An UWB Relative Location System

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Abstract—This paper describes an UWB location system that employs relative location principles to provide enhanced location performance in wireless networks. The system takes advantage of peer-to-peer range measurements between the devices and their neighbors. The collective range information is used to jointly estimate the location of the devices in the network providing enhanced performance.

I. INTRODUCTION

UltraWideBand (UWB) radios employ very short pulse waveforms that spread their energy over a broad swath of the frequency spectrum. Due to the inherently fine temporal resolution of UWB, arriving multi-path components can be sharply timed at a receiver to provide accurate time of arrival estimates. This characteristic makes UWB ideal for high precision radiolocation applications. The combination of high bandwidth wireless communications with the ability to achieve accurate positioning opens an amazing world of possibilities for wireless networks. Location enabled networks can be used for asset and personnel tracking and to enable a variety of location-aware services.

Many location systems have been developed. GPS is a spaced-based system where satellites are used as reference points and receivers compute their locations using measurements of the travel time of radio signals from multiple satellites. GPS does not function well indoors as the building structure itself hampers reception of the satellite signals. Local Positioning Systems (LPS) measure the physical properties of the radio signal between a device and a lattice of pre-deployed access points. Received Signal Strength (RSS), Angle of Arrival (AOA), Time of arrival (TOA), Time Difference of Arrival (TDOA) are commonly used in these systems. An example of such system is presented in [1]. In this system direct sequence spread spectrum signaling is used to implement an "indoor GPS" system based on TOA measurements. Because of the relatively narrow bands that allow operation practical wideband direct sequence spread spectrum systems realize indoor accuracies in the order of 10 to 20 meters. An UWB ranging technique that uses round trip time of flight measurements has been reported in [2]. An UWB location system that achieves a 3 to 5 ft RMS accuracy in an open space cargo hold was described in [3]. An UWB positioning system where devices achieve location using shared ranging information is reported in [4].

As opposed to the conventional approach for location estimation that treats each device as if it were the only device in the system and ignores its associations with the rest of the devices, relative location estimation regards range measurements between devices and its neighbors as pertinent information to the location estimation problem. A relative location system is presented in [5], in which the sensor location estimation problem is explored for sensors that measure range via received signal strength information (RSSI) and (TOA) between themselves and neighboring sensors. Results from the measurements and testbed experiments demonstrate 1 meter to 2 meters root-mean-square (RMS) location errors by using RSSI.

In this paper we present and evaluate via simulation and experimental measurements the performance of UWB relative location for a wireless network. This paper is organized as follows: Section II describes the approach used for peer-to-peer ranging, Section III considers relative location for wireless networks, simulation results are presented in Section IV, followed by measurement results on Section V. Conclusions are given in Section VI.

II. Peer-to-Peer Ranging

A. Ranging

The system employs time-of-arrival (TOA) techniques that derive a range value using an estimate of signal propagation time between two nodes. Our approach to TOA relies on accurate measurements of the total elapsed time for a two-packet exchange to within a few nanoseconds.

Figure 1 illustrates this approach where two radios (node A and node B) exchange packets while node A maintains a high-precision timer that measures the total elapsed time for the exchange.
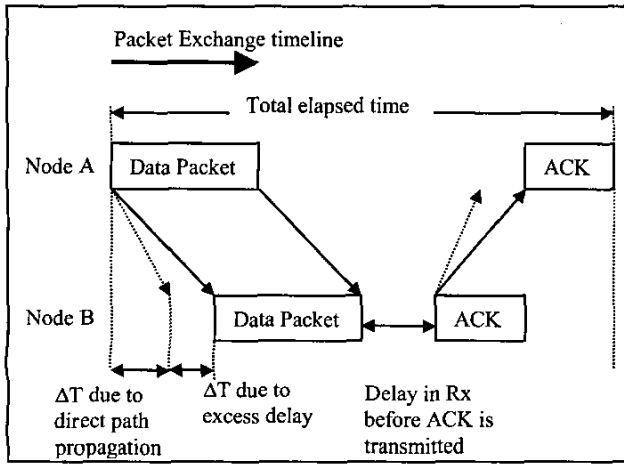

Fig. 1 Timeline for a packet exchange showing delays in the system

Elapsed time consists of various time intervals that can be determined and subtracted to obtain the desired round-trip propagation time. Analysis of the performance of this algorithm was initially performed using computer simulations with both measured and simulated UWB channels and verified via field measurements.

III. Relative Location

The classical approach to radiolocation is based on measuring characteristics of the radio signal from/to an individual device to/from fixed access points and then essentially using geometric principles to estimate the location of the device. In contrast to the classical approach, relative location distills location estimates from a collection of pair wise range measurements between devices and their neighbors [5]. A relative location system features two types of devices: reference devices, which are devices that have a-priori knowledge of their absolute location, and blindfolded devices whose location needs to be estimated.

Relative location provides two key advantages. It can provide increased accuracy and range extension. A simple example can be used to appreciate the first issue. Let us assume a one-dimensional system with two reference devices at each end (their fix location represented as nails) and two "floating" blindfolded nodes. The pairwise ranges between the network devices are denoted $d1$ thru $d5$. This system is displayed in Figure 2.
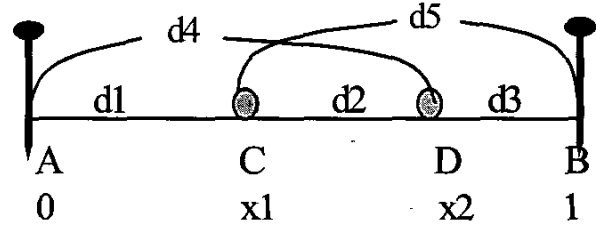

Fig. 2 One-dimensional network with 2 reference devices and 2 blindfolded devices.

With the classical approach, to compute the location of device C, only the distances d1 and d5 would be used. Similarly for device D only distances d4 and d3 would be employed. Under the assumption that the TOA errors are iid $N(0,\sigma_d)$ random variables, the average error for the classical approach would be $\bar{\sigma} = 0.707\sigma_d$. With a relative location system, by including the peer-to-peer distance $d2$ in the error minimization process the location error is reduced to $\bar{\sigma} = 0.61\sigma_d$.

IV. Simulation Results

Computer based simulations were used to investigate system performance for a two story 20x20x 6 meter building structure. The TOA errors

were modeled as iid. zero mean normal random variables with standard deviation of 1 meter. We assume that all devices are in communication range of one another. Four reference devices located around the building are used. Figure 3 shows the resulting 3-D location error as more blind devices are added to the network. This figure illustrates that increasing the blind device density in the wireless network can provide accuracy improvements via relative location.
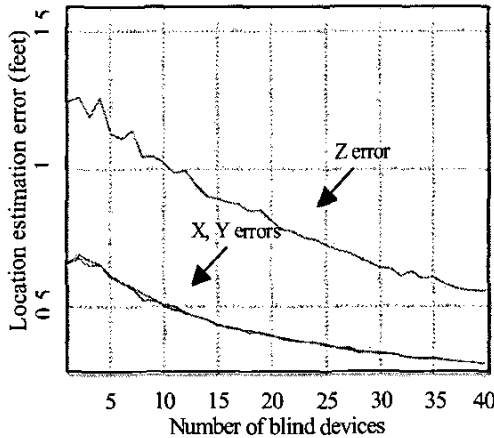

Fig. 3 Location error Vs. Number of blind devices

V. MEASUREMENT RESULTS

This section describes a measurement campaign that was performed to assess the baseline performance of the UWB relative location system. These measurements were taken in the Florida Communications Research Labs office area in Plantation, FL.

A. Measurement Technique

In these baseline measurements, the antennas were placed above the partitions in the cubicle area to ensure that the range measurements were made with the devices in direct line-of-sight of each other. Measurements were performed on the weekend to ensure freedom from random effects due to movement of people and materials. Before making the measurements the two prototypical UWB units were calibrated at a known separation distance. Subsequently, point-to-multipoint range measurements were performed by fixing one device at a given location, placing the second device at

each one of the test points and collecting 500 point-to-point range measurements for each location. A map of the area of interest with the location of the test points is presented in Figure 4.
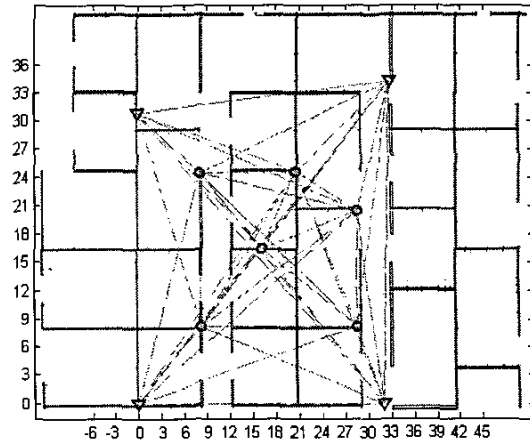

Fig. 4 Floorplan of the plantation office showing the location of the test points as circles and triangles. Triangles will be the locations of the reference devices.

After collecting the data, the next step was to investigate the statistical distribution of the pairwise ranging errors. Figure 5 shows a histogram of the range error data set. The mean of the distribution is 0.439 ft and the standard deviation is 1.6 feet.
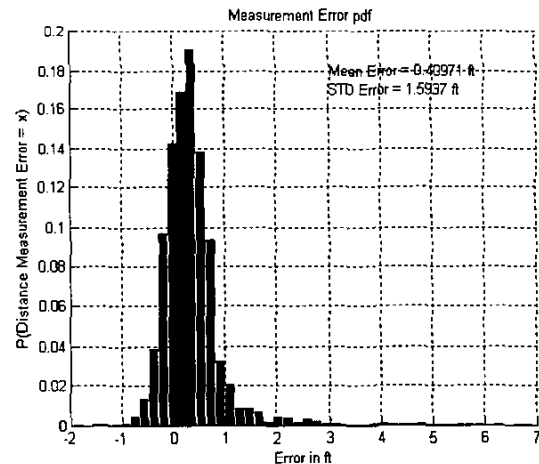

Fig. 5 Histogram of the round-trip measurement error data set.

While the distribution is not normally distributed, we will initially make the assumption that the statistics of the ranging error are zero mean Gaussian random variables and apply the joint position estimation algorithms to the data set.

Based on the Gaussian error assumption, a ML estimator can be formed that will result in location discovery by minimizing:

$$\sum_{i=1}^{M}\sum_{j=i+1}^{N}\left(D_{i,j} - d_{i,j}\right)^2 \qquad (1)$$

where $d_{i,j}$ and $D_{i,j}$ are the true and observed distances from node j to i and M and N are the number of blind and total nodes respectively. The relative location then results in a Root Mean Square (RMS) location error for the network of 0.21 feet with an RMS error in the x and y directions of 0.16 feet and 0.14 feet respectively. Next, we proceeded to take into account the fact that the distribution has a non-zero mean. An improved biased estimator that uses the median of the data set was used to calculate the location of the devices. The result was a RMS 2-D location error of 0.16 feet with an RMS error of 0.1 and 0.12 feet in the x and y directions respectively. Figure 6 shows the estimated locations of the devices.
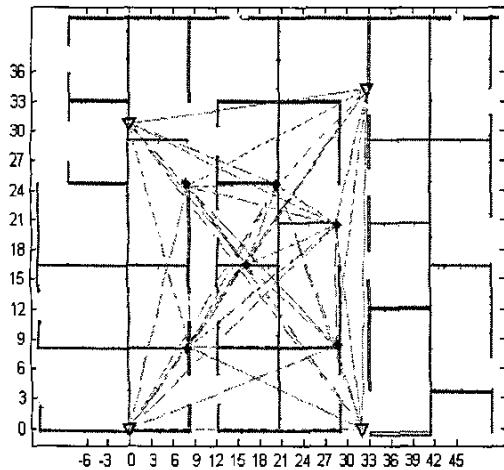

Fig. 6 Floorplan of the plantation office showing the estimated locations of the test points (indicated by solid stars). The triangles correspond to the reference devices.

As a reference classical multi-lateration calculations were performed using the four reference devices as base-stations. This resulted in a RMS location error of 0.46 and RMS location errors of 0.32 feet in the x and y directions. We see from these experiments that in this particular case relative location reduced the RMS location error by almost a factor of 3.

VI. CONCLUSION

An UWB location system based on relative location principles was introduced. Initial measurement results were presented. Future plans include performing a comprehensive measurement campaign to characterize the performance of the UWB relative location system in indoor and outdoor environments.

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