Distributed Constraint-based Location Discovery in Ad hoc Networks

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Abstract

Location discovery is a fundamental building block for many mobile applications. Yet dedicated infrastructure for determining node locations is expensive, energy-consuming, and simply unavailable under certain deployment scenarios. This paper presents an accurate, cheap and scalable protocol for location discovery. Called Zoom, this protocol operates by setting up and solving a system of geographic constraints based on connectivity information from the underlying communication network. Zoom achieves high accuracy by aggressively extracting constraints from the link layer, by propagating this information across multiple network hops and by explicitly tracking the set of possible locations for any given node instead of a single position estimate. Physical experiments with motes show that a large number (98%) of the nodes in a network can determine their positions based on a small number (30%) of landmark nodes with high accuracy (median error less than 30% of transmission range).

1 Introduction

Many critical applications for wireless networks require determining the physical location of network nodes. For instance, sensor applications usually require sensor data to be tagged with the physical location of the measurements. Geographic routing protocols rely on node location in order to forward packets with low overhead. And context-aware applications need to determine the locations of network participants in order to customize content for users depending on their location. These, and many other location-sensitive applications [9, 3, 8], require determining the position of mobile nodes with high accuracy and low cost.

There are three fundamentally different techniques for location discovery based in the type of hardware used for inferring location. The first and simplest technique is to statically record the location of each node at deployment time. This approach clearly fails when nodes move. Even in static sensor networks, this approach requires an extra step during deployment that is often costly and sometimes, for instance, in the case of aerial sensor dispersion, simply infeasible. A second approach is to outfit each device with dedicated positioning hardware, such as infrared transmitters, ultrasound transcievers and GPS receivers. These schemes require a substantial pre-deployed hardware infrastructure in the environment. The dedicated hardware on each node is often expensive, takes up volume and consumes a significant portion of the total energy budget. Finally, the third and last approach is to extract geographic information from wireless communication hardware that is already present on wireless nodes.

In this paper, we present a distributed location discovery protocol that extracts geographic information from cheap, already-present wireless links and use this information to infer node location with high accuracy. The overall goal of our protocol, called Zoom, is to enable large groups of cheap nodes that lack dedicated positioning hardware to determine their location. Zoom operates by setting up a system of relative geographic constraints among the network participants based on network connectivity and solving this system in a distributed and efficient manner with the aid of absolute position information provided by a small number of landmarks. A landmark is a node whose absolute position is known; Zoom landmarks can be cheap static nodes whose positions are fixed, or they may be mobile nodes equipped with dedicated hardware, such as GPS. We show that in realistic deployment scenarios, a very small percentage of landmark nodes (30%) is sufficient for a large percentage of nodes in the network (98%) to determine their location to GPS-level accuracy without GPS hardware. Zoom achieves high accuracy through three mechanisms: (1)

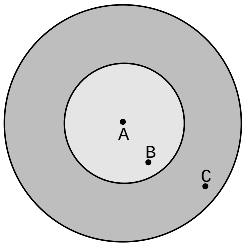


Figure 1: Using both positive and negative information enables node position to be narrowed down significantly. If C can receive beacons from B (positive information), but not from landmark node A (negative information), its position is limited to an annulus, shown in dark gray.

it aggressively extracts geographic constraints from the link layer, (2) it propagates constraints throughout the network and (3) it explicitly tracks the set of all possible locations for any given node.

Zoom aggressively extracts positive and negative information from the link layer and converts it into geographical constraints 1. By positive information, we mean a constraint of the form $\mathcal{E}_C \in \alpha$, where $\mathcal{E}_C$ denotes the estimated position of node C and α denotes an area tracked by the link layer, such as the transmission range of some node B. Receiving a direct beacon from a nearby node enables such a constraint to be established. In contrast, negative information corresponds to a constraint of the form $\mathcal{E}_C \notin \alpha$, and can be generated when a node indirectly determines the existence and position of another node C but fails to receive direct transmissions.

Zoom translates these constraints into geographic terms and disseminates them transitively throughout the network, creating an interdependent web. Transitively propagating location information enables nodes that are not within the immediate vicinity of landmarks to determine their location. It also enables nodes to extract negative information by discovering the presence and estimated location of other nodes in the network. Transitively combining position estimates enables information from sparsely distributed landmarks to be coalesced together to reduce positioning error.

A critical issue in location discovery is the representation of a node's position. Assuming a standard wireless signal strength attenuation model, a system that tracks only positive connectivity information will generate a set of convex constraints. The addition of negative information introduces concave boundaries and disconnected areas, which make location estimation difficult. One approach is to keep and update only a single point estimate of each node's position. While this approach requires little state, it also introduces errors that may compound. Zoom uses Bezier curves to explicitly represent the set of *all* points at which a node can be located. Since this set may consists of disjoint polygons, explicitly representing it as a set avoids estimation errors. Bezier curves are resilient to small errors in the location of control points [1], and in addition, can be represented very efficiently, reducing packet size. Zoom can pass this set to location-aware applications that can handle sets of positions, or perform a final mapping to a point to support legacy applications without introducing errors into the system.

Overall, this paper makes three contributions. First, it makes a case for the use of both positive and negative information derived from the physical layer, for the transitive dissemination of location information, and for explicitly representing location estimates as sets of points. These mechanisms enable Zoom to greatly improve the fidelity of its location estimates. Second, it outlines a distributed, efficient and scalable algorithm for estimating node location. This protocol enables nodes without any dedicated hardware to determine their position with high accuracy based on a small number of landmarks. Finally, this paper reports results from an actual physical deployment as well as simulations to show that the approach is both effective and practical. We have implemented the location discovery protocol described in this paper and tested it on MICA motes [7], laptops and StrongArm-based PDAs equipped with 802.11b cards. This paper evaluates Zoom both through extensive simulation and a physical deployment on MICA motes. The physical experiment validates the simulations, and shows that Zoom is effective at accurate location discovery.

The rest of this paper is structured as follows. Section 2 describes our design goals and provides an overview of Zoom's operation. Section 3 provides a detailed description of the Zoom protocol. Section 4 describes an efficient implementation of Zoom that uses Bezier curve segments to represent areas. Section 5 evaluates Zoom using both simulations and physical experiments. Section 6 describes optimizations that take advantage of extra information from the link layer, where available. Section 7 suggests directions for future work, Section 8 highlights some of the related work, and Section 9 provides a summary of the contributions.

2 Goals and Approach

An ideal location discovery protocol would have the following properties:

- **Cheap:** Location discovery should be cheap and consume little power, with minimal dependence on infrastructure in the environment and dedicated hardware on each node.
- **Accurate:** Location discovery should achieve high accuracy. The degree of accuracy should be tunable by the network administrator.
- **Scalable:** The protocol should scale well with increasing number of nodes. Packet sizes should be independent of the area of network coverage and number of nodes.
- **Heterogeneous:** The protocol should support heterogeneous networks where nodes have differing capabilities, such as varying transmission power levels, antenna arrays for determining angle of arrival, configurable angle of transmission and signal strength measurement hardware for relative position estimation.
- **Easy to deploy:** Finally, the protocol should be practical and easy to deploy. Assumptions made in calculating locations should hold in the field.

Zoom achieves these properties by its extensive use and propagation of information gleaned from the data link layer. Zoom nodes operate by exchanging information about their relative positions and geographic constraints. Each node keeps track of its *estimated location* $\mathcal{E}$, represented as a possibly disjoint set of points. Zoom nodes also keep track of two additional regions as seen in Figure 2. First, each zoom node A tracks its *maximal coverage area* $\mathcal{M}_A$, which is the upper bound on the region A's beacons can reach. A node can derive its maximal coverage area from its location set and knowledge of transmission properties. The maximal coverage area is used as part of positive information; when a node B can receive direct transmissions from node A, B can infer that it is located in A's maximal coverage area, i.e. $\mathcal{E}_B \subset \mathcal{M}_A$. Second, each node A keeps track of its *assured coverage area* $\mathcal{A}_A$, which is the (possibly empty) region in which another node would be guaranteed to receive A's beacons. When a node B learns of node A's existence, but cannot receive direct transmissions, it can infer that is is located outside A's assured coverage area, i.e. $\mathcal{E}_B \cap \mathcal{A}_A = \emptyset$.

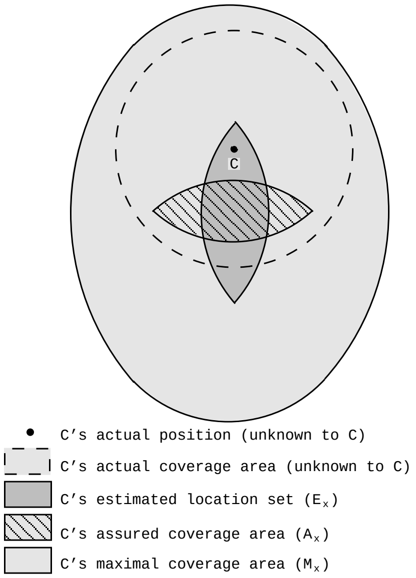
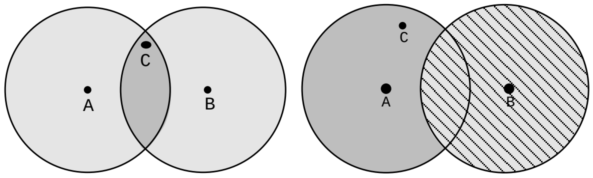


Figure 2: Illustration of key terms. A node C that is within the beacon range of two landmarks, A and B, can determine its *estimated location set* $\mathcal{E}_C$ via intersection. It can determine its *maximal coverage area* $\mathcal{M}_C$ by taking the union of all transmission ranges originating from $\mathcal{E}_C$, and its *assured coverage area* $\mathcal{A}_C$ by taking the intersection.

Zoom works in rounds, combining both negative and positive information at each round and propagating estimated positions throughout the network. Consequently, it sets up and partially solves a system of geographic constraints at each round, producing location estimates of increasing fidelity at each round. Zoom converges in a few rounds in practice. A compact representation of node positions using Bezier curves, coupled with optimizations to prune constraints that are too far away to refine local estimates, keep packet sizes small.

Geographic constraints in Zoom are set up pair-wise between one-hop neighbors in the network. The main assumption that Zoom makes is that nodes have an estimate of the area in which their transmissions can be received. The shape and size of this area can vary from node to node in a heterogeneous network, and the protocol will take these areas into account as it derives its geographic constraints. There are no constraints on the shape or size of this area – it need not even be simply connected. The protocol does not rely on heavyweight mechanisms like clock synchronization. Similarly, it does not mandate access to link-layer information such as signal strength measurements, time of arrival, or angle-of-arrival information, though such data can be used where available to improve the fidelity of



(a) C hears A and B. (b) C hears A; not B.

Figure 3: A simple example of single-hop operation. A and B are landmark nodes. C locates itself inside the dark gray region.

location information. We later describe and quantify the potential improvement provided by signal strength and directional transmission.

3 Protocol

In this section, we describe in detail the operation of the Zoom protocol. We note where we make simplifications in the presentation for clarity.

The Zoom protocol operates by keeping track of several regions for each node. We assume that each node knows its *transmission pattern* $\mathcal{T}_A$, which is the set of points that A's transmissions can reach. This pattern may be parameterized by both A's transmitter capabilities and by A's location. To simplify the discussion, we will describe a homogeneous network with omnidirectional antennas and no obstacles, which yields circular transmission ranges around each node. We show later on that Zoom can accomodate heterogeneous networks with more complex transmission patterns. Without loss of generality, assume that nodes farther than a certain threshold R distance away from A cannot receive A's beacons, and that nodes closer than a certain distance r distance away from A can. These two radii define two circles γ_r and γ_R, respectively, which govern where A's beacons can be received.

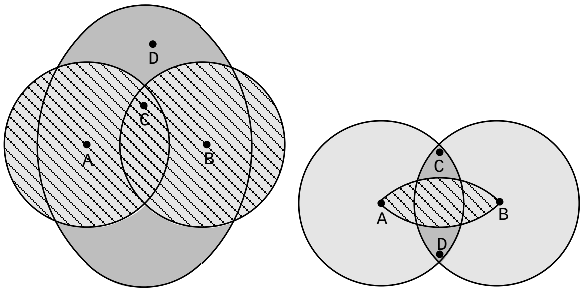
Each node A defines and keeps track of three areas around itself – the *estimated location set* $\mathcal{E}_A$, the *maximal coverage area* $\mathcal{M}_A$ and the *assured coverage area* $\mathcal{A}_A$. Figure 2 shows the relative locations of these areas. The estimated location set $\mathcal{E}_A$, as previously discussed, consists of a possibly disjoint set of points at which the node might lie. It represents the system's best determination of that node's position and is derived by combining the geographic constraints related to that node. The maximal coverage area $\mathcal{M}_A$ is defined as the upper bound on the region A's beacons can reach. A node can derive its maximal coverage area from its location set and knowledge of transmission properties. Specifically, $\mathcal{M}_A = \bigcup_{i \in \mathcal{E}_A} \gamma_R(i)$, where $\gamma_R(i)$ is the circle with radius R centered at i. This corresponds to the set of all points p such that the minimum distance from p to some point in the estimated location set is less than R. The assured coverage area $\mathcal{A}_A$ for a node is the (possibly empty) area to which the node is guaranteed to be able to transmit. Specifically, $\mathcal{A}_A = \bigcap_{i \in \mathcal{E}_A} \gamma_r(i)$. This corresponds to the set of all points p such that the minimum distance from p to *all* points in the estimated location set is less than r.

Zoom relies on the presence of some landmark nodes in the network in order to anchor the system of relative constraints in absolute space. By definition, landmark nodes determine their own position independently through external means, such as statically encoding it at deployment time or through dedicated hardware, such as a GPS receiver. For a landmark node L whose position is known, $\mathcal{E}_L$ is a circle centered at the node's estimated location, with a radius equal to positioning error.

Zoom determines the location of non-landmark nodes in the following fashion. Initially, the estimated location set for all nodes spans the entire space. The following rules, depicted in Figure 3, are applied to progressively narrow down node positions:

- If node C can receive direct transmissions from node A, then C must be inside A's maximal coverage area and therefore C must update its $\mathcal{E}_C \leftarrow \mathcal{E}_C \cap \mathcal{M}_A$. We term this type of information *positive*; conceptually, it is combined with a node's position estimate through intersection.
- If C cannot receive direct transmissions from B, then C must be outside B's assured coverage area and therefore C must update its $\mathcal{E}_C \leftarrow \mathcal{E}_C \setminus \mathcal{A}_B$. We term this type of information *negative*; it is combined with a node's position estimate via subtraction.

Every node participating in the Zoom protocol keeps track of its estimated location set, maximal coverage area and assured coverage area. Each node, for example C in Figure 4, periodically broadcasts its own maximal coverage area every $\mathcal{P}$ seconds. When D hears this broadcast, it intersects its own estimated location set with this area. These broadcasts are useful only at



(a) D hears only C; C hears A and B

(b) D hears A and B; not C

Figure 4: An example of multihop constraint dissemination. A and B are landmark nodes. (a) D subtracts A's and B's assured coverage area from C's maximal coverage area. (b) D subtracts C's assured coverage area from the intersection of A's and B's maximal coverage area. In both cases, D concludes it is inside the dark gray regions.

the first hop and are not propagated further. Each node also periodically broadcasts its own assured coverage area and the assured coverage areas of other nodes that it knows about. If a node D that is not in the one-hop neighborhood of A learns about A's assured coverage area then D subtracts A's assured coverage area from its own estimated location set. It then forwards A's assured coverage area to other nodes that may be interested. These broadcasts are forwarded a limited number of times based on the configured time-to-live parameter. Note that when a node joins the network, it needs to wait for a grace period (typically of $\alpha\mathcal{P}$ seconds, where α is the broadcast loss rate) in order to provide a sufficient grace period to its immediate neighbors to send a beacon. New nodes refrain from processing negative information during the grace period in order to provide their neighbors with the opportunity to send a beacon. The interval between two broadcasts at a node is chosen from a uniformly distributed neighborhood around the configured interval length to prevent packet trains.

Zoom requires every node O to locally maintain the following data and parameters.

r,R	Radii of inscribing and circumscribing circles for O's own coverage area.
$\mathcal{E}_O$	O's estimated location set.
$\mathcal{M}_O$	O's maximal coverage area.
$\mathcal{A}_O$	O's assured coverage area.
V_O	A freshness label for location information related to O.
Neg_O	$\{\langle d_1, \mathcal{A}_{d_1}, \mathcal{T}_{d_1}, V_{d_1}\rangle, \ldots, \langle d_l, \mathcal{A}_{d_l}, \mathcal{T}_{d_l}, V_{d_l}\rangle\}$ A set of negative constraints discovered by O, along with associated freshness labels.
Pos_O	$\{\langle d_1, \mathcal{M}_{d_1}, V_{d_1}\rangle, \ldots, \langle d_l, \mathcal{M}_{d_l}, V_{d_l}\rangle\}$ First neighborhood of O, their maximum coverage areas and associated freshness labels.
$\mathcal{T}$	Time-to-live for transitive information.
$\mathcal{P}$	Inter-round delay.

Each invocation of the Zoom protocol operates in a series of rounds, in which information is disseminated one-hop from each node. At each round, a node O broadcasts a beacon containing $\mathcal{M}_O, V_O, \{\langle o, \mathcal{A}_O, \mathcal{T}, V_O\rangle\} \cup Neg_O$. Since positive constraints are useful only at the first hop, nodes need only transitively disseminate negative information. The time-to-live ($\mathcal{T}$) field is set by the originating node in order to curb the extent of information dissemination. The freshness label V_O is a monotonic counter, incremented by O every time it updates its estimated location set and used, as shown below, to prune out stale constraints from the system.

After a node transmits a beacon, it then waits for $\mathcal{P} \pm \delta$ seconds where δ is a small random interval. These broadcasts need not be reliable since subsequent broadcasts will propagate more refined estimates. The penalty for losing packets, however, is slow convergence.

Upon receiving a beacon from node O, node Q updates its own estimated location set based on new negative or positive information, generates a new freshness label if necessary, and transitively propagates the new constraints to other nodes. Specifically, node Q first adds $\langle O, \mathcal{M}_O, V_O\rangle$ to Pos_Q if V_O is larger than the previous V_O for node O in Pos_Q, and removes any preexisting entries from node O with a lower freshness label. Similarly, Q updates Neg_O to reflect the latest information extracted from O's beacon. Specifically, for each $X = \langle x, \mathcal{A}_x, \mathcal{T}_x, V_x\rangle$ appearing in O's beacon ($x \neq Q$), Q checks to see if the information is fresh by comparing V_x to the freshness value it has for node x in Neg_Q, if any. If the information is fresh and $\mathcal{T}_x > 0$, Q sets $\mathcal{T}_x \leftarrow \mathcal{T}_x - 1$ and inserts X into Neg_Q, replacing stale data from x if necessary. Finally, node Q computes its estimated location set according to:

$$\mathcal{E}_Q = \bigcap_{\langle x, \mathcal{M}_x, V_x\rangle \in Pos_Q} \mathcal{M}_x \setminus \bigcup_{\langle x, \mathcal{A}_x, \ldots\rangle \in Neg_Q \wedge \langle x, \ldots\rangle \notin Pos_Q} \mathcal{A}_x$$

If the newly calculated estimated location set differs from the previous estimated location set, node Q increments V_Q and uses this incremented value in its subsequent beacons. Each node also increments its freshness label every Δ seconds. Nodes whose freshness labels have not changed in $\alpha\Delta$ seconds are automatically deleted from Pos_Q and Neg_Q. Thus, the beacons serve as a failure detection mechanism without which stale information might persist in the network and lead to overconstraint. Note that loosely synchronized clocks are sufficient for this purpose. Ultimately, Q calculates a new $\mathcal{M}_Q$ and $\mathcal{A}_Q$ using r, R as described later in Section 4.1.

4 Implementation

To be efficient and practical, a Zoom implementation needs to represent coverage areas in a compact manner, intersect, subtract and union them efficiently and be able to derive $\mathcal{M}_x$ and $\mathcal{A}_x$. In addition, given $\mathcal{E}_x$, an implementation should be able to find an estimated point position that is likely to be close to the true position.

4.1 Areas bound by Bezier curves

Zoom uses Bezier curves to represent regions. Bezier curves are a natural choice when some errors are present in the measurements of the control points, as these errors are not magnified along the curve and thus intersect, subtract and union operations have the same error bounds as that of the original control points [1]. If there is negligible error in the measurement of a node's transmission range, then the same error bound applies even after the expand and contract operations used to generate $\mathcal{M}_x$ and $\mathcal{A}_x$ from $\mathcal{E}_x$. In addition Bezier curves can be represented in compact form, thereby decreasing the broadcast packet sizes.

Since the areas in the system are seeded with the circles of radius r and R centered at each landmark node, the areas resulting from the subtraction, expansion and contraction operations must be comprised of circular arc segments. We use 2^{nd} order Bezier curve segments to represent an arc of a circle using such curves. Algorithms implementing intersection, subtraction and union of areas represented as collections of curves are well known. We rely on these operations and use them to calculate $\mathcal{M}_x$ and $\mathcal{A}_x$ given $\mathcal{E}_x$. $\mathcal{M}_x$ is equal to $\mathcal{E}_x \cup \mathcal{M}_x \setminus \mathcal{E}_x$, and all points in $\mathcal{M}_x \setminus \mathcal{E}_x$ lie at a distance $d < R$ from some point on the boundary of $\mathcal{E}_x$. Consequently, one can determine $\mathcal{M}_x \setminus \mathcal{E}_x$ by taking the union of all circles of radius R centered on the boundary of $\mathcal{E}_x$. Similarly, $\mathcal{A}_x$ is the intersection of all circles of radius r centered on the boundary of $\mathcal{E}_x$.

Extending the planar representation used in Zoom to support 3-D node placement is straightforward. We can use the same approach to consider volumes of coverage using Bezier surfaces instead of areas of coverage with Bezier curves. Maximal and assured coverage volume counterparts of the respective coverage areas can be computed in an analogous manner, and nodes can intersect, subtract and union these volumes to get an estimated location set that comprises a region in 3D space.

4.2 Location Estimation

The best representation of a node's location is $\mathcal{E}_x$, its estimated location set, as it represents the full range of possibilities for the node's actual location. However, most legacy applications are not equipped to deal with such sets of possibilities and instead require that the node's location be represented as a single point. Consequently, a node has to pick a single location based on $\mathcal{E}_x$ to use as its location estimate. Ideally, an implementation should pick a point that minimizes the error in its location estimate. For location sets that form convex surfaces, the "center" is well defined and easy to locate; however, regions computed by Zoom may not be convex, and may not even be simply connected, that is, they may be disjoint or contain holes. Simple techniques for establishing a bounding box around disconnected components and determining its center may lead to a location estimate that lies far outside any region that a node may actually be in.

To avoid these pitfalls, we use a Monte-Carlo technique for mapping the rich point sets Zoom tracks internally to a single position estimate. We consider the set of points inside the bounding box of $\mathcal{E}_x$ and find the point that minimizes the mean distance to a set of other random points that lie inside $\mathcal{E}_x$. This approach captures the intuition that a node has high probability of lying inside a large connected component and therefore that component should influence the location estimation process more than a small component.

4.3 Transmission Overhead

In order to scale to large networks, Zoom has to decouple the amount of data propagated across the network from the system size. Every node periodically broadcasts its estimated location set and its assured coverage area. In addition, every node forwards packets from nodes that are at most $\mathcal{T}$ hops away where $\mathcal{T}$ is the configured time-to-live parameter. This gives us a bound of $\mathcal{O}(bd^T)$ on the transmitted data per node where d is the average degree of the connectivity graph and b is packet size. This is independent of the number of nodes in the network thus allowing Zoom to scale very easily to large networks without incurring additional overhead. In typical networks, d is around 7 and our physical experiment suggests that b is around 500 bytes and that $\mathcal{T} = 3$ is sufficient. Therefore Zoom introduces about 171 kB transmission overhead at each node every $\mathcal{P}$ seconds, where $\mathcal{P}$ is the configured inter-round delay.

5 Evaluation

In this section, we demonstrate that the approach described in the previous sections is effective i.e. a high percentage of non-landmark nodes accurately discover their location based on a very small subset of relatively more expensive landmark nodes. Further we show that extensively harvesting constraints from the network leads to low median error rates. We provide insights into network designers to select the optimal parameters for Zoom based on simulation and experimental results.

5.1 Simulation

For our simulation experiments, we use the following parameters. We assume that both landmark and non-landmark nodes are uniformly distributed at random on a square field of size 1000m by 1000m. We set the time to live parameter to 3 and the number of nodes to 100 yeilding an average degree of 10 in the simulations where they are held constant. Finally, we set both $r = R = 200$m for the simulations.

We compare four different location discovery systems to provide insights into how the system achieves its accuracy. Zoom is the Zoom protocol as described in this paper. Zoom`--` is a modified version of the Zoom protocol where only positive information is propagated; Bezier curves and Monte Carlo estimation are used for determining node locations, but negative information does not affect position estimates. LimitedZoom is a modified version of the Zoom protocol where the TTL has been restricted; LimitedZoom-TTL0 effectively disables multihop dissemination of location information. Finally, we compare our system to GPS-Less [4], a well-established algorithm for localization.

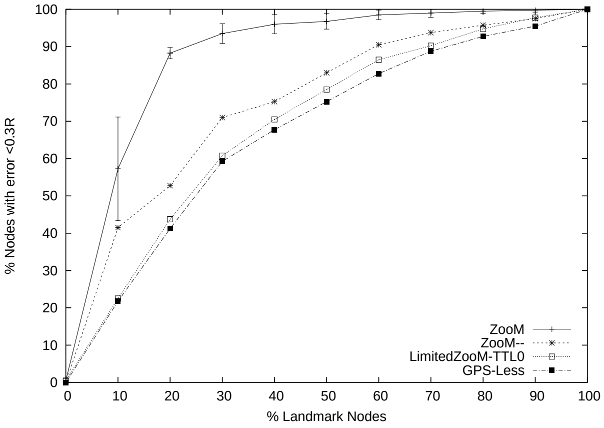


Figure 5: Percentage of nodes accurately estimating their position as a function of percentage of landmark nodes and time-to-live (TTL).

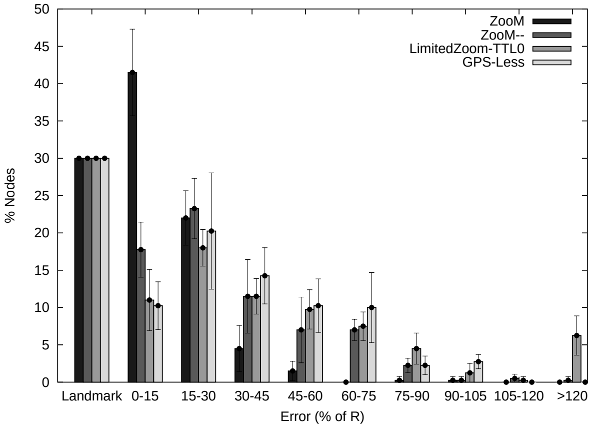


Figure 6: Histogram of error distribution of Zoom and GPS-Less.

Figure 5 plots the percent of nodes that can discover their location with sufficient accuracy versus the percent of landmark nodes seeded throughout the system. The graph demonstrates the effectiveness of the Zoom approach, where a large percent of nodes in the network can determine their position. Specifically, when more than 20% of the nodes are landmark nodes, more than 90% of the nodes in the system can discover their location accurately. The graph also quantifies the benefits of multihop dissemination of location information as well as the benefits of using negative information to supplement positive constraints. Single-hop schemes like LimitedZoom, and GPS-Less can determine position only when non landmark nodes are within range of

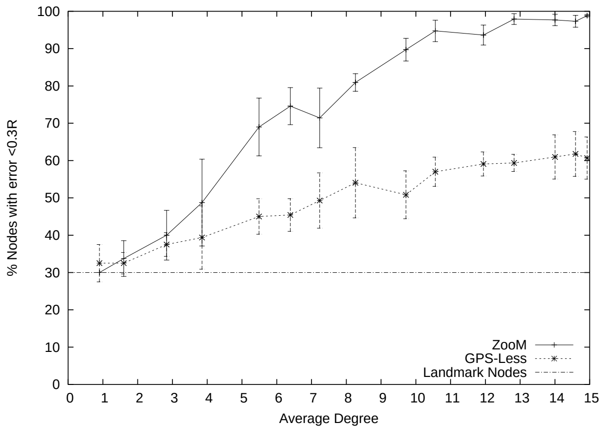


Figure 7: Percentage of nodes accurately guessing their position as a function of average degree of nodes

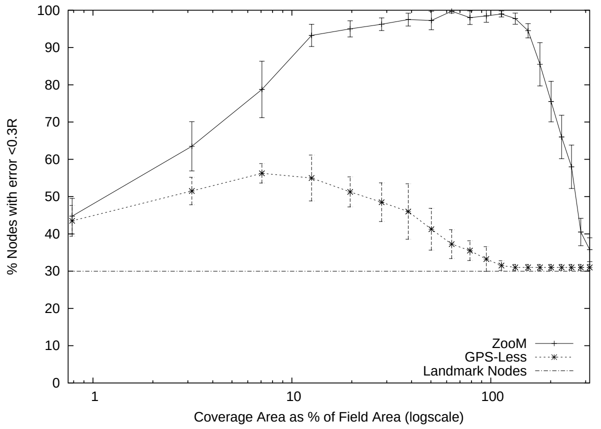


Figure 8: Percentage of nodes accurately determining their position vs. coverage area of each node

some landmark nodes; consequently, their effectiveness is lower. Similarly, Zoom-- demonstrates that schemes limited only to positive information are less effective. For this experiment, Zoom converges to its solution in 3 iterations; further rounds do not improve accuracy.

Figure 6 shows the positional error in Zoom location estimates, where positional error is the distance between estimated location and actual position. Compared to the other approaches, more Zoom nodes know their location to a higher degree of accuracy. This is partly due to use of negative information to complement the positive information in the network, and partly due to transitive network wide constraint setup that Zoom uses instead of single hop triangulation.

Figure 7 shows the effect of increasing the node degree while keeping the percent of landmark nodes fixed.

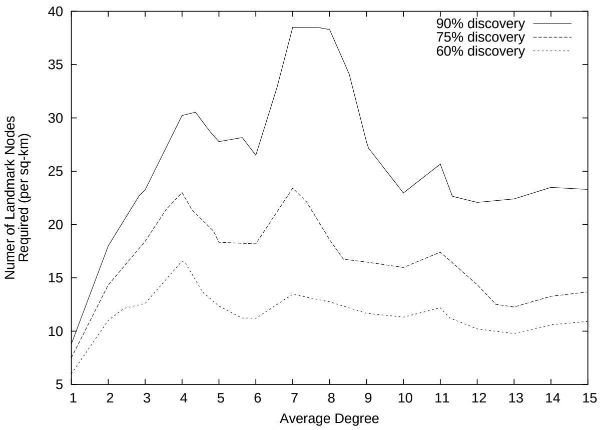


Figure 9: Number of landmark nodes required to maintain 75% location discovery as the total number of nodes increases.

Increasing the degree increases the connectivity in the graph thereby increasing the constraints in the system. This naturally leads to an increase in the fidelity of location estimates.

Figure 8 shows the performance of the system as node transmission power and consequently coverage area is increased. With one-hop triangulation in the GPS-Less system increasing the coverage area increases the number of one-hop landmark nodes a node can detect. Beyond a threshold this introduces an averaging effect and eventually all non-landmark nodes estimate their position to be at the centroid of all landmark nodes. With Zoom, however, as the coverage areas grow so does the assured coverage area, therefore balancing the averaging effect by subtracting larger areas of assured coverage. As a result Zoom is able to maintain its performance as transmission area increases. Only when coverage area exceeds field size, the non-landmarks nodes lose their ability to differentiate their position and only then does the system collapse. Overall Zoom is effective across a wide range of transmission powers.

As observed previously, with a small percent of landmark nodes, most of the nodes can discover their location once the degree is increased beyond a certain threshold. This suggests that it is possible to improve the fidelity of location estimates by decreasing the percentage of expensive landmark nodes and instead increasing node degree by adding cheap non-landmark nodes. Figure 9 plots the number of landmark nodes required to ensure that a targeted percentage of the total nodes discover their location versus node degree. Surprisingly, we find that certain threshold, the number of landmark nodes required to achieve a targeted percentage is a constant

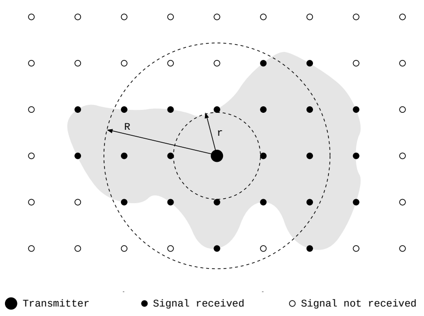


Figure 10: Coverage area of a MICA mote without an antenna. Grid separation is 30cm. While the transmission pattern is not symmetrical in practice, the model outlined previously with r,R accomodates the irregularities.

based on the size of the area to be sensed. Effectively, transitive propagation of constraints enables a small set of landmarks to help collapse the constraints and aid in non-landmark nodes' location discovery.

5.2 Physical Validation

In this section, we report on a physical deployment of Zoom and show that the simulation results can be achieved practically in the field. We first use Berkeley MICA motes [7] with integrated RF radios laid out on a grid of 34 nodes with a separation of 30cm[1]. The connectivity data gathered from this experiment was used to determine the r, R parameters. Figure 10 shows that physical devices have non-uniform transmission ranges; nevertheless, they can be accomodated using he model outlined in the preceding sections. The median transmission range is 43cm, the third quartile is 68cm (set as R). The minimum distance between non-neighbor nodes is 30cm (set as r).

We then examine the performance of different location discovery algorithms on a network where 112 motes are tiled on a grid of separation 30cm. The average node degree is 6 while the average number of landmark neighbors is 2. Figure 11 shows that both Zoom and Zoom`--` can locate more nodes than GPS-Less due to transitive dissemination of location estimates. GPS-Less fails to locate 55% of the non-landmark nodes since they do not have any landmark neighbors. In contrast Zoom fails to locate 2% of the nodes.

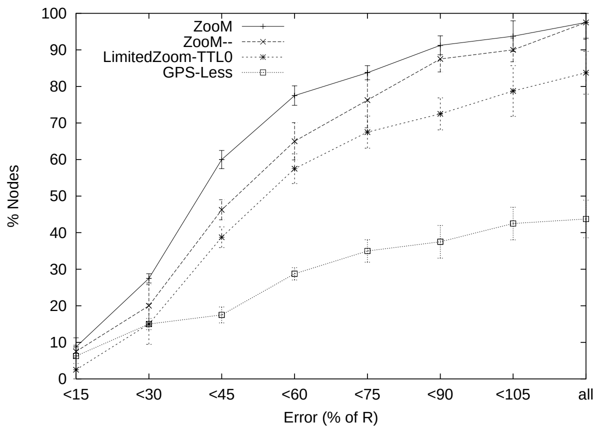


Figure 11: Cumulative number of nodes estimating their position as a function of the positional error with 112 total nodes, 80 non-landmark nodes. Negative information and transitive dissemination improve location estimates significantly.

Figure 12 shows that Zoom, which benefits from the negative information, is more accurate than other approaches. Zoom locates 61% of the total located nodes to within $0.45R$ (30cm) of their true position, whereas Zoom`--`, LimitedZoom and GPS-Less locate 48%, 41% and 40% nodes to the same accuracy, respectively. The median error for Zoom is 30% of R while the median error for the other approaches is significantly higher.

6 Optimizations

The previous sections discussed and analyzed the core Zoom protocol, which has minimal hardware requirements. Specifically, it relies solely on the connectivity information form the data link layer. Below we present two optimizations to improve the accuracy of location discovery when the communication hardware provides additional data. Zoom can take advantage of signal strength provided by hardware to refine node coverage areas to rings. Similarly, it can take advantage of directed transmissions to restrict node coverage areas to fractions of a circle. Both optimizations improve data fidelity by reducing the uncertainty in calculating the estimated location set. The trade-off, however, is that additional coverage areas need to be calculated and transmitted.

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[1] We were restricted by pragmatic concerns in our choice of hardware for the physical tests. We ran out of space at our university arboratum when we deployed Zoom on PDAs with 802.11b cards, whose drivers did not allow us to manipulate the transmission radius!

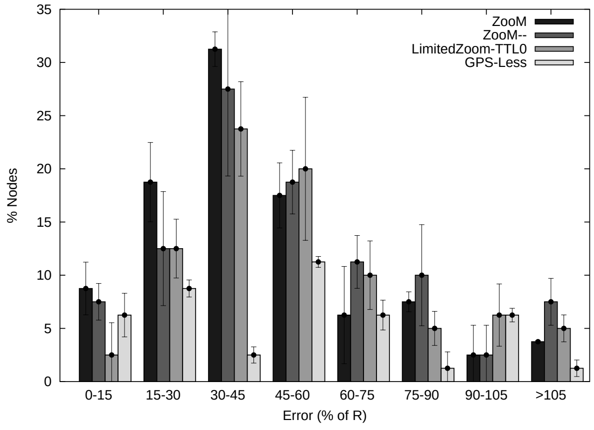

Figure 12: Histogram of error distribution of Zoom, Zoom-- and GPS-Less with 144 nodes, 80 non-landmark nodes

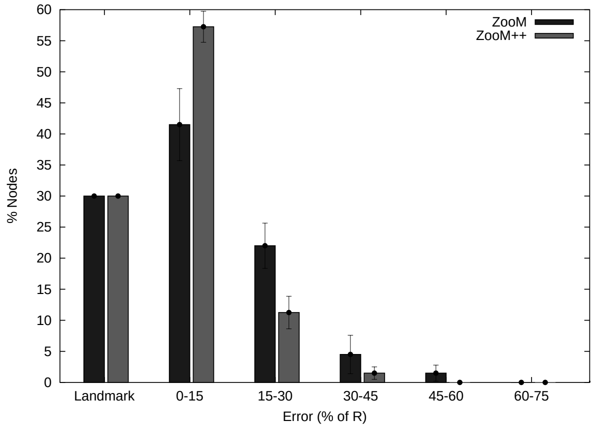

Figure 13: Histogram of error distribution for Zoom with and without the annulus optimization

If a node's communication hardware provides per-packet signal strength information, it is possible to extract more refined location constraints. Specifically, the signal strength can be mapped at the receiver through an attenuation model to estimate the distance from the sender. This enables a node to represent coverage areas not as simple circles but as rings of drastically smaller areas. The width of the ring depends on the error in the signal strength measurement as well as the accuracy of the attenuation function.

Some wireless radio cards provide signal strength information in ad hoc mode from other ad hoc nodes through a special interface in the device driver. The signal strength information is of sufficient accuracy to divide the transmission range coarsely into a few annuli of overlapping areas. Using the standard wireless attenuation model of $1/r^2$, we map the simulated signal strengths into 3 annuli of width 0-100, 50-150, 100-200m. Nodes with range estimates from 0-75 pick annulus 1, those with range estimates of 75-125 pick annulus 2 and above 125 pick annulus 3. We implemented the signal strength optimization (called Zoom++) with these parameters and examined the increase in data fidelity due to this optimization. Figure 13 shows the improvement in coverage and accuracy as a result of this optimization. We find that for Zoom++ 81% of the non-landmark nodes estimate their location to within $0.15r$ as compared to 70% for the non optimized version. In addition, with the optimization, 97% of the non-landmark nodes have errors of less than $0.30r$ as opposed to 90% in the unoptimized case.

A similar optimization exists for hardware that allows nodes to manipulate the angle of transmission on a per packet basis. Such data requires directional antennas but can enable Zoom to propagate tighter constraints. Each landmark node separates its coverage area into overlapping wedges similar to the way in which the signal strength optimization separates it into overlapping annuli. The spread of the directional antenna governs how the wedges need to overlap similar to the way the error in range measurements governs the annuli in the previous section. Information about each wedge is broadcast in the relevant direction. This approach is also applicable when the coverage area of the radio is not a circle but instead an elliptical region due to the physical construction of the node.

7 Future Work

Location discovery through a system of geographic constraints, solved in a distributed fashion, opens up many avenues for futher research. In the near future, we plan to examine the interaction of obstacles with the Zoom protocol. While obstacles can be a problem in cluttered environments, we find that Zoom often discovers many redundant constraints. Such redundant constraints can be used to actually *detect* obstacles. In addition, the basic Zoom approach can be combined with a topographic map of the area to take the terrain into account when determining a node's tranmission range ($\mathcal{T}_A$).

Directional antennas may lead to asymmetric transmission ranges. That is, the area in which a node's transmissions can be received may not be circular but, for instance, highly elliptical or directional instead. In order to use Zoom in this setting, nodes need to determine their orientation as well as position. This makes the set of constraints more complex; however, the problem is still amenable to the approach presented in this paper.

8 Related Work

Previous work has examined location discovery in both indoor and outdoor environments, with and without the aid of specialized hardware.

In indoor systems, administrators usually have sufficient control over the environment to deploy and maintain significant infrastructure. Systems designed for this environment can rely on communication between clients and the infrastructure to determine node position. Active Badge [12] is one of the earliest systems for indoor location discovery. It requires clients to periodically transmit unique infrared beacons that are received by landmark nodes equipped with infrared (IR) sensors placed at known locations within a building. Active Badge estimates the location of a client from the location of the nearest IR sensor. Cricket [10] operates by having the landmarks periodically transmit unique radio-frequency (RF) and ultrasound (US) beacons simultaneously. Non-landmark nodes receiving these beacons determine their distance to the landmark based on the time delay between corresponding RF and US beacons. Active Bat [13] locates nodes in the indoors environment with the aid of a grid of ultrasound receivers. RADAR [2] operates by mapping the signal strength of RF beacons from multiple landmark nodes to an estimated location. This mapping is performed either through an empirically measured signal strength database, or a physical model of signal attenuation combined with a map of the closed building. In all cases, these approaches require pre-existing infrastructure to be present throughout an environment for their operation.

GPS-Less [4] estimates node position through triangulation against multiple landmarks in the immediate vicinity. A node that can receive transmissions from landmarks L_1, L_2 and L_3 estimates that it is at the centroid of the landmarks. Since this approach does not disseminate position estimates beyond the first hop, it does not support nodes that are outside the range of landmarks. Consequently, it requires a large percentage of nodes within the network to be landmarks, increasing system cost and power requirements.

GPS-Free [5] is an alternative approach that uses range measurements to build a network coordinate system. It relies on measuring the time of arrival for packets in order to estimate the range between pairs of nodes. Time of arrival measurements are typically not practical as they require clock synchronization hardware that costs far in excess of the sensor nodes themselves. In Robust Positioning [11], nodes use range measurements to estimate their positions by triangulation against their one-hop neighbors and propagate the new estimates of their location at each round. This approach needs to be coupled with verious heuristics as the algorithm is not guaranteed to converge. Convex position estimation [6] uses geographic constraints in a manner similar to ours, but differs fundamentally in how it interprets and solves the resulting system of constraints. First, it uses only positive connectivity information in building its convex constraint set. Second, it uses efficient convex computational methods which handle poorly the cases where the estimated location of a node consists of several disjoint areas. Finally, it depends on a centralized server to solve the constraint system and is not a distributed protocol. Zoom`--`, as described in Section 5.1, mimics Convex position estimation in that it uses only convex constraints.

9 Conclusions

In this paper we outlined a distributed, accurate and scalable protocol for location discovery in ad hoc networks. This protocol enables nodes that are multiple hops away from landmarks to determine their position with high accuracy. Zoom aggressively extracts both positive and negative geographic constraints from the wireless link layer. The protocol then simultaneously sets up and solves these constraints to determine node locations with the aid of a small number of landmarks. Physical experiments with motes show that the protocol is effective at locating 98% of the nodes to within 30cm with the help of 30% landmark nodes. We also show that the protocol places a light load on the network, sending small packets at intervals determined by the mobility rate of the nodes. Representing possible node locations as sets throughout the protocol, instead of collapsing them to a single, best-estimate point, enables Zoom to keep track of locations accurately. Future applications that can utilize such information can benefit significantly; while a mapping from the possible location set to a single point can support legacy applications.

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