HiPR: High-Precision UWB Ranging for Sensor Networks

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ABSTRACT

We present a distance estimation technique based on ultra-wideband (UWB) time-of-arrival measurements. Experiments with IEEE 802.15.4-2011 devices by Decawave show that this solution is about 30 times faster and achieves a higher precision than Decawave’s native technique for a single estimation. The reduced acquisition delay can be further exploited to improve the precision by an order of magnitude.

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1 INTRODUCTION

There is a growing demand for indoor localization in logistics, robotics, monitoring, and other fields [1–3]. Common to many localization techniques is the need for distance estimation, also called ranging, between two or more devices. Of course, the distance estimates should be accurate (near true value) and precise (have low statistical variability), and the process of acquiring the estimates should be fast. The latter is especially crucial for real-time control tasks, as required in aerial robotics, to give an example.

We propose a ranging technique based on ultra-wideband (UWB) technology, called HiPR, which is designed to be much faster and more precise than the native solution implemented in off-the-shelf UWB transceivers from a market leader Decawave [4]. Experiments show that HiPR obtains one estimate in about 1/30th of the time required by the native technique and yields a precision that is about 40% better. These gains are achieved by reducing systematic errors in the time-of-flight estimation, which occur due to the delay from the moment a timestamp is made to the moment it is actually sent. Our approach utilizes hardware interrupts and short dummy beacons to acquire and communicate precise timestamp timestamps. The actual timestamp values are communicated in a subsequent standard message.

The significantly reduced acquisition time along with the short beacons allows HiPR to perform a burst of multiple estimates for a given distance in the time period required by the native solution for a single measurement. With this iterative approach, HiPR achieves a precision that is an order of magnitude better than that of the native solution.

The paper is organized as follows: Section II describes the hardware platform and network architecture. Section III discusses ranging and introduces the HiPR protocol. Section IV presents the experimental results, including a comparison to Decawave’s ranging capabilities. Section V addresses related work. Section VI concludes.

2 SYSTEM

Our UWB testbed was developed for industrial and aerospace environments [5–7]. It uses Decawave EVK1000 boards [4] and a self-developed communication protocol with automatic node discovery and scheduling based on time division multiple access (TDMA). HiPR runs on top of this protocol. The board features an IEEE 802.15.4-2011-compliant transceiver [8] enabling a data rate of 6.8 Mbps and a packet length of 1023 bytes. The nodes are tuned to operate at a center frequency of 4.5 GHz (channel 3) and a bandwidth of 500 MHz. The preamble length is set to 64 symbols with a pulse repetition frequency of 64 MHz. The non-standard start-frame-delimiter and extended physical layer header are used.

The system operates in a centralized manner, where one UWB node acts as access point (AP) to manage the node discovery, TDMA scheduling, ranging procedure, and to forward measured data to a computer for evaluation.

3 RANGING

3.1 Definitions: Error, Accuracy, and Precision

A measurement \( i \in \mathbb{N} \) yields a distance estimate \( d_i \) between two nodes. The error of this estimation is given by the difference between \( d_i \) and the true distance \( d \), defined by \( \epsilon_i(d) = d_i - d \). This error can in general be positive or negative but is always positive in our setup, due to the nature of the involved error.

Ideally, a ranging technique is both accurate and precise. It is accurate if the average distance estimate is close to the true distance. Along these lines, the accuracy of a ranging technique, for a given distance, is defined as the average value of the distance errors, i.e.,

\[
\bar{\epsilon}(d) = \frac{1}{n} \sum_{i=1}^{n} \epsilon_i(d)
\]

In addition, a ranging technique is precise if the distance estimates are close to each other. The precision can therefore be defined as the variance of the distance errors, i.e.,

\[
\sigma^2(d) = \frac{1}{n} \sum_{i=1}^{n} (\epsilon_i(d) - \bar{\epsilon}(d))^2
\]

3.2 Sources of Ranging Errors

The distance \( d \) between two devices can be computed from the time that a signal travels in the air between the devices, where this time is often called the time of flight (ToF). Both the native and our ranging technique uses timestamps to mark the moments at which a message is transmitted and received. The difference...
between these timestamps, denoted as propagation time $T_{prop}$, is in general not equal to the true ToF. Candidate reasons causing this deviation are imprecise clocks, imprecise synchronization, and imprecise timestamps.

The clock in a device runs slightly faster or slower than the nominal clock frequency $f$; say, it runs at $k f$ with $k$ close to 1. The EVK1000 board employs a 20 ppm crystal oscillator, which means that $0.999980 \leq k \leq 1.000020$. The clock-induced error in a distance measurement between two devices is [9]

$$T_{ClkErr} = T_{prop} \left(1 - \frac{k_1 + k_2}{2}\right), \quad \text{(1)}$$

which yields some picoseconds only [9]. For example, a relatively large operating range of $d = 100$ m yields $T_{ClkErr} \approx 7$ ps, which relates to a distance error below 3 mm.

To avoid ranging errors caused by inaccurate synchronization, we can employ a protocol that eliminates the need for synchronization, for instance, the double-sided two-way ranging (DS-TWR) protocol with three messages (MSGs) shown in Fig. 1 [10]. TS marks the moments when timestamps are created for the transmission (TX) or reception (RX) of a message, with $T_{prop}$ defining their difference. The timestamp difference between transmission and acknowledgment of a message is referred to as $T_{round}$ and $T_{reply}$, respectively. For each distance measurement $i$, the ToF can be estimated from the timestamps as follows [10]:

$$\overline{ToF} = \frac{T_{\text{round}1} T_{\text{round}2} - T_{\text{reply}1} T_{\text{reply}2}}{T_{\text{round}1} + T_{\text{round}2} + T_{\text{reply}1} + T_{\text{reply}2}}. \quad \text{(2)}$$

**Figure 1: Double-sided two-way ranging protocol.**

The limiting factor for precision is the time stamping process itself. A delay occurs between the timestamp generation and the actual moment a message with its timestamp is physically sent or received. Whereas the antenna delay can be compensated by hardware calibration [11]1, an additional nondeterministic error occurs, which is reduced by HiPR.

### 3.3 HiPR Protocol

We utilize beacons and hardware interrupts to capture the precise moment a message is transmitted and received. Instead of adding a TX timestamp to the header of a message, as is usually done, we use hardware interrupts to trigger and timestamp the moment a short beacon is emitted at the antenna. This allows for more precise

$^1$The antenna delay is hardware specific and therefore requires calibration of each individual sensor node. To reduce the calibration effort, reference values are provided by Decawave to account for this error [11].

**Figure 2: Static test environment with one access point and a single sensor node deployed at nine test locations between 50 cm and 450 cm marked as blue dots on the table.**

ToF estimations by reducing the delay that occurs between message creation and the actual moment of transmission. This solution requires a subsequent message to include the timestamp of the preceding beacon. HiPR optimizes the process by embedding previous timestamps into follow-up messages of the DS-TWR protocol.

Furthermore, HiPR includes an error handling, which detects and re-initiates lost messages. This enables us to repeat single measurements individually without the need for repeating the entire DS-TWR protocol. The re-initiation can further be used to quickly execute a larger number of consecutive measurements in each direction (e.g., initiator $\leftrightarrow$ responder). This avoids delays due to frequent switches between transmission modes (e.g., transmission $\leftrightarrow$ reception) and consequently leads to a much faster ToF acquisition.

The pseudocode shown in Alg. 1 states the logical sequence of HiPR. The protocol is flexibly designed to suit application-specific needs with the aim of supporting ranging tasks in a sensor network. In the initiation phase, sensor nodes are discovered and scheduled into a TDMA structure. The AP controls the scheduling of nodes and monitors the ranging progress.

Error handling is performed to validate each measurement. In the case of lost or corrupted timestamps, necessary procedures are re-initiated. Once the ToF has been calculated, the information gets either stored for later use, forwarded to a computer for evaluation, or broadcast to sensor nodes. Broadcasting of distance information in a ranging network enables 1) passively obtaining distances between pairs of nodes and 2) reducing the number of network-wide messages to populate distance information. A dedicated broadcast slot is therefore reserved in the TDMA structure allowing for higher duty cycling and longer sleep periods of sensor nodes.

### 4 EXPERIMENTAL EVALUATION

This section presents an experimental assessment of range estimations in an office environment. We evaluate HiPR and Decawave’s native ranging application in terms of acquisition time, accuracy, and precision. To obtain sufficient statistical validity, one thousand point-to-point ranging measurements are conducted for each of nine test positions. All tests are performed in a static environment under quasi-identical conditions.
The antennas are characterized to avoid unintended signal attenuation due to their relative orientation. The characterization determines the maximally permitted tilt angle in order to not compromise the quality of the measurements. The standard antennas exhibit a deep notch on their vertical axis and a maximum gain on their perpendicular direction. Therefore, nodes are positioned in a way that the antenna orientation is aligned with the main lobe. We operate only one AP with a single sensor node in a point-to-point manner and forward the distance information to the computer. Three $T_{prop}$ measurements with their TX and RX timestamps are required to estimate the ToF as described in (2). The access point remains at a fixed location marked as AP in Fig. 2. A single sensor node is positioned at one of nine test locations. These locations represent steadily increasing distances from the AP’s location, covering a range between 50 cm and 450 cm. After thousand completed measurements, the sensor node is repositioned at the next test location. We establish an accurate ground truth between AP and sensor node using a laser range finder with an accuracy of ±2 mm (Bosch PLR 50 C). The test procedure the same for both HiPR and the native ranging application.

In a first measurement campaign, we evaluate the acquisition time of distance measurements. This is done at a location in the middle of the testbed with a distance of 2 m. In a second campaign, we assess the accuracy and precision for several distances.

### 4.2 Acquisition Time

In order to measure the time required to perform distance estimation, we utilize the tick count to obtain the exact time from the triggering to the completion of a distance measurement at the microcontroller. We present the average ranging acquisition time normalized to a single measurement and evaluate the performance for an increasing number of range estimations. A distance estimation $i \in \mathbb{N}$ yields an acquisition time $t_i$. The average value of consecutive acquisition times, i.e., $\bar{t} = \frac{1}{n} \sum_{i=1}^{n} t_i$ is calculated when using $n = 1, 10, 100, \text{or} 1000$ iterations (number of measurements used for one distance estimate). To obtain statistical validity, $\bar{t}$ estimates are repeated and averaged for $m = 1000$ iterations each, i.e., $\bar{T} = \frac{1}{m} \sum_{i=1}^{m} \bar{t}_i$. Due to the overhead of initiating the DS-TWR protocol, multiple measurements are expected to yield a shorter normalized acquisition time.

Decawave’s native ranging is operated in two variants: as an unoptimized out-of-the-box version and as a modified version where we eliminate unnecessary peripheral interactions (e.g., LCD output, switching of LEDs, etc.).

The acquisition times are presented in Table 1. A single measurement (first column) is expected to be done in $\bar{T} = 25\text{ ms}$ using HiPR, whereas it takes 881 ms (native) and 761 ms (optimized) with Decawave’s ranging application. This corresponds to a 30 times faster acquisition for HiPR compared to the optimized version of Decawave’s ranging. The use of hardware interrupts shows a significant improvement to the software defined polling used by Decawave. Beyond this, the iterative approach for distance estimation further reduces the protocol overhead (e.g., ranging initiation) that affects a single measurement more severely and is distributed.

<table>
<thead>
<tr>
<th>Number of Iterations</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>HiPR</td>
<td>25</td>
<td>14</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Decawave unoptimized</td>
<td>881</td>
<td>564</td>
<td>508</td>
<td>506</td>
</tr>
<tr>
<td>Decawave optimized</td>
<td>761</td>
<td>426</td>
<td>389</td>
<td>387</td>
</tr>
</tbody>
</table>

### 4.1 Testbed and Setup

The antennas are characterized to avoid unintended signal attenuation due to their relative orientation. The characterization determines the maximally permitted tilt angle in order to not compromise the quality of the measurements. The standard antennas exhibit a deep notch on their vertical axis and a maximum gain on their perpendicular direction. Therefore, nodes are positioned in a way that the antenna orientation is aligned with the main lobe. We operate only one AP with a single sensor node in a point-to-point manner and forward the distance information to the computer. Three $T_{prop}$ measurements with their TX and RX timestamps are required to...
Figure 3: Histogram of measured distances for a true distance of two meters and distribution fitting.

Figure 4: Ranging accuracy over distance. The boxplots show the upper and lower quartiles (blue box), the median (horizontal red line in box), whiskers, and outliers (red +). The mean values are marked with a red dot and connected with a red line. A higher deviation of mean to median values indicates a larger skewness.

4.3 Accuracy and Precision

We now assess the accuracy and precision. Figure 3 shows histograms of the estimated distances at a true distance of $d = 200$ cm. Fitting a normal distribution shows that the mean values are similar for both techniques (namely $\bar{e} = +29$ cm for HiPR and $+27$ cm for Decawave) but Decawave suffers from a higher variance ($1.5$ cm compared to $1.9$ cm). Thus, in this particular setup, Decawave is slightly more accurate and HiPR is more precise. The histogram of HiPR appears to be symmetric around its mean.

This analysis is now extended to other distances. Due to its faster acquisition, HiPR is able to make about 30 distance estimations when Decawave performs one. Such multiple estimations can be exploited to either address multiple sensors or to perform multiple measurements with a single sensor to improve accuracy and precision. We focus on the second case. Each distance estimate by HiPR is the average value of 30 ToF estimates. The time required to collect and process the data is the same as the time required to obtain a single distance estimation with Decawave ranging.

Figure 4 shows the ranging error $\epsilon$ for different distances $d$. The following can be observed: In terms of accuracy, HiPR tends to have slightly lower ranging errors than Decawave for short distances but higher ones for longer distances. In terms of precision, HiPR always results in more precise ranging results. Its interquartile and interwhisker ranges are much smaller than those of Decawave ranging, for all distances, and the number of outliers is much smaller. Its average variance is only $0.15$ cm, compared to $6$ cm, which is on average about forty times more precise in this setup. The largest deviation occurred for a distance of one meter, where HiPR achieves an improvement by a factor of more than hundred.

All in all, the HiPR performance is more favorable under the condition that systematic errors can be compensated using a precise ranging technique, at least much easier than using an imprecise technique.

5 RELATED WORK

Localization systems are categorized in many different ways: into technologies [12]; parametric (e.g., position computed based on prior knowledge) and non-parametric localization techniques [13]; or the type of sensors used [14]. Commonly used positioning techniques use radio signal strength (RSS), time of arrival (ToA), time difference of arrival (TDoA), angle of arrival (AoA) and hybrids...
We proposed, implemented, and tested the HiPR technique for dis-
environments and plan to deploy and further evaluate HiPR with
additional measurement campaigns in other environments are needed
to draw firm conclusions on the factor of the improvement.

6 CONCLUSIONS AND OUTLOOK

We proposed, implemented, and tested the HiPR technique for dis-
tance estimation. It shows favorable properties in terms of precision
and delay compared to Decawave’s native ranging application. Ad-
ditional measurement campaigns in other environments are needed
to draw firm conclusions on the factor of the improvement.

We are currently working on accuracy compensation in dynamic
environments and plan to deploy and further evaluate HiPR with
small drones that require autonomous positioning. HiPR’s distance
estimations will be the basis for the lateration to reference points.

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