P2PLoc: Peer-to-Peer Localization of Fast-Moving Entities

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P2PLoc envisions wearable Internet of Things devices that compute the relative positions of each user, resulting in a topology or configuration of mobile users that can be tracked in real time for group-motion applications.

FROM THE EDITOR

Precise indoor locations systems are coming of age, and enabling context-aware operations will result in a wide range of effective Internet of Things (IoT) applications.[1] However, for many of these systems to operate, they need location reference points, or some fixed nodes of known location. This article makes the case that there are many peer-to-peer location applications that only require the relative positions of the mobile nodes, and explores the issues that need to be considered to accurately determine their topology. *—Roy Want*

Localization has been extensively studied in various contexts, both indoor and outdoor. Yet, emerging applications continue to ask for new requirements that challenge existing localization mechanisms. For instance, a team of soccer or basketball players might seek their precise positions during a game—this is valuable to coaching and sports analytics applications. As another example, a swarm of wirelessly connected IoT drones carrying chemical probes might need to fly in precise formations to analyze water samples from a polluted lake while constantly reporting their sensor readings and each drone's relative position in the swarm to a central aggregator. Similarly, an army troop on the ground or a group of first responders

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in a disaster-relief effort could benefit from the ability to continuously visualize their group's configuration. However, GPS might not be adequately precise or even available on a battlefield, and environmental infrastructure might not be available, for example, on a basketball court.

As a solution, P2PLoc (peer-to-peer localization) envisions wearable IoT devices on users' arms or wrists that exchange wireless messages to ultimately compute the relative positions of each group member. The outcome is a topology or configuration of mobile users that can be tracked in real time. We believe this can be a valuable primitive to various group-motion applications.

Existing localization approaches are usually based on creating a large database of received signal strength from a few fixed access points and then matching the measured signal strength to report the approximate location of the user. However, in the sports or army contexts, we might not have the liberty to create such a fingerprint of the entire arena. Instead, we propose to use the time wireless signals take to travel between two devices as a measure of the distance between them. The precision of this time measurement directly correlates with the bandwidth of the wireless signal used. Therefore, we use ultra-wideband (UWB) radios with a 1 GHz bandwidth. When used with a packet-handshake protocol called two-way ranging (TWR), today's UWB platforms can estimate the distance between two devices with about 10 cm precision without clock synchronization.

A group of players or military personnel can be abstracted as a network topology (see Figure 1), with each node representing an individual and the edges representing the distance between them. Given n nodes, TWR performed between every pair generates the distance of each edge in the network. These distances naturally over-determine the system, producing the *relative* topology graph (relative because the produced topology could be a rotated version of the true topology) of all the participating devices. Our goal is to localize dynamic nodes whose locations change over time. Tracking mobile nodes requires fast collection time to prevent measurements from becoming too stale. Collecting each pairwise distance is not possible because each TWR handshake consumes time and there are $O(n^2)$ pairwise distances to be measured, scaling poorly as the number of devices, n, grows. Of course, instead of over-determining the system through n^2 measurements, we can still solve the topology with $\frac{3n}{2}$ pairwise measurements. This would significantly reduce the total localization time. Thus, the essential question for this approach comes down to which $O(n)$ pairwise distance measurements will result in fast and accurate tracking of the topology.

There are three main factors to consider when choosing the pairs:

- the total number of wireless message exchanges while executing the TWR protocol;
- the geometric dilution of precision, which changes with the topology; and
- occlusions caused by humans that makes some links unusable.

TWR PROTOCOL OPTIMIZATIONS

Figure 2a shows the original TWR protocol. It is simply a ping-pong of messages with precisely measured timings at both participating devices. It is comprised of three time-stamped messages exchanged between a device pair—an initiator and a responder. We obtain the time of flight by averaging the difference between the two

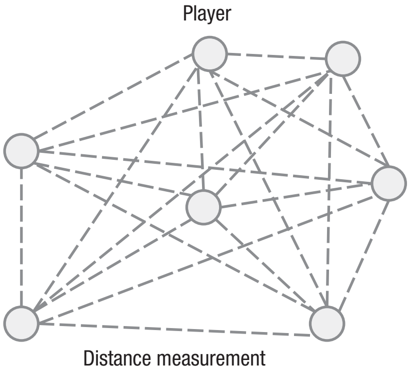

Figure 1. A group of players abstracted as a graph. Nodes represent the players and edges denote each distance measurement performed.

round-trip times and the two turnaround times. For a group of devices, one would require all three messages to be exchanged between each selected device pair. This would mean $3 \cdot d$ messages need to be exchanged to obtain d distance measurements (see Figure 2b). Also, we need at least three distance measurements for every node to uniquely solve a topology. By carefully picking the edges, it is possible to obtain a solution in $\lceil \frac{3n}{2} \rceil$ distance measurements for n nodes. Figure 2b shows one such careful choice.

The original TWR protocol is designed for one-to-one distance measurement. However, the broadcast nature of wireless channels permits one-to-many operations, providing an opportunity to reduce the total number of messages exchanged. As shown in Figure 2, the initiator's POLL message can be heard by all other nodes. They can then take turns to send the RESP message back to the initiator. A single FINAL message then suffices for all the responders to calculate their distance from the initiator. A further optimization is possible where all initiators take turns to send their POLL messages, and the responders take turns

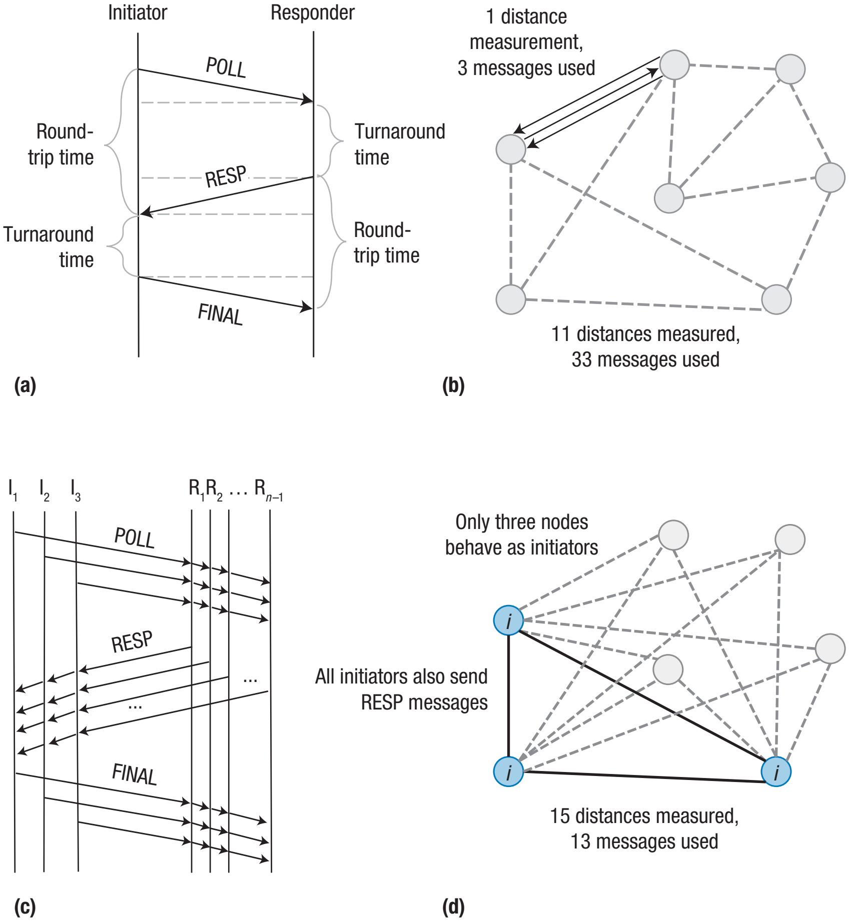

Figure 2. (a) The original two-way ranging (TWR) protocol. Each distance measurement needs three messages. (b) For triangulation, each node must have at least three edges. (c) Our modified TWR protocol to minimize the number of wireless messages exchanged in a group of nodes. (d) Only three nodes initiate TWR—a minimal number of messages exchanged ensures faster overall protocol time.

to send only one RESP message each. This is followed by the initiators sending FINAL messages. Just three initiators are required to solve the topology. This optimized ranging protocol and the resultant set of distance measurements are shown in Figure 2c and 2d, respectively. While this protocol is suboptimal in the number of distances measured, it is *optimal* in the number of wireless messages exchanged. Ultimately, minimizing the message exchanges speeds up localization.

DILUTION OF PRECISION

The optimized TWR protocol provides an upper bound on the system update rate for *n* nodes. However, it makes no claims about the accuracy obtained through a particular choice of three initiator nodes. If all distance measurements were precise, this choice would not matter. However, if distance measurements have even small errors, such as those introduced by hardware noise, then the localization accuracy can be severely affected by the choice of initiator nodes. The dark overlapping area in Figure 3 shows the region of confusion—node T could be anywhere within this region. Observe how the geometry of the initiators (labeled A1, A2, and A3) affects this dark region.

This problem, called *geometric dilution of precision* (DoP), occurs in GPS receivers as well. GPS DoP solutions[2,3] should be applicable in this situation. However, there is a key difference in the way GPS estimates DoP and what would be required in a short-range system like ours. GPS only uses the angles between vectors formed by the initiator positions but ignores the magnitude. While this works reasonably well for GPS (because of the very large distance between Earth and the satellites), ignoring the magnitude can lead to poor choices in short-range systems. Instead, we calculate the estimated localization error directly and select the best initiators.

HUMAN OCCLUSIONS

Accurate distance measurements depend on the wireless device's ability to identify the direct line of sight (LOS) path between two nodes. This can become challenging due to body blocking when the device is worn by humans. Non-line-of-sight (NLOS) paths can then be misinterpreted as being the first path, causing large-ranging errors. Figure 4 demonstrates the impact of body blocking with a set of nodes (blue squares) arranged in a semicircle around a person wearing a UWB device on his or her arm. Distance estimates for devices blocked by the person's body are significantly scattered and erroneous (red streaks), while those obtained by non-occluded devices are more precise (green dots). Using distance estimates from occluded nodes to solve for the topology can cause severe localization errors. In a fast-moving topology, human occlusions are common and a scheme that does not cater to such situations will fail miserably. Thus, even if DoP considerations indicate a set of initiators to be optimal, occlusions might render that choice infeasible.

Determining occlusion based on link quality between every node pair is time-consuming. Fortunately, because every device can overhear all ongoing communication, a device can deduce its link quality with all other devices just by listening to the channel without incurring time costs. Each device independently deduces occlusions and produces an exclusion list, which is updated at every round of the pipelined TWR protocol.

EVALUATION PLATFORM AND RESULTS

We invited 10 volunteers to wear UWB arm bands while playing basketball. The volunteers took specific positions on a basketball court, creating a topology. Each UWB node (https://www.decawave.com/products/evk1000-evaluation-kit), shown in Figure 5, ran our modified TWR protocol and chose a set of appropriate initiator nodes based on DoP and occlusions. The volunteers moved into 22 different topologies, mimicking important positions in a basketball game. Overall, the 75th percentile localization accuracy for all the volunteers across all topologies was around 0.8 m. Of course, some topologies provided poor occlusion-free choices, causing a relatively long tail. In a real game, we expect such cases to be few and short-lived. To measure the impact of occlusions alone, we repeated the game by mounting the UWB nodes on tripods. The resulting localization error stayed under 0.2 m, showing the significant impact of human occlusions.

IMPLEMENTATION IN IOT DEVICES

We have discussed specific optimizations and pitfalls in implementing a peer-to-peer relative localization scheme in the context of sports and other group activities. Whereas we used UWB devices for performing the distance measurements, the fundamentals discussed here remain applicable for any ranging technology. Recent advancements in the IEEE 802.11-REVmc protocol[4] allow for wireless time-of-flight measurements on commodity WiFi devices and access points, which can easily be adapted to perform the peer-to-peer measurements envisioned in this article. IoT devices that support this technology can be built today. P2PLoc can thus transform ad hoc playgrounds into sports-analytics arenas without relying on expensive tracking technology.

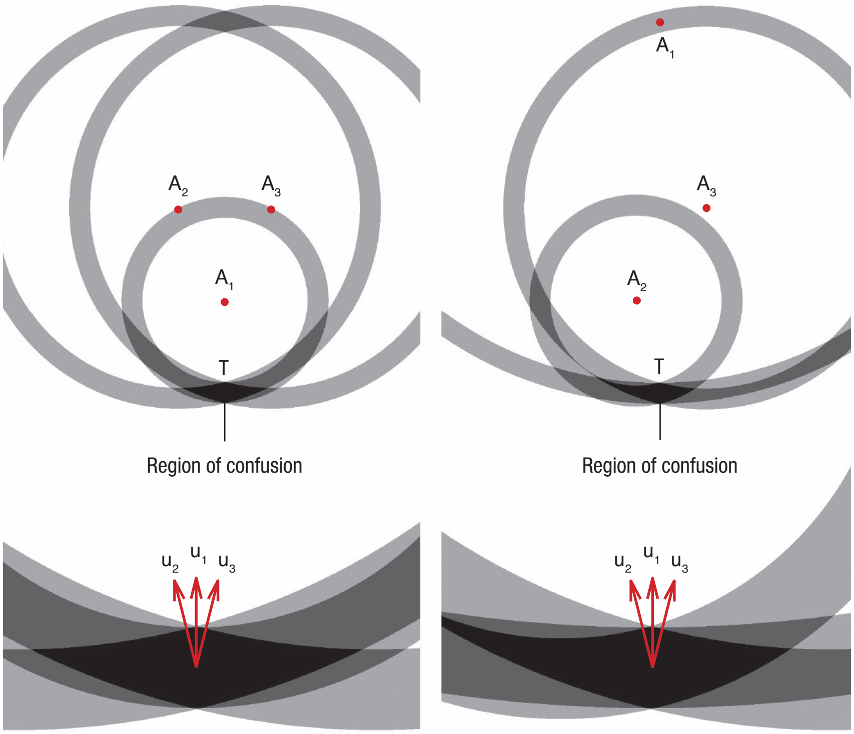

Figure 3. The node's location can be estimated to be anywhere in the region of confusion. The shape and area of this region depends on both the magnitude and the angle of radius vectors formed by the initiators.

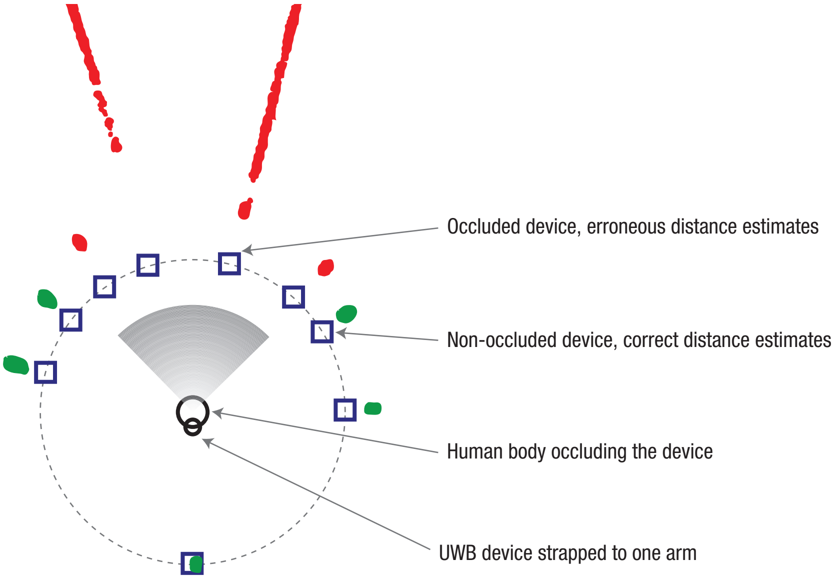

Figure 4. Effect of human occlusions on estimated distance. Ultra-wideband (UWB) devices that are blocked by a person's body obtain erroneous distance estimates.

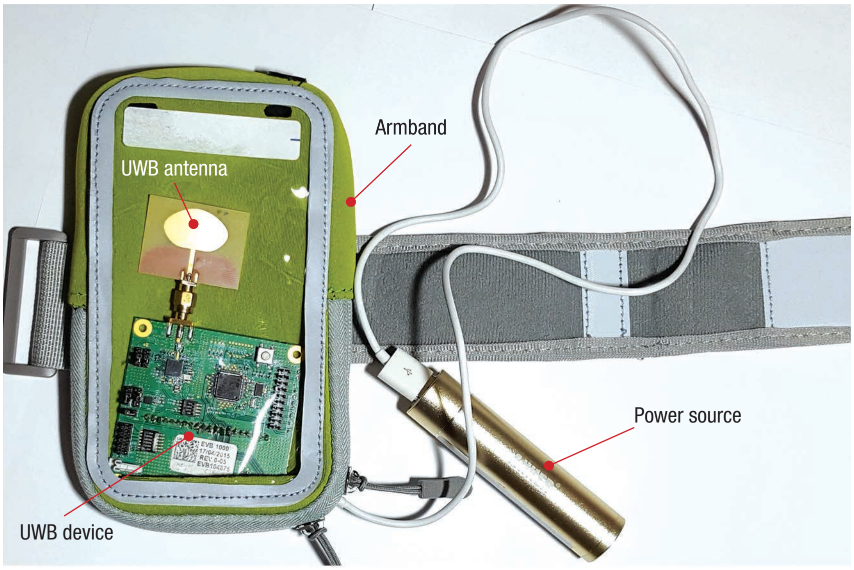

Figure 5. A wearable arm band carrying a UWB device.

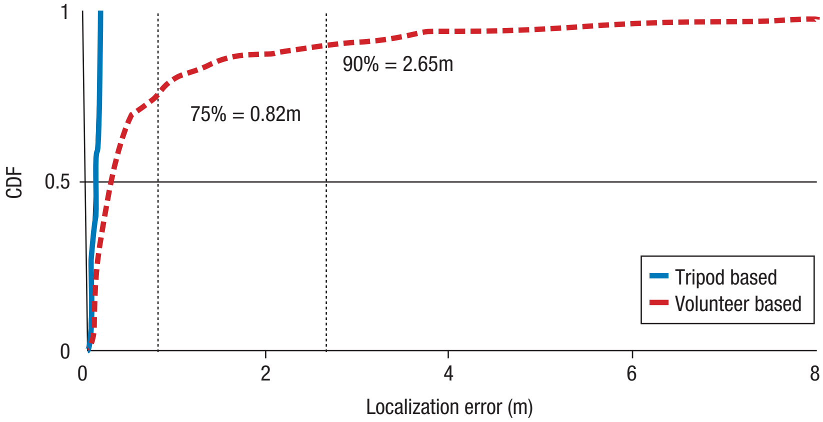

Figure 6. Overall localization error remains under 1 m for most cases, even with human occlusions. Without human occlusions, localization error is under 20 cm. CDF: cumulative distribution function.

The proliferation of IoT devices in everyday sensing and analytics is pushing the envelope for location tracking. P2P location tracking is well suited for many of these applications due to its low energy footprint and extreme robustness under any environmental condition. Despite the challenges of peer-to-peer location tracking, from our results, we see the potential in the feasibility and vast utility of such a primitive. P2PLoc is only a first step in this direction, enabling accurate and fast tracking of a team of devices in the absence of external infrastructure. **C**

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