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Authors(s)	Makki, Ahmed, Siddig, Abubakr, Saad, Mohamed M., Cavallaro, J. R., Bleakley, Chris J.
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High Resolution Time Of Arrival Estimation for OFDM-Based Transceivers

Ahmed Makki, Abubakr Siddig, M. M. Saad, J. R. Cavallaro, and C. J. Bleakley

This letter presents a novel algorithm for Time Of Arrival (TOA) estimation for Orthogonal Frequency Division Multiplexing (OFDM) based transceivers. The algorithm processes the sampled baseband signal to obtain a high resolution estimate of the TOA of the OFDM symbol. In the first step, the algorithm obtains a sample resolution estimate of the TOA by finding the peak of the absolute value of the cross-correlation of the in-phase and quadrature received signals with the known transmitted symbol. In the second step, the algorithm refines this estimate to sub-sample resolution by estimating the phase delay of the received signal based on the gradient of a linear fit to the phase difference between the transmitted and received sub-carriers (in the frequency domain). The algorithm was applied to the Long Training Sequence (LTS) symbol of the IEEE Wireless Local Area Network (WLAN) 802.11g preamble. In real-world experiments, the algorithm was found to achieve a mean TOA estimation error of 49 cm in a low multi-path Line Of Sight (LOS) environment for ranges of 1-7 m.

Introduction: Positioning devices with high accuracy in indoor environments is of interest in a wide range of applications. Current indoor location systems for the ubiquitous IEEE 802.11 WLAN standard are based on Received Signal Strength Indicator (RSSI) mapping and fingerprinting. The mapping process is time consuming and the maps are subject to changes in the environment, such as the movement of people and equipment. To date, the reported accuracy of 802.11 RSSI fingerprinting is roughly 3 m [1]. Range based positioning has the potential to eliminate the mapping step but requires high resolution TOA estimation. Previously, Nur *et al* [2] tackled this problem by increasing the RF sampling frequency to 1 GS/s and introducing an Improved FOCUSS for Arrival Time Estimation (IFATE) algorithm to estimate the channel and the TOA. In experiments and simulations, sub-meter accuracy (average error of 0.62 m) was achieved in indoor LOS environments. Their approach achieved high accuracy, however, it is costly in terms of power consumption and is not supported by conventional receiver architectures which typically have a 40 MHz sampling frequency. Frequency domain super resolution methods [3] have been applied to the conventional baseband signal. MUltiple SIgnal Classification (MUSIC) [4] and Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT) [5] separate the signal subspace from the noise subspace using eigen-decomposition of the correlation matrix. These super-resolution approaches have been shown to provide accuracies around 3-5 meters [6]. However, they require high Signal to Noise Ratio (SNR), need prior estimation of the number of multi-path components, and have high computational complexity [2].

Herein, we propose a novel TOA estimation algorithm that uses the baseband signal from a conventional WLAN transceiver. To the best of the authors' knowledge, this is the first work which proposes a combined cross-correlation and phase adjustment method for TOA estimation in WLAN receivers.

Proposed Algorithm : The TOA estimation algorithm consists of two steps: coarse (sample-level) estimation and fine adjustment (sub-sample). It is assumed that the RF symbol is received at the antenna and is directly down converted to in-phase and quadrature baseband signals. These signals are sampled at f_s Hz to give the received signal $x(n) = x_I(n) + j.x_Q(n)$ where $x_I(n)$ and $x_Q(n)$ are the in-phase and quadrature baseband signals, respectively. The algorithm seeks to estimate the TOA of the known transmitted OFDM baseband symbol $s(n)$ of length L samples.

In the coarse estimation step, the cross-correlation between the received signal and a locally synthesised copy of the transmitted symbol is calculated:

$$r(n) = |\sum_{l=0}^{L-1} x(n+l)s(l)| \tag{1}$$

The sample level TOA estimate is obtained as the delay of the maximum cross-correlation value:

$$t_{\text{coarse}} = \frac{n_{\text{peak}}}{f_s} \text{ where } r(n) \text{ is maximum at } n_{\text{peak}} \tag{2}$$

To overcome the sampling frequency limitation, sub-sample adjustment of the coarse estimate is required. Consider a single sinusoidal sub-carrier which is subject to a delay d of less than a single sample. It can be seen that the phase of the sub-carrier is increased by:

$$\delta_\phi = \frac{2\pi d}{t_{\text{sc}}} = 2\pi d f_{\text{sc}} \tag{3}$$

where t_{sc} and f_{sc} are the period and frequency of the sub-carrier, respectively. Hence, the phase increase due to the sub-sample delay is linear with the frequency of the sub-carrier. The delay can then be estimated based on the phase difference between consecutive sub-carrier frequencies δ_f.

$$d = \frac{\delta_\phi}{2\pi\delta_f} \tag{4}$$

Based on this analysis, the fine adjustment is calculated as follows. The Fast Fourier Transform (FFT) $X(k)$ of the received signal, time aligned according to the coarse TOA estimate, is calculated:

$$X(k) = \sum_{n=0}^{L-1} x(n_{\text{peak}} + n)e^{-j2\pi kn/L} \tag{5}$$

The sub-carrier phase shift $\theta(k)$ is calculated by subtracting the phase of the sub-carriers in the transmitted signal from the phase of the received signal:

$$\theta(k) = \angle X(k) - \angle S(k) \tag{6}$$

where $S(k)$ is the FFT of the transmitted symbol. A linear fit to the phase shift variation with frequency is obtained in the minimum mean squared error sense where m is the gradient of the fit. The fine time adjustment is then calculated as:

$$t_{\text{fine}} = \frac{m}{2\pi\delta_f} \tag{7}$$

The final TOA estimate is:

$$t_{\text{final}} = t_{\text{coarse}} + t_{\text{fine}} \tag{8}$$

Experimental Method: The algorithm was evaluated using the Wireless Open Access Research Platform (WARP) [7], see Figure 1. The platform consists of a 802.11 transceiver with Field Programmable Gate Array (FPGA) baseband implementation. This allows easy access to the physical layer signals. Two boards were used in the experiments: one as transmitter and one as receiver. Directional antennas with beam width of 34° were used to reduce the effects of multipath. Frequency offset was eliminated by sharing the carrier frequency and sampling clocks of the transmitter and the receiver using a wired connection. Offset can be estimated separately. Synchronisation was achieved by sending the start of symbol signal from the transmitter FPGA to the receiver using a wired digital connection. This signal was used to initialise the sample counter at the receiver. The time from the start of symbol signal going high to the actual RF time of emission is fixed in the transmitter design. The Long Training Sequence (LTS) (64 sample duration) of the IEEE 802.11g preamble was used for TOA estimation. The received data was captured immediately at the output of receiver Analog to Digital Converter (40 MHz sampling frequency) and passed to Matlab for offline processing. The distance between the transmitter and the receiver was varied between 0 m and 7 m in steps of 1 meter. To assess the effects of multipath, this process was repeated at three different locations on the 3rd floor of the 4-storey Complex and Adaptive System Laboratory at University College Dublin - a typical open plan office space.

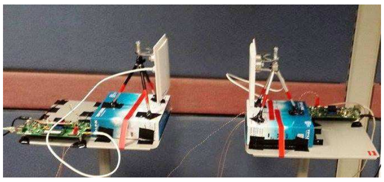

Fig. 1. WARP Platform.

Experimental Results: Figure 2 shows the histogram of the estimated coarse TOA obtained for each symbol over 45,000 LTS symbols at a Tx-Rx separation of 1 m. The double peak arises from timing errors in the capture of the digital start of symbol signal. If the secondary peak were caused by coarse TOA estimation errors, this would lead to fine adjustments greater than 1 sample, which were not observed - see Figure 5. The mode of the coarse TOA estimates was taken as the correct coarse TOA estimate.

Figure 3 shows a typical plot of phase shift versus sub-carrier index, together with the linear fit. The linearity of the measured phase spectrum due to the sub-sample delay can be clearly seen. It is thought that deviations from linearity are due to multipath. The gradient of the fit was found to be roughly constant over consecutive LTSs, as shown Figure 4. A histogram of the final TOA estimate per symbol for a 1 m separation is shown in Figure 5. The adjustment has a mean value of 40.7829 samples and a standard deviation of 0.0068 samples.

The TOA estimation process was performed for Tx-Rx separations of 0 m to 7 m in steps of 1 m at three locations in the building. The mean final TOA estimates per symbol obtained over 45,000 symbols are listed in Table 1. The final TOA estimates were converted to range estimates by subtracting the mean TOA estimate at 0 m, multiplying by the sampling frequency to convert to time and multiplying by the speed of light. Figure 6 presents the range estimates obtained for three different test locations. A summary of the ranging error is presented in Table 2. The accuracy of the method in estimating range is clearly seen.

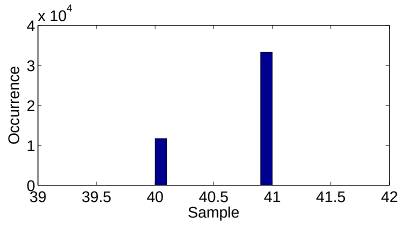

Fig. 2. Histogram of coarse TOA estimates for 45,000 symbols, at 1 m.

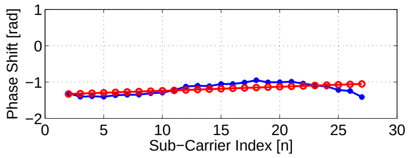

Fig. 3. Sub carrier phase spectrum (red) and linear fit (blue), at 1 m.

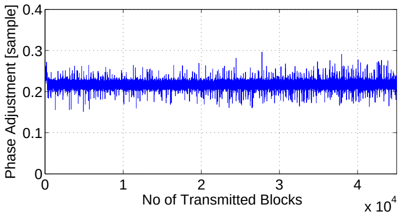

Fig. 4. Variation of linear fit gradient over 45,000 consecutive symbols.

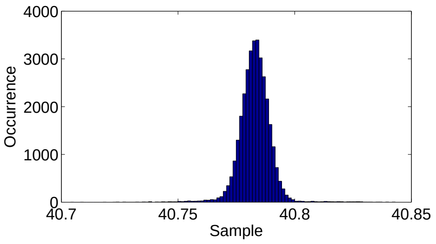

Fig. 5. Histogram of final TOA estimates for 45,000 symbols, at 1 m.

Table 1: Final per symbol TOA estimates statistics in sample numbers.

[m]	Test1 [Sample]		Test2 [Sample]		Test3 [Sample]	
	Mean	Var$*10^5$	Mean	Var$*10^5$	Mean	Var$*10^5$
0	40.6775	5.93	40.6738	48	40.6767	140
1	40.7249	6.37	40.7829	4.67	40.7556	4.47
2	40.9127	5.69	40.9056	4.29	40.8568	6.56
3	40.9688	5.71	40.9931	5.04	41.0571	10.8
4	41.1939	9.60	41.3031	6.03	41.2508	8.86
5	41.368	25.0	41.2295	28	41.2766	37.2
6	41.5419	6.11	41.4698	9.29	41.539	8.44
7	41.6688	410	41.7623	130	41.4627	60.2

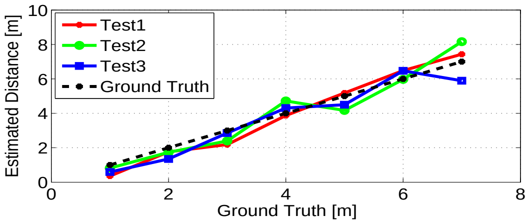

Fig. 6 *Final range estimates versus ground truth for three different test locations (red, blue and green).*

Table 2: Summary of Ranging Results.

Experiment	Max Error [m]	Min Error [m]	Mean Error [m]
Test 1	0.815	0.127	0.417
Test 2	1.164	0.03	0.542
Test 3	1.105	0.147	0.512
Max/Min/Mean	1.164	0.03	0.49

Conclusion: This letter presents a novel method to estimate the TOA of OFDM symbols. The algorithm consists of two steps: coarse estimation based on cross-correlation and fine adjustment using the gradient of a linear fit to the phase difference between the received and transmitter LTS sub-carriers. In real-world experiments, the proposed algorithm achieved an average mean TOA estimation error of 0.49 m using the LTS of IEEE 802.11g with Tx-Rx separations in the range 1-7 m in a LOS and low multipath environment. In future work, we plan to extend the algorithm so as to better mitigate the effects of multipath.

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Ahmed Makki, Abubakr Siddig, Mohamed Saad, and Chris Bleakley (*School of Computer Science & Informatics, University College Dublin, Dublin, Ireland*)

J. R. Cavallaro (*Department of Electrical and Computer Engineering , Rice University, Houston, USA*)

E-mails: ahmed.makki@ucdconnect.ie

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