A Relative Ad hoc Localization Scheme using Optical Wireless.

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Abstract— **Directional communication (for example, using directional antennas or free-space optics) has the potential to dramatically increase capacity reuse in multi-hop wireless mesh and ad hoc networks. What is less appreciated is that directional communications can also simplify network layer functions. In this paper, we show how directionality (combined with ranging) can be used to construct a scalable, fully distributed localization system and assign "relative" coordinates to each node (without the need for GPS) that can be used by highly scalable geographic routing systems. We show that range and orientation-based localization schemes (ROL) scale better than range-only or orientation-only localization schemes (e.g., triangulation) for such applications. We present simulations studying scalability, effect of errors (both range and directionality) and compare performance with triangulation methods. Finally, we discuss how such an ROL scheme can be realized with optical wireless nodes, based upon our ongoing efforts to build ad hoc and meshed networks using both FSO and RF technologies.**

I. Introduction

Mobile ad hoc networks, meshed wireless networks, sensor networks, vehicular networks, disruption-tolerant networks and peer-to-peer networks are examples of highly dynamic networks, where the graph structure, node availability or link weights change rapidly. A important realization of recent research is that such dynamic networks benefit from efficient node localization (or embedding in a Euclidean coordinate plane), since it enables stateless geographic routing within the network [7]. Efficient localization has therefore been studied both in wireless and overlay/P2P contexts, and some techniques can be used in both contexts. The most important aspect of the localization algorithm is scalability, especially for applications with thousands of geographically dispersed nodes. Also, very low cost dynamic networks benefit from localization schemes that work with few or no anchor nodes; that can accommodate low density deployment of the nodes in the network; and with minimally centralized infrastructure. For example, when sensor nodes are sprinkled from an aeroplane onto a geographic location, node density and careful placement of anchors cannot be always guaranteed. Applications like E911 over such dynamic networks require a node to be able to be located accurately and rapidly.

Novel indoor applications (e.g., coordinating hundreds of sensors in a RF-unfriendly factory floor or inside a airplane) cannot use either GPS or RF-based techniques. Traditionally triangulation is used for node localization using ranging between nodes. It can achieve localization relative to a few (localized) anchor nodes [3]. Achieving a scalable relative coordinate system, without anchors using a range-only technique is difficult. In this paper, we show that when *both* range and orientation are used, we can obtain a more scalable localization scheme to assign a relative coordinate system for the network.

There are also other benefits if both range and orientation are used for node localization in wireless networks [4]. Localization schemes that use only range or orientation (trilateration or triangulation) require at least *three* localized neighbors so as to localize a node. On the other hand when both range and orientation are used, node localization can be achieved with a *single* localized neighbor. The method achieves 100% node localization as long as the underlying graph is *connected*, irrespective of the average node degree and node density (i.e. even for sparse networks!).

We present a distributed algorithm to calculate the relative coordinates of the nodes in the network using both range and orientation between adjacent nodes without relying on any centralized coordination or anchor nodes. We focus on the scalability issues of this localization scheme that uses both range and orientation and compare it with triangulation in terms of the cost of communication and number of iterations needed to converge. We also study how an error in estimating the range and orientation effects the localization and how it propagates in the network.

The method described in our paper can be implemented with any physical layer directional communications technology, provided that a node is capable of measuring both the range and the orientation of its 1-hop neighbors. We are motivated by the possibility that low-cost Free-Space Optics (FSO) can be the enabling technology (even in RF-contexts) to realize localization schemes that use both range and orientation in a cost effective manner.

FSO uses light for communication between two nodes with air as the medium. FSO is known for its high capacity, low power per bit, low-cost and easy deployment [1]. We propose to use the "directionality" of the light beams to measure the orientation between the two nodes and laser ranging instruments [15] or time-of-flight between two nodes to measure the range, thus obtaining the position "vector"

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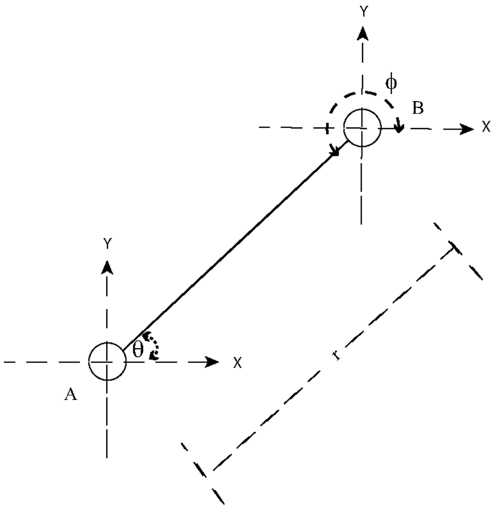


Fig. 1. Illustration of the principle of an FSO based location system.

of any node relative to another. FSO needs the presence of clear line-of-sight between the nodes making it not suitable during adverse weather and situations with lot of physical obstructions between nodes. Due to this limitation of FSO communication technology, recent proposals recommend the use of hybrid FSO/RF communication systems where in a high bit rate FSO link is backed up by a low bit rate RF, to improve the link reliability. The proposed localization method can be implemented using such hybrid FSO/RF systems, but discussion of such systems is out of scope for this paper.

The paper is organized as follows: In Section II, we briefly present the prior work on ad hoc localization. In section III, we briefly describe the basic principle of localization based on range and orientation, and discuss the details on how the nodes can be implemented using FSO technology. In section IV, we present our distributed algorithm to obtain the relative coordinate system and in section V, we evaluate its performance using simulations and compare it with triangulation in terms of scalability. In section VI, we discuss how the localization error is propagated in the network due to estimation errors in range and orientation of nodes. Section VII concludes the paper.

II. Prior Work

Depending on the application and the context for which location information is used, there are several types of location systems that exist. [6] reviews a host of such location systems. Based on the method used to obtain position information, we classify the localization schemes into range-free techniques, range-only techniques, orientation-only techniques, and both range and orientation based techniques. We briefly describe each of these in the following:

- *Range Free Techniques*
  Robotic localization techniques are typically range free. These techniques usually involve learning a map prior to performing localization, and later predict the location and iteratively correct it. We do not elaborate on these techniques here, as they do not directly compare with range/measurement based localization techniques in terms of accuracy, coverage, and scalability.

- *Range Only or Orientation-Only Techniques*
  Localization schemes that are based on estimating the range between nodes typically use trilateration to compute coordinates. Trilateration schemes need a minimum of three range measurements from already localized nodes so as to fix the position of a node in 2-D space. The most popular method of obtaining location information in 3-D is using range based triangulation in GPS (Global Positioning System).
  In range based schemes, an estimate for the range between the nodes can also be obtained by the number of hops [9], [12] or by RTT [5], or an explicit range [3] and then it is translated into virtual or (global or relative) physical coordinates using triangulation. In order to implement a distributed localization scheme using triangulation, a very high node density and a very high average node degree [4] are needed to achieve acceptable node localization percentages (for example, localization for a ring topology is hard to achieve using triangulation). In the past literature, the average node degree ranged from 6 to 16 [8], [3],[14], [13] to achieve a reasonable coverage (extent of node localization). Also, distributed localization schemes to achieve relative coordinates (without anchors or landmarks that have global positioning information) using triangulation incur high cost of communication [3], [8].
  Orientation-only schemes [10] are equivalent to range-only schemes in the number of constraints needed to localize a point. As in the range based schemes, orientation only schemes need three estimates of angular orientation relative to three localized nodes.

- *Techniques using both Range and Orientation for localization*
  Techniques that use both range and orientation can localize a point as long as the node can communicate with a single other node which is already localized [4]. The localization scheme achieves a relative coordinate system for any topology as long as the underlying graph is connected, irrespective of the node density. In this paper we show that such a scheme is amenable for fully distributed approach and is also more scalable than the above two techniques in terms of the cost of communication and number of iterations needed to localize. Henceforth, we refer to these schemes as Range and Orientation Localization (ROL) schemes.
  ROL schemes demand more hardware capabilities for the wireless node so as to estimate both the range and orientation. Free-space optics technology can offer these capabilities inexpensively, within the form factors and power limitations set by ad hoc or sensor applications. In addition to using it as a localization technology, FSO

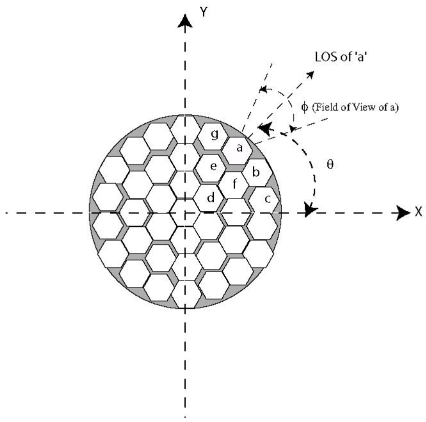


Fig. 2. FSO antenna for localization.

can also be used for communication between ad hoc and sensor nodes under good weather conditions [1]. In the next section we briefly describe how FSO can be used to realize a practical ROL system.

III. FSO Localization Scheme

Figure 1 illustrates the basic principle of the localization scheme. Then, any node, in this case, node A measures the range r and the orientation θ of its 1-hop neighbor, node B and computes the coordinates of the node B, with itself at the origin as following [4]:

$$x_b = rcos\theta$$

$$y_b = rsin\theta$$

If node A is already localized with coordinates (x_a, y_a) then the coordinates of node B can be obtained by simple vector addition:

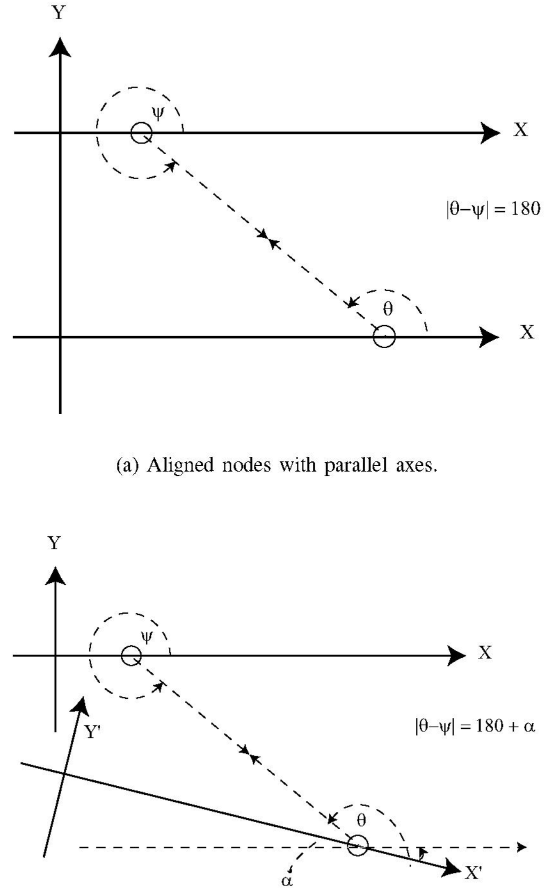
$$x_b = x_a + rcos\theta$$

$$y_b = y_a + rsin\theta$$

Thus each node can compute its 1-hop neighbor's coordinates relative to itself. A leader is selected to be at the origin and a relative coordinate system of the entire network can be obtained in a distributed manner with respect to this origin. Thus this scheme requires only *one* already localized node for any given node to localize. When the underlying graph is connected, even if it is a sparse one, we can have all the nodes in the network (100% coverage or extent) localized.

A. FSO System

The "directionality" of the optical signals inherently make it convenient to estimate angular orientation between nodes. Unlike RF, where phased arrays are needed to detect the angle of arrival, it is much easier in FSO due to the directionality of the light beam. In [2], the authors proposed and demonstrated a spherical optical structure with tesselated optical transceivers. We refer to it as an "optical node". These optical nodes have line-of-sight in (almost) all directions and can communicate in 360^o steradians like an RF antenna. The concept of which is illustrated in Figure 2. Each node has a set of perpendicular axes passing through it. Every transceiver on the node is composed of a light source like an LED or a diode laser and a receiver like a photo-detector. Each of such transceivers has a direction defined by its line-of-sight. The orientation of the line of sight of the individual transceivers with respect to the node's axes is fixed and can be measurable.



(a) Aligned nodes with parallel axes.

(b) Non-aligned nodes.

Fig. 3. Alignment procedure between two nodes.

Two such optical nodes within each others range can always find a common line of sight between them, thus aligning with one another. When nodes move relative to each other, different set of transceivers on them will come into line of sight and hence once again are aligned. The hardware and the electronics used for such an alignment is presented in [2]. The alignment procedure for the nodes needed in our localization scheme is illustrated in Figure 3.

Consider two FSO nodes as shown in Figure 1. A sees B at (θ, r) and B sees A at (ϕ, r), when they find a common line-of-sight. The two nodes exchange this information while aligning with each other. When the X- and Y- axes of A and B are aligned, as shown in Figure 3.a, the condition $|\theta - \phi| = 180$

is satisfied. When the axes are not aligned, say by an angle $\pm\alpha$, then the equation becomes $|\theta - \phi| = 180 \pm \alpha$ as in Figure 3.b. Nodes can make this simple computation to check their alignment. In reality, the line of sight is not just a line, but is a 3-D cone since each transceiver has a finite field of view (Ψ) causing an estimation error of $\pm\frac{\Psi}{2}$ in orientation. We study the effect of such an error on the localization in Section VI.

FSO based location systems can be implemented using inexpensive off-the-shelf components. Optical components can be chosen to have the form factors suitable for energy constrained ad hoc applications. The accuracy of estimating the orientation of the 1-hop neighbor can be tuned by the density with which the transceivers are tessellated on the node and the field of view of these transceivers. Range between two nodes can be measured using time-of-flight techniques or laser ranging instruments like SICK sensor [15].

IV. FSO Localization Algorithm (FLA)

We assume that each node has a set of perpendicular axes passing through it as shown in Figure 1. As described in the previous section, FSO nodes have the capability of measuring the range and the orientation of the 1-hop neighbors. Further, the nodes in the network have unique IDs. We assume that network is connected and all the nodes at bootstrap have $(0, 0)$ as coordinates.

Then, the network localization problem is defined as follows: At bootstrap, the nodes are randomly located and the axes of different nodes are oriented randomly with respect to each other. The objective of the FSO localization algorithm (FLA) is to orient the axes of all the nodes such that they are parallel to each other and compute their coordinates relative to an elected leader.

The FSO localization algorithm has three steps. First, the node with the "highest ID" is elected as the leader in a distributed manner. Then all the nodes align their axes with the leader node's axes. Then each node computes the coordinates of its neighbors with lower IDs by estimating its relative range and orientation.

At bootstrap each node communicates with all its 1-hop neighbors and the IDs of the neighbors are exchanged. Each node becomes aware of the 1-hop neighbor with the highest ID and orientation with respect to itself and saves that information. Whenever a node updates to a new higher neighbor ID, it sends an update messages to its 1-hop neighbors. This process of exchanging the highest ID happens until there are no updates at any node. At that time, all the nodes in the network are aware of the leader node's ID and its orientation information. Each node waits for a pre-assigned time duration and when it does not hear any more updates from its neighbors, it aligns its axes according to the leader node's orientation information. The actual alignment procedure is explained under section 3. This completes the leader selection and alignment step.

Once aligned, each node can measure the range and orientation of its neighbor with a lower ID. When a node computes the coordinates of the nodes with lower IDs it sets the nodes "Highest-CoOrd-ID" to the leader ID. A node becomes eligible to compute the coordinates of the neighboring nodes when it receives its coordinates from a node whose Highest-CoOrd-ID is equal to the leader ID. By default, the leader with the highest ID has this condition satisfied at bootstrap, so it starts to compute the coordinates of its 1-hop neighbors by measuring their range and orientation. The leader thus establishes itself as the origin. The 1-hop neighbors of the leader node receive their coordinates from the leader and update their coordinates. These 1-hop neighbors of the leader, in turn become eligible to calculate the coordinates of their 1-hop neighbors who have not already received the coordinates from the leader. The pseudo-code of the algorithm is shown in Algorithm 1.

Algorithm 1 $FLA - Relative - Localization$

if $MyLeaderIDChangeFlag = 1$ **then**
    UPDATE to neighbors of this new highest ID
end if
repeat
    Listen for more updates from the neighbors
    if Received an update from the 1 hop neighbor **then**
        if $ReceivedID > MyLeaderID$ **then**
            $MyLeaderID = ReceivedID$ and $MyLeaderIDChangeFlag = 1$
        end if
    else
        $MyLeaderIDChangeFlag = 0$
    end if
until No update from the neighbors for time T
ALIGN axes with the highestID neighbor
if $HighestCoOrdID = LeaderID$ **then**
    COMPUTE coordinates of lower ID neighbors
end if

If a new node joins the network it simply communicates with the nearest neighbor and calculates its coordinates from its position with respect to the neighbor and the neighbor's coordinates with respect to the origin, irrespective of its ID. A node that either goes into sleep or dies will not have any affect on the coordinate system, thus the coordinate system is robust for topological changes as long as the nodes do not move. Mobility issues are out of scope for this paper, so we do not address them.

V. Performance of the Localization Algorithm

What kind of scalability benefits does the FLA algorithm based on ROL scheme offer over traditional triangulation based distributed localization schemes? We address this question in this section. Beyond the advantages offered by the basic scheme in terms of the node degree / density requirement for localization, FLA distributed scheme is more scalable in other metrics too.

We evaluated the performance of our algorithm for scalability using simulations for the following metrics:

- **Extent of node localization**: As mentioned in the previous section, ROL schemes localize all the nodes in the network if the underlying graph is connected. Thus, the extent of localization is always 100%, irrespective of the average node degree of the graph.

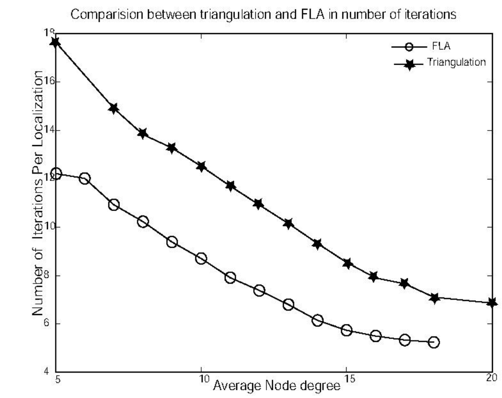
- **Convergence time**: Using our algorithm, we measured convergence time as the number of iterations needed to achieve 100% localization. This is a useful metric to understand how the ROL based distributed algorithm scales with the number of nodes in the network and how quickly it converges on a coordinate system. Since leader election and identification is implemented in a hop-by-hop manner, the maximum number of iterations taken by the algorithm is a function of how many hops away a node is from the leader node.

- **Number of messages per node to localize**: Communication cost for control messaging is an important metric for scalability. Specially for energy constrained nodes,having a low communication cost per localization is crucial.

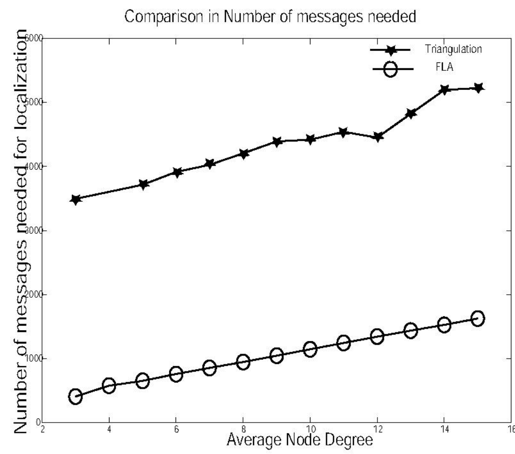
We simulated a random network in an area of 200X200 sq. units for two node densities, 0.0025 nodes per sq. unit. (100 nodes) and 0.01 nodes per sq. unit (400 nodes) in a C++ that we developed. We compared the metrics against a simple distributed triangulation scheme with three landmark nodes. The triangulation scheme *does not* give a relative coordinate system, but just localizes the nodes relative to three landmark nodes which are already localized in a hop-by-hop manner. Whereas with our algorithm, we obtain a relative coordinate system for the entire network relative to the topology also in a hop-by-hop manner. We observe that even this simple version of triangulation scales worse than our algorithm.

Figure 4 compares the above three metrics between triangulation and FLA scheme. Figure 4.a, and Figure 4.b show that FLA based localization algorithm scales better in terms of number of iterations and control messages as compared to triangulation. The reason is that the number of iterations needed to converge on a location system for FLA is a function just of the network diameter. The number of hops the farthest node is away from the node with the highest ID decides the number of iterations. Where as in triangulation, not only the network diameter affects the number of iterations, but also the nodes' spatial distribution because only nodes with *at least three* localized neighbors can obtain their coordinates, and this might take several iterations before all the nodes in the network such neighbors. Figure 4.c illustrates the extent of localization (coverage). Again, triangulation needs a high average node degree to achieve a reasonable extent of localization, where as FLA achieves 100% localization when the average node degree is just about 2.

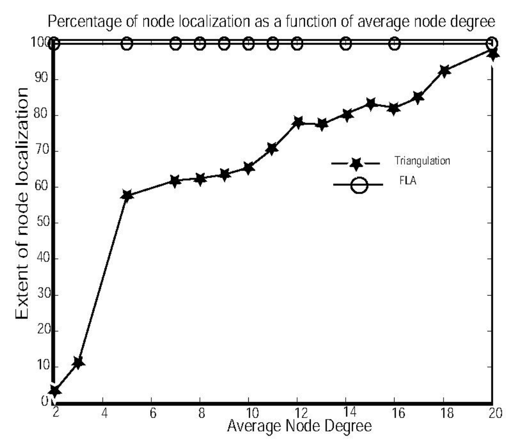
Apart from comparing with metrics with triangulation, we evaluated how FLA scales with increasing number of nodes in the network. In Figure 5.a shows that as the node degree increases, the number of iterations needed to localize decreases, since the information about the leader node spreads more



(a) Comparison of the number of iterations for localization for FLA and triangulation.

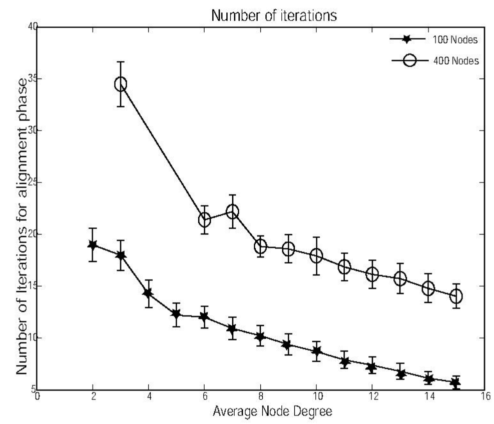


(b) Comparison between FLA and triangulation in terms of the number of control messages exchanged for localization.

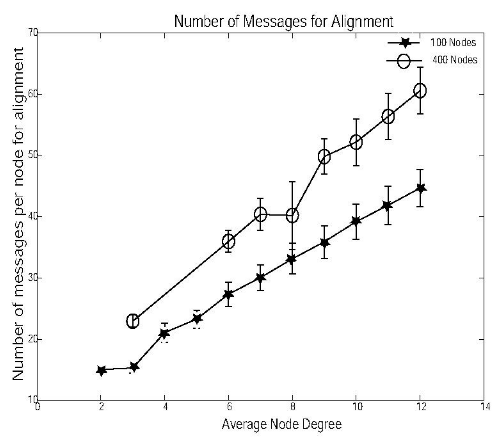


(c) Extent of localization as a function of average node degree.

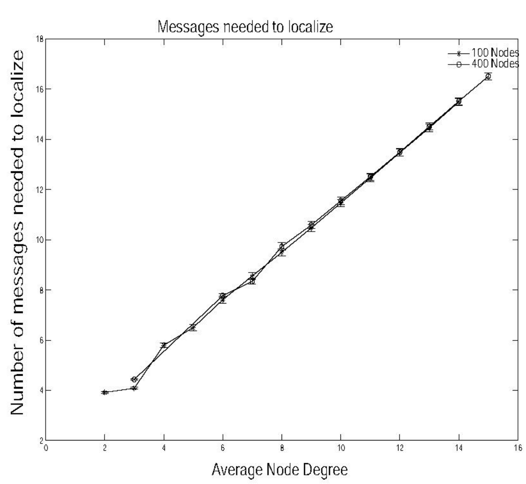
Fig. 4. Comparison between FLA and Triangulation. (FLA for relative coordinates, triangulation just to localize relative to three landmark nodes.)



(a) Number of iterations needed to localize as a function of average node degree.



(b) Number of messages per node for alignment and leader selection as a function of average node degree.



(c) Number of messages per node for localization as a function of average node degree.

Fig. 5. Scalability of FLA with node degree is illustrated.

quickly. Whereas as the node density in the network increases, the number of iterations increase because then hop length becomes smaller and the number of hops from the leader node increases.

Another important metric is the cost of communication to localize, specially for energy constrained nodes. Figure 5.b shows the total average number of messages each node needs to align with all the other nodes in the network. The number of messages for higher node density is higher because with density, the hop length shortens and there are more hops between any node to the leader increasing the number of iterations needed. As we observe, the number of messages increase linearly with node degree. Messages needed for per node localization after alignment is independent of the node density, making the algorithm more scalable in Figure 5.c.

From the above comparison, we argue that the additional cost of implementing both range and orientation pays off in terms of scalability. In a practical system, communicating nodes can be designed to have both FSO and RF hybrid capability. FSO technology can be used to localize using ROL scheme, which is quick and more scalable than triangulation. Also FSO can be used for communication in clear weather conditions since is less power consuming than RF and has a higher bit rate. RF can be optionally switched on, when FSO communication is unavailable due to line-of-sight requirements and during adverse weather conditions.

VI. Measurement Errors and Accuracy of Localization

In this section we evaluate the robustness of our localization scheme in the presence of measurement errors in both the range and the angle. Using simulations we understand how error propagates from the origin to other nodes which are several hops away. This also gives us an insight to the design considerations of the optical nodes (or any other physical layer technology used to implement ROL schemes), when deciding the parameters like accuracy with which each nodes should estimate the range and orientation to obtain an average error performance for the entire network and the working range of each node.

The error creeps into the location system from the following sources:

- Finite field of view of the photo-detectors.
- Finite package density of the transceivers.
- Measurement error of the range r.

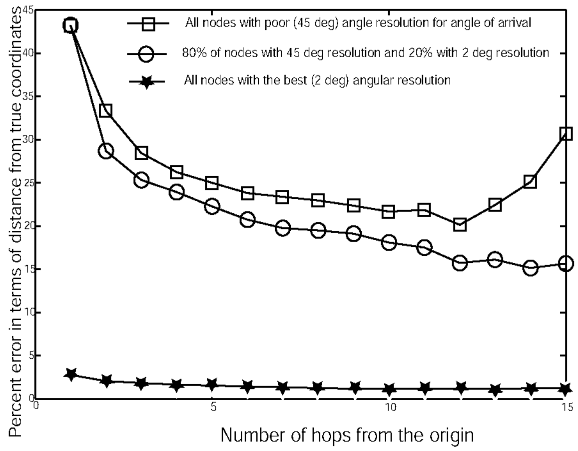
The first two sources of error cause an error in the nodes' axes alignment as well as in estimating the relative orientation. As shown in Figure 2, the transceiver a has a finite field of view, a magnitude denoted by the angle Ψ. Consequently, the transceiver, when trying to measure the orientation at which it "sees" another node, the angle becomes $\theta \pm \Psi/2$. A similar error results when the number of transceivers on the FSO node are few, thereby reducing the resolution of the angle with which a neighbor is perceived. We performed simulations to understand how the error due to an error in estimating the orientation effects node localization and how this error propagates with the number of hops away from the origin. We also studied the case where nodes have varying accuracy for orientation estimation. Nodes may be differing in the number of transceivers on each node or the angular resolution per transceiver. Thus, accuracy and the cost of the component can be engineered according to the specific application. For example, we have a very large error of $\pm 45^o$ (i.e., four transceivers per node) for a randomly selected fraction of nodes and the rest of the nodes to have better accuracy of $\pm 2^o$. We repeated the same experiment with an error of $\pm 10^o$ (specification of most of the off-the shelf components) and $\pm 2^o$. The results of the simulations are illustrated in Figure 6.a and Figure 6.b. The encouraging observation with localization error propagation is that it stays more or less constant for the most hops mainly for smaller angle estimation errors. For larger estimation errors we see occasional drops in the localization error. Localization is very sensitive to the sign of angle estimation error. If the consecutive hops have an angle estimation error with same sign, depending on the sign, the error might go up or go down.

Similarly, we introduced an error of $\pm 10\%$ in estimating the range between two nodes compliant with industrial laser ranging instruments. Error in terms of distance from the true coordinates are shown in Figure 6.c. The error increases linearly with the number of hops, i.e., as we move away from the origin, the error accumulates. Another observation is that for shorter node ranges, this increase is smaller compared to having longer node range, as the error is proportional to the range.

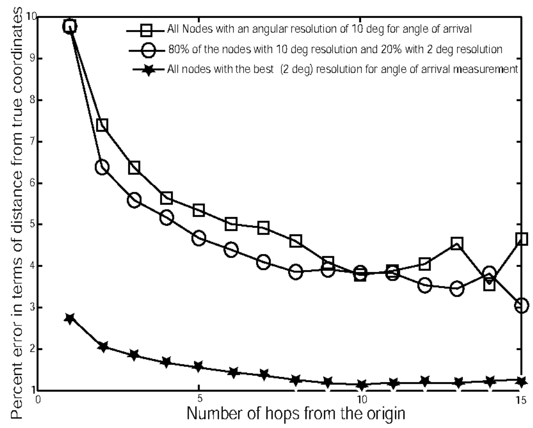
VII. Conclusion

In this paper we explored how directional communications can play a role in layer 3 protocols through efficient, distributed localization. We presented a distributed algorithm to build a relative coordinate system for a network without any anchor nodes. We evaluated the performance of the algorithm for its scalability and sensitivity to range/direction errors. We proposed the use of free space optics technology to realize a practical localization system based on range and orientation. We compare our scheme to a distributed anchor-based triangulation scheme where nodes try to localize in a hop-by-hop manner using three anchor nodes and compared it with our algorithm. Without the anchor nodes, obtaining a relative coordinate system in triangulation is very expensive and not scalable[3]. We showed through simulations that ROL based distributed algorithm outperforms triangulation in terms of convergence time and number of control messages exchanged for localization. We simulated the error in localization due to measurement errors in range and orientation and studied its propagation with the number of hops from the origin.

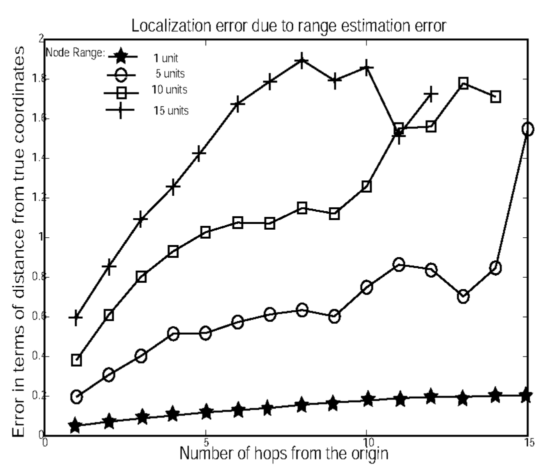
In the future, nodes can be equipped with hybrid RF and FSO capability (with the latter either used to supplement capacity, or support higher-layer functions such as localization). FSO can be used to achieve quick and scalable localization and also for communication under good weather conditions, where as RF can be switched on optionally when FSO is not



(a) Absolute error in terms of (percent) distance from correct coordinates due to an estimation error in orientation because of coarse angular resolution.



(b) Absolute error in terms of (percent) distance from correct coordinates due to an estimation error in orientation.



(c) Absolute error in terms of distance from correct coordinates due to an estimation error in range.

Fig. 6. Error Propagation in FLA with the number of hops away from origin due to errors in range and orientation estimation

available due to line of sight requirements and adverse weather conditions. Such hybrid designs can offer higher average bit rates and energy savings.

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