# Improving Signal of Opportunity Localisation Estimates in Multipath Environments

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Abstract: Network based geographic localisation has been widely researched in recent years due to the need to locate mobile data communication nodes to a level of accuracy equivalent to that provided by global navigation satellite systems (GNSS) in multipath urban and indoor environments. This paper investigates whether direct sequence spread spectrum (DSSS) signal processing can be applied to narrow-band radio channels to improve the ranging estimates. The DSSS signal processing application is then developed further to provide a method of deriving a measurement confidence indicator, allowing the optimisation of time separated measurements in a dynamic signals of opportunity radio environment. A set of validation tests demonstrates that the proposed method provides a significant improvement in the accuracy and robustness of the ranging estimate compared to simple threshold analysis in multipath environments.

## 1 INTRODUCTION

Radio positioning systems have achieved common use in a diverse range of systems. The most commonly used radio positioning systems are global navigation satellite systems (GNSS). These systems use signals received from satellite to calculate the position of the user to within 4m during 95% of the time (Norman Bonnor, 2012). GNSS systems rely on a line of sight (LoS) view of at least 4 satellites. This requirement cannot however, be guaranteed in urban or indoor environments where ‘urban canyons’ and roof cover, block sight to much of the surrounding sky. Research has been carried out into using signals of opportunity for localisation in such environments, particular success has been achieved by using time of arrival (ToA) systems to derive a user’s location (Norman Bonnor, 2012), even in urban or indoor environments where multipath propagation is one of the main sources of system error 0. Constructive and deconstructive interference between the non-line of sight (NLoS) propagating signals can destroy or obscure the LoS signal that is required to derive an accurate ToA estimate.

Ultra wide band (UWB) signal analysis techniques, originally developed for low emission radar 0, have achieved promising results when applied to localisation in wide bandwidth direct sequence spread spectrum (DSSS) networks (00). These techniques rely on the differing multipath properties of the wide spread of frequencies to provide an improved leading edge time of arrival (ToA) estimate and to achieve GNSS levels of accuracy in wide bandwidth multipath environments.

This paper builds on the use of prior art wide bandwidth signal processing techniques and investigates their use in signals of opportunity networks that commonly collect time separated narrow bandwidth measurements such as frequency hopping spread spectrum (FHSS) networks. FHSS networks are typical to military 0 and civilian (IEEE, 2014. *IEEE 802.22)* systems and challenges remain to use them to achieve GNSS levels of location accuracy in multipath environments 0 due to the time separated nature of the received signals.

This paper proposes a method that allows the system to use time separated ToA estimates and, without prior training or additional data collection, generate a low latency and high bandwidth filtered ranging estimate. The benefits of the proposed method are verified through simulation. The accuracy and responsiveness of the ranging estimate shall be analysed in both static and mobile receiver environments.

This paper is organised as follows; Section 2 discusses the prior art. Section 3 proposes a method to use the leading edge detection algorithm to extract

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the data required to weight the values in a recursive filter. Section 4 provides details of the simulation environment and evaluates the ranging estimate performance. Section 5 concludes and discusses further work.

# 2 PRIOR ART

## 2.1 Leading Edge Detection

Basic ToA detection systems commonly use simple threshold based leading edge detection 0), which relies on the assumption that the LoS message will arrive first via the shortest direct path. In many situations however, the LoS component may be heavily attenuated by deconstructive multipath interference providing a leading error driver for indoor or urban ranging system accuracy.

Search-back algorithms improve on the ToA accuracy by analysing the received packet and performing a search-back to determine physical layer properties of the message to determine the time of arrival more robustly (Haneda K., 2009). These algorithms require prior knowledge of the multipath environment which cannot be provided in many applications.

The Multiple Signal Classification (MUSIC) algorithm (Schmidt R. O. 1986) extends the analysis to allow multipath signals to be used as a further information source and has become widely used in research. This algorithm requires a substantial training period to determine the number of multipath signals present to achieve better performance than relying on leading edge detection alone. Again, a training period is not practical in many applications where the device is to be used to navigate around an unknown area.

UWB signal processing techniques utilise the wide frequency range of the received signals to provide an improved ToA estimate. The analysis of the full frequency range available allows the user to determine frequency specific multipath variations and make an improved estimation of the true ToA reading. A widely implemented example of an existing UWB signal processing technique, described in 0, has been selected for further development in this paper. This technique was developed to detect the leading edge of a signal obtained from a wide bandwidth transmission. It has been selected for further development due to the fact that the running filters applied to the raw data may provide additional data to the user following further analysis.

The UWB signal processing technique is applied to any wide band received data as follows: if $h(t)$ represents the received signal in the time domain, it is first passed through a rectified moving average filter as shown in (1).

$$y(t) = \frac{1}{n}\sum_{i=t-n+1}^{t} abs(h([t])) \tag{1}$$

The averaged signal $y[t]$ is then passed through two filters of sizes $n_1$ and $n_2$ which return the maximum value from a sliding window, as shown in (2) and (3).

$$\max\_n_1[t] = \max(y_{t\text{-}n_1} \ldots y_t) \tag{2}$$

$$\max\_\ n_2[t] = \max(\ y_{t-n_2} \ldots y_t\ ) \tag{3}$$

A binary indicator of whether a leading edge has been detected can be obtained from (4).

$$\begin{aligned} r[t] &= (\max\_\ n_1[t] * 2 > \max\_\ n_2[t]) \\ &\ \&\ (\max\_\ n_2[t] > thresh) \end{aligned} \tag{4}$$

The threshold detection level, *thresh*, is typically set to 3σ of inter message in-channel received signal noise.

## 2.2 Application Considerations for Navigation Filters

Recursive averages are commonly used in navigation systems to produce a low noise and low latency location estimate from a noisy measurement input. In order to provide an efficiently filtered output, the measurement system that populated the recursive filter must provide not only a measurement value, but also a dynamic confidence indicator.

When using a simple threshold detection algorithm to detect the leading edge of a received signal, the only information that can be provided to the navigation filter is the time when a received value is greater than the selected threshold. If this information is available for each FHSS channel, a simple un-weighted recursive filter shown in (5) can be constructed to update the users filtered location based on the its previous position and the latest sensor data where, as commonly used in filter notation, $\hat{x}$ represents the filter output, $\overline{x}$ represents the previous state and $\tilde{x}$ represents the latest sensor value. The measurement confidence is represented by α.

$$\hat{x} = \alpha\bar{x} + (1-\alpha)\tilde{x} \tag{5}$$

The filter represented in (5) may be tuned by adjusting the value of α by a predetermined value.

A value of $\alpha < 0.5$ reduces the noise of the filter output at the expense of a higher latency if the receivers true location changes. A value of $\alpha > 0.5$ generates a more responsive, lower latency filter output but the filter output noise will be adversely affected. Both of these options are unsuitable for many system applications.

## 3 PROPOSED METHOD

The leading edge detection algorithm described in section 2.1 has been developed for wide band signal processing and analyses all of the data from the wide frequency range with each measurement.

The receiver system to be developed by this paper makes a ranging estimate upon detection of the leading edge of a received signal using the signal processing technique described in section 2.1. The process of running the $n_2$ filter (3) to return the maximum value in the longer sliding window continues for the duration of the first message in the current FHSS channel. The data obtained from the maximum value sliding windows is placed into a column vector and a standard deviation taken to determine the presence and magnitude of multipath present throughout the message. This is then correlated to provide a numerical confidence value.

The process is represented in equations (6) and (7). The standard deviation, σ, is first calculated in (6) with $n_2$ as the filter length, $x_i$ is each iterative filter value and $x_a$ is the current filter average. This standard deviation is then normalised in (7) to produce a dynamic measurement confidence, α.

$$\sigma_{n_2} = \sqrt{\frac{1}{n_2}\sum_{i=1}^{n_2}(x_i - x_a)^2} \tag{6}$$

$$\alpha = (1 - \frac{\sigma_{n_2}}{\mu_{n_2}}) \tag{7}$$

α represents a confidence factor with a weighted value between 0 and 1 for low to high confidence measurements respectively. This confidence measure can then be used to dynamically tune the filter shown in (5) to generate a recursive filter input that benefits from both low noise and low latency. This has been achieved by providing a high weighting value to ranging estimates received with good confidence and a low weighting to estimates with a low confidence, even if there has been true movement by either the transmitter or receiver.

The ability to achieve this from a multipath data source dynamically and without prior knowledge is of a key benefit in higher level navigation systems, as discussed in section 2.2. This confidence weighting has been achieved without the use of any additional information or averages over the ones implemented to allow the improved leading edge detection.

## 4 SYSTEM VALIDATION

### 4.1 Simulator Validation

A simulated radio frequency (RF) environment was modelled in Matlab® and Simulink® to evaluate the effectiveness and performance of the techniques discussed in section 3. The simulation uses the standard multipath simulation model (Alsindi N.A, 2004) shown in (8) where $L_p$ is the number of multipath components, $\alpha$ is the complex attenuation and $\tau$ is the propagation delay.

$$h(t) = \sum_{k=0}^{L_p-1} \alpha_k \delta(t - \tau_k) \tag{8}$$

The simulation assumes that an idealised transmitter generates a single frequency modulated pulse; for validation, the FHSS network parameters included 100 20 kHz channels evenly spaced from 3 to 5 GHz. The transmitted pulse is then subjected to empirically derived propagation and receiver distortions to produce a received signal for analysis. The resulting signal includes simulated effects of multipath with the use of separate propagation channels, the number of which can be set by the user. The simulations evaluated throughout this paper will consider a LoS propagation path of 10 m with several multipath reflection paths with an apparent time path from the transmitter to the receiver consistent with 10.1 m to 11.2 m propagation distances.

This simulated environment has been used to ascertain the performance of a simple threshold detection algorithm in a Monte Carlo based simulation of a wide range of FHSS channels in a fixed geometry. A typical single transmitted message and the received signal patterns in a high multipath environment can be seen in Fig 1.

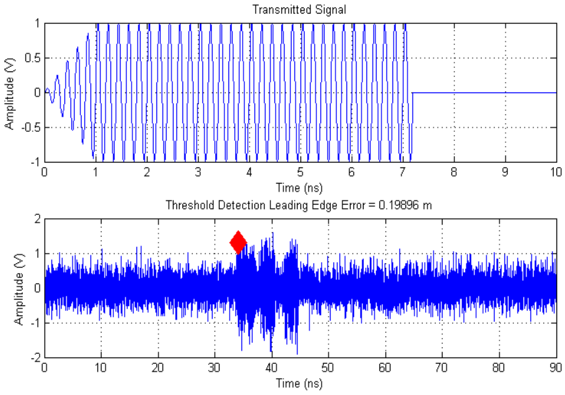

Figure 1: Transmitted (top) and received (bottom) pulse with the location of the detected leading edge of the pulse marked by the red symbol.

The threshold detection algorithm has been simulated assuming a static receiver and transmitter across a range of FHSS channels to benchmark the simulation. The results can be seen in Fig. 2 and shows properties that are expected in multipath environments, as seen in (Norman Bonnor, 2012)] and 0). The similarity to data collected by practical test in previous research provides confidence that the simulation is representative.

## 4.2 Technique Validation

A comparison of edge detection seen by employing UWB signal processing techniques to each narrow bandwidth channel as opposed to simple threshold detection can be seen in Fig. 2.

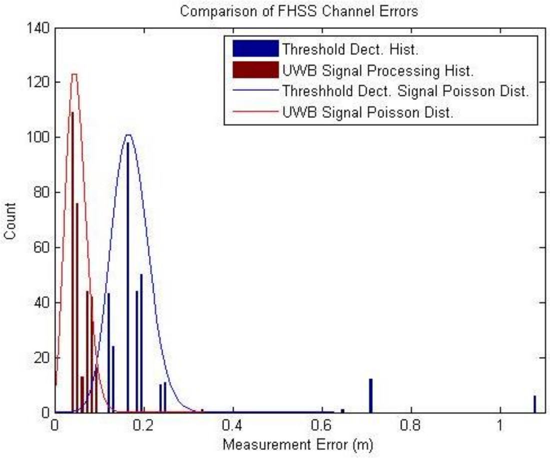

Figure 2: Comparison of threshold based and UWB signal processing leading edge detection methods.

Analysis shows that the Poisson distribution variance has a λ value of 17 for the threshold detection algorithm and an improved λ value of 5 for the UWB threshold detection. The received estimates across the range of networks not only have less average error but also a greater distribution density than can be obtained from simple threshold detection alone. As well as a significant improvement in the Poisson distribution, the UWB based edge detection algorithm removes the erroneous outliers seen at ≈ 0.7 m and ≈ 1.1 m error in the threshold detection algorithm. This behaviour may account for the high multipath uncertainty seen in (Faragher R. M., 2007) where a simple threshold detection algorithm was used to detect the ToA to estimate range.

Detail of the detected trigger timing at the leading edge of a signal with light multipath is shown in Fig. 4.

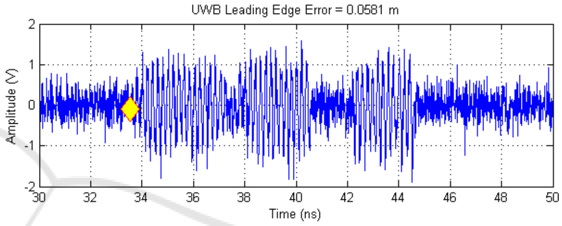

Figure 3: UWB leading edge detection of pulse in a noisy multipath environment.

Figure 3 is a magnification of the area of interest, related to the transmission pulse as shown in Fig. 2. Areas of constructive and deconstructive multipath effects can be seen throughout the 34 ns to 42 ns region where a non-multipath signal would be expected to produce a stable series of 1 V peaks.

The simulation has shown that the evaluation tests for the UWB algorithms discussed in section 2.1 produce a significant improvement over threshold detection when providing ToA estimation in high multipath FHSS networks when only a single narrow bandwidth channel can analysed at a time.

Further to the improvement shown in ToA estimates in a high multipath environment, the application of the additional data available, described in section 3, to a recursive navigation filter is analysed in the remainder of this section.

The application of threshold analysis data, where no weighting data is available for the new samples, into the simplified recursive filter leads to a noisy and poorly filtered position estimate. Fig 4. compares a plot of the raw measured and filtered ranging estimate obtained from a simulation of a static system that sweeps through 100 FHSS channels over a 5 second period.

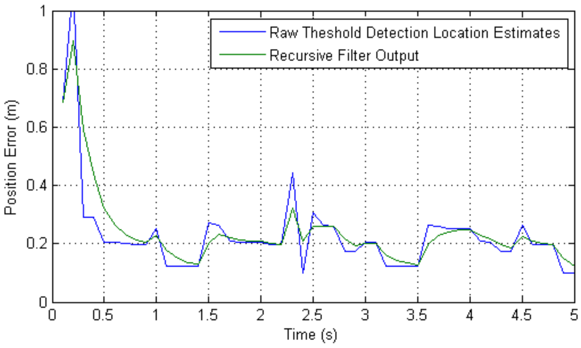

Figure 4: The raw and filtered output from the threshold detection algorithm with a pre-selected static confidence interval.

The results displayed in Figure 4 verify that the filtered position estimate from an un-weighted recursive filter is comparatively noisy and produces a large filtered error in the event of a multipath $\tilde{x}$ leading edge detection received from the sensor, as seen approximately 0.2 seconds into the simulation. The application of the position estimates and the relative variance derived using the method described in section 3 has been applied to a weighted navigation filter. The application of this navigation filter in the simulation leads to improved stability to the position estimate which, combined with the improvement in leading edge detection reliability and the absence of outliers, leads to a greatly improved position estimate over the threshold detection algorithm, as shown in Fig. 5.

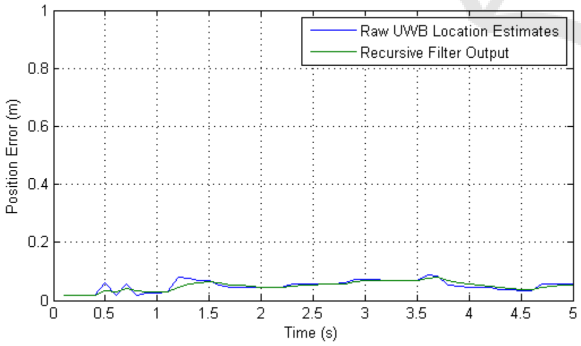

Figure 5: The raw and filtered output from the navigation filter with UWB leading edge detection and dynamically obtained confidence interval. This should be compared with Fig 6 to see the improvement achieved.

In a physically static system, as simulated in Fig 4 and Fig. 5, where the relative position of the transmitter and receiver does not change, the sensitivity to erroneous data could be mitigated by weighting the raw sensor data by a pre-determined factor of < 1 depending on sensor noise. While this will limit the filter error in the event of erroneous multipath readings and produce a more accurate location estimate, it also introduces high latency if the receiver or transmitter truly moves location. The application of a dynamically weighted recursive filter prevents an erroneous multipath ToA reading from causing filter noise. If however, the system truly moves, a new filter input with a new position estimate with a high weighting will be received and the filter output will respond with little latency.

A further simulation was run to evaluate the effect of a true receiver motion on the filter output. To simplify the simulation, a single narrow bandwidth channel with no frequency hopping was used throughout the experiment. After approximately 1.2s into the simulation, the receiver node instantaneously moves 1m within a multipath environment and remains static for the remainder of the simulation.

Fig. 6 shows a comparison of the filter response to the applied motion with both threshold detection and UWB detection inputs.

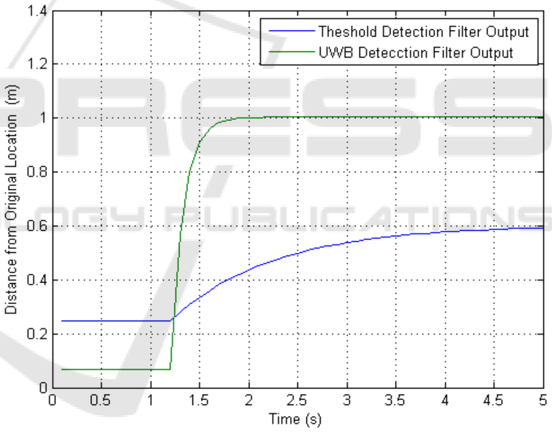

Figure 6: The response of the filters to an instantaneous 1 m movement of the receiving node.

The threshold detection filter still has a greater error before and after the 1 m move of the receiver node than the UWB filter, as expected. The area of interest highlighted by this simulation is the difference in time taken for the filter output to identify the change in location. The dynamic weighting to $\tilde{x}$ allows the UWB filter to respond with minimal latency in the event of true receiver or transmitter movement. The improvement seen in Fig 6 is due to both the improved UWB ranging estimate, shown in Fig 2 and the ability to weight the measurements. These contributing factors have not been analysed separately due to the fact that the weighted recursive filter may be implemented without any additional data collection and should always be used to provide an optimised solution.

## 5 CONCLUSIONS AND FURTHER WORK

This paper proposed a set of algorithms and application techniques that improve narrow bandwidth channel ranging estimates in signals of opportunity environments. The novel application and further development of DSSS signal processing techniques to provide not just an improved ranging estimate but, by re-analysing existing data, an additional confidence weighting.

By re-analysing the available data, a filter confidence factor can be obtained that can be calculated dynamically without the need for a training period and without any prior knowledge of the radio system and environment. More specifically, the use of UWB signal processing techniques provided an approximately 4 times improvement in ranging estimation over simple threshold detection even in narrow bandwidth channels, including a better Poisson distribution and higher resilience to false detections.

The main benefit of applying this technique is that a filtered ranging estimate can be obtained that is more accurate, lower noise and lower latency than can be obtained by using simple threshold detection techniques to detect the leading edge of a message.

The analysis of the proposed technique performance throughout this paper has been carried out only in multipath environments. It is anticipated that the benefits of the technique will be significantly less apparent in less hostile environments.

Future work should include the physical test of this system to verify the model. The integration of the algorithm into higher level systems is also required to verify the higher level benefits shown during simulation. The close coupling of this system with higher level navigation systems, in particular Kalman filtering schemes may also allow the development of a significantly improved signal of opportunity based localisation system.

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