the sender node is to the closest anchor. Hence, even though more accurate information is available, the choice results in increased localization errors as can be seen in Figure 2(b). We found that the best triangulation result is obtained at the first attempt since the received localization information sets have been propagating from anchor nodes towards the nodes with higher ranks at skirts of the network.

B. Lower the Rank the Better

In this heuristic, we first assign a "localization rank" of 0 to a GPS-enabled node. When a node triangulates using localization information obtained from two neighbors, it attains the localization rank of maximum of the two neighbors added by 1. If we assume that the network has only one pair of GPS-enabled nodes and the distribution of the nodes form a sphere-like shape in 3-D, nodes that are closer to the core where the two anchor nodes reside, will have lower localization ranks and the outer skirts of the network will have larger localization ranks indicating that they are more distant from the core in number of hops. Hence, when a node is about to decide the pair of neighbors for triangulation, it may choose them in such a way that summation of the two ranks is minimized. This heuristic ensures that neighbors that are closest to anchor nodes are selected for triangulation. Figure 2(a) shows nodes' ranks as subscripts. Assuming the node in the middle is triangulating, it will select the information sets that came from C_0 and B_1 since they have the lowest ranks.

C. Angular Prioritization

One of the hard cases to triangulate using only directionality information is when the triangulating node lies on the straight line that passes through the both two nodes (collinearity). Results become more accurate when the two nodes are chosen in such a way that they attain a certain angle between each other (e.g., $90°$). Throughout our experiments we found that one major factor that was causing increased localization error was ill-formed (flat) triangles that were the result of unwisely chosen 2 candidate information sets. A natural way to remedy the problem is to impose a lower bound on the angle between the two nodes (e.g., $0.005 * \pi$) and favor those sets making an angle close to $90°$ (orthogonality, in 3-D). Figure 2(a) shows θ_{BC}, θ_{AB}, θ_{AD} and θ_{AD} angles made by all 4 nodes. Assuming θ_{BC} is closest to $90°$, the triangulating node will choose information sets sent by node B and node C for triangulation.

V. Performance Evaluation

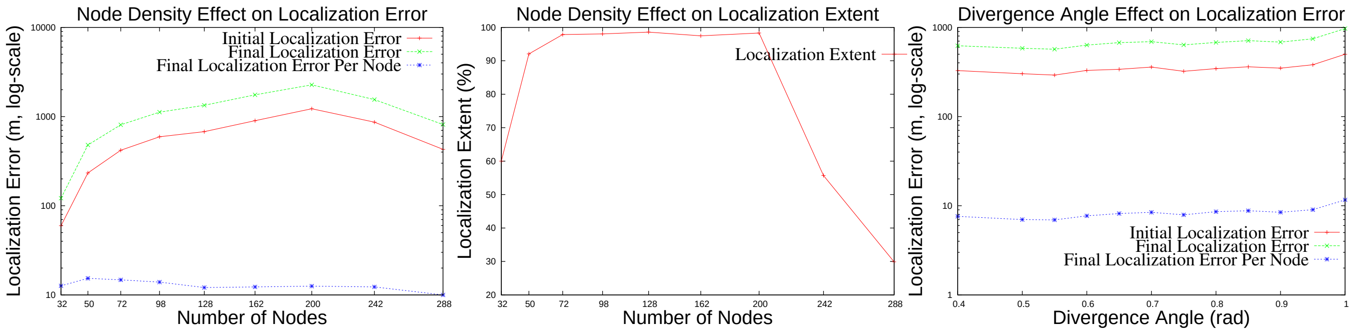
We looked at a number of metrics while justifying the performance of our approach. The first metric is initial localization error. Initial localization error indicates the *aggregate absolute difference* between calculated location and actual location of all nodes in the network. This metric is calculated for a node when it localizes itself for the first time. Nodes in the network continue to re-localize themselves as they receive more packets. We stop the simulation when all the nodes are localized or simulation time reaches 10 seconds, whichever happens first. Since the simulated network is stationary, 10 seconds is enough as an upper bound for simulation duration. We calculate final localization error using the last calculated locations of each triangulated node before the simulation ends because of either of the reasons. Another metric that needs to be considered is final localization error averaged by the number of all localized nodes.

A. Comparison of Heuristics

We ran simulations of 100 nodes with 14 interfaces on each for 10 iterations using each heuristic. Each interface had a divergence angle of 600 mrad (-$34°$). There were 8 GPS-enabled nodes (making 4 pairs) and all nodes were placed on the 3-D volume randomly. We found that selecting the latest information set gives the worst results since the error is neither predictable nor close to a desired level. Similarly, angular prioritization gives elevated localization errors as well but still better than selecting the latest information sets and is relatively stable. Among the 3 heuristics, the one based on localization ranking resulted the lowest localization error per-node as depicted in Figure 2(b). Hence, throughout the rest of the simulation sets, we used this ranking based heuristic to determine which 2 sets to use for triangulation.

B. Node Density

Our second simulation set is designed to determine the effect of node density in the network on localization extent. For this experiment we increased the number of nodes from 32 to 288. There are 26 interfaces with 400 mrad of divergence angle on each node. There are 16 anchor nodes in the network and all of the ordinary nodes are placed randomly on a 3-D terrain. We ran the simulation setup for 5 iterations and averaged the results. As depicted in Figure 4(b), we found that as we increase



(a) Node density effect on localization error. (b) Node density effect on localization extent. (c) Divergence angle effect.

Fig. 4. Effect of node density on localization error and localization extent and different node designs with varying divergence angles.

the node density, the localization extent first gets higher, but later reduces as more neighbors start falling into their blind regions (i.e., no line-of-sight) and start becoming obstacles to each other. A similar trend is observed in localization error (Figure 4(a)) as well. However, the final per-node localization error steadily benefits from more neighbors.

C. Anchor Density

In Figure 3(a) and Figure 3(b), one can see that in a simulation of 100 nodes, when the number of GPS-enabled nodes is increased from 4 to 40, both *aggregate* and *per-node* localization errors decrease. Also, it is an important observation that the localization extent makes a significant jump from 2 pairs (4 nodes) to 4 pairs. However, increases after that point reduce the localization extent. We conclude that because of the scattering effect of the random node placement algorithm, the volume that the nodes are distributed is increased, which in turn makes the LOS a more significant problem.

D. Divergence Angle

Figure 4(c) shows the how divergence angle affects the overall and per-node localization error. As we increase the divergence angle, it reduces the accuracy of the default-normal estimates. Hence, the localization error is increased. We conclude that designing multi-element optical antennas with more transceivers on them not only increases throughput [3], but it also increases the accuracy of localization.

E. Message Overhead and Localization Extent

A key practical metric is how long it takes the whole network to localize. In this set of simulations, we investigated the localization extent after each message exchange. We used 200 nodes each with 26 transceivers using 400 mrad divergence angle. There were 8 GPS-enabled nodes and we ran the simulations for 10 iterations. We ran two separate simulation setups for this scenario. In the first setup, we placed the nodes on a 10x10x2 perfect grid and in the second setup, we placed all the nodes randomly. As depicted in Figure 3(c), we saw that placement of nodes on the terrain is a significant factor in extent of localization and message exchange overhead. First setup with deterministic placement reaches over 90% localization extent in 10 message exchanges. However, the setup with randomly placed nodes reaches 90% after 90 message exchanges and 80% after 33 message exchanges.

VI. Summary

In this paper, we proposed a novel approach to the problem of node localization in stationary ad-hoc networking context via multi-element free-space-optical antennas. We used readily available directionality information to perform a simple triangulation. Our approach is light-weight in processing needs, does not a need complex tuning phase, stingy in terms of required extra hardware. We conclude that optical wireless is attractive because of both its high throughput and easy-to-exploit directionality benefits that is helpful in solving the localization problem.

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