Abstract

Indoor localization of mobile devices and tags has received much attention recently, with encouraging fine-grained localization results available with enough line-of-sight coverage and enough hardware infrastructure. Synchronicity is a location system that aims to push the envelope of highly-accurate localization systems further in both dimensions, requiring less line-of-sight and less infrastructure. With Distributed MIMO network of wireless LAN access points (APs) as a starting point, we leverage the time synchronization that such a network affords to localize with time-difference-of-arrival information at the APs. We contribute novel super-resolution signal processing algorithms and reflection path elimination schemes, yielding superior results even in non-line-of-sight scenarios (with one to two walls separating client and APs). We implement and briefly evaluate Synchronicity on the WARP hardware radio platform using standard 20 MHz wireless LAN channels.

Categories and Subject Descriptors

C.2.1 [Computer-Communication Networks]: Network Architecture and Design—Wireless communication

Keywords

TDoA; Synchronization; Distributed MIMO; Location tracking

1. INTRODUCTION

Recently, indoor wireless LAN-based localization systems have broken the meter accuracy barrier both for WiFi devices [1, 8] and RFID tags [7], but to achieve these results, they need many APs and antennas, an RF environment without too many obstacles blocking the line-of-sight from client to AP, or a combination of both.

The most promising approaches to indoor localization involve analyzing the signals clients send jointly: both in the spatial domain, analyzing the angle-of-arrival (AoA) of the signal to the access point, and in the time domain, analyzing the time-of-arrival of different parts of the signal. But time-of-arrival analysis has a particular challenge: for a typical 802.11g WiFi channel with only 20 MHz bandwidth, the signal is sampled once every 50 nanoseconds, during which light travels a full 15 meters, as shown in the first row of Table 1. As the next rows of the table show, later 802.11n and 802.11ac standards enhance this resolution, but still achieve just 1.9 meters, limiting the utility of time-of-arrival analysis on its own for the purpose of accurate localization. Even ultrawideband systems, whose expensive high-speed A/D converters sample at a rate of at least 300 MHz, achieve just 60 cm spatial resolution.

However, two recent advances in knowledge are changing the above landscape of time-of-arrival analysis:

1. First, a new class of array signal processing algorithms, informally known as “super-resolution” algorithms [2, 5], can look deeper into the received signal to overcome the naïve resolution limit of Table 1.

2. Second, recent work making distributed MIMO wireless LANs practical [4] raises the possibility of leveraging the fine-grained time synchronization such systems achieve to measure the time-of-flight difference between APs, thus computing time-difference of arrival (TDoA) in the distributed MIMO LAN.

Synchronicity is a system that leverages both above observations to achieve high localization accuracy in a typical, relatively narrowband (20 – 40 MHz) distributed MIMO wireless network (our techniques are also applicable to Distributed Antenna Systems). Synchronicity breaks through the 15 meter resolution barrier of the 20 MHz wireless channel illustrated in Table 1, to achieve localization accuracy on the order of one meter with just four single-antenna APs, as shown experimentally in §3. A rough system sketch (see Figure 1) highlighting our novel idea contributions, is as follows:

Synchronicity first measures time-difference of arrival of a client’s transmission at pairs of APs in the network. In order to do this, Synchronicity combines elements of two state-of-the-art super-resolution algorithms, looking at the correlation between incoming signals on different subcarriers as improvements of MUSIC [6] do [2], and performing generalized eigenanalysis (as “matrix pencil” schemes do [5]), crucially, just on data identified as coming from the signal. This allows Synchronicity to achieve a higher accuracy in the impulse response profile at one AP than either prior super-resolution algorithm. To synchronize time across APs, Synchronicity uses

<table>
<thead>
<tr>
<th>Physical layer</th>
<th>Bandwidth</th>
<th>Resolution</th>
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</thead>
<tbody>
<tr>
<td>802.11g WiFi</td>
<td>20 MHz</td>
<td>15 m</td>
</tr>
<tr>
<td>802.11n WiFi</td>
<td>40</td>
<td>7.6</td>
</tr>
<tr>
<td>802.11ac WiFi</td>
<td>&lt; 160</td>
<td>&gt; 1.9</td>
</tr>
<tr>
<td>Ultrawideband</td>
<td>&gt; 500</td>
<td>&lt; 60 cm</td>
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Table 1: Popular physical layers used in localization, their frequency bandwidth, and naïve spatial resolution—the resulting distance light travels between sampling instants at that bandwidth.
we note that MUSIC can also be applied in the time domain [2].

with the MUSIC algorithm [6]. Previous work on angle-of-arrival
APs in the network in order to estimate and refine the mobile client’s
(A1, A2, and A3) measures time difference of arrival (TDoA) to
MUSIC pseudospectrum has applied MUSIC in the spatial (bearing to AP) domain [8], but
To A
In the first stage, Synchronicity measures the time of arrival (T)
section, we expand on the design of each stage in turn, motivating
2. DESIGN
finally the paper concludes.
imental evaluation comparing Synchronicity with super-resolution
periments to justify key design choices. A brief WARP-based exper-
chronicity, supplementing our description with microbenchmark ex-
exists methods [3] as a starting point, and leave improvements to
time synchronization functionality as near-term future work.
Next, Synchronicity analyzes the output of the above step (the
MUSIC pseudospectrum) to identify useful spectra, retrieving ac-
curate information even when the overall spectrum is not accurate
due to the resolution limit of MUSIC. Synchronicity also poten-
tially eliminates multipath propagation which is the major challenge
for indoor localization. Here novel peak classification algorithms
identify the accurate direct-path peak on the spectrum for further
localization processing.
Finally, Synchronicity compares TDoA readings across pairs of
APs in the network in order to estimate and refine the mobile client’s
location. Here a novel algorithm based on the classical triangle
inequality discards measurements that must have arisen from a
multipath reflection. Then clustering, outlier rejection, and averaging
complete the processing chain, yielding the location estimate from
a mobile client’s transmission. Synchronicity does not need any
offline training, calibration or decoding of the packet: the preamble
of a single packet is enough for it to work well.
In the remainder of this short paper, we sketch the design of Syn-
chronicity, supplementing our description with microbenchmark ex-
periments to justify key design choices. A brief WARP-based exper-
imental evaluation comparing Synchronicity with super-resolution
MUSIC in a cluttered working office environment follows, and
finally the paper concludes.

2. DESIGN
As mentioned above, Synchronicity operates in three stages. In this
section, we expand on the design of each stage in turn, motivating
design choices with microbenchmarks conducted over cabled RF
links. In §3, we evaluate the design over the indoor wireless channel.
We assume AP locations are known and pre-configured.

2.1 Super-resolution spectral processing
In the first stage, Synchronicity measures the time of arrival (ToA)
of a client’s transmission at one AP. This is done with the following
super-resolution processing on the received signal. We begin
with the MUSIC algorithm [6]. Previous work on angle-of-arrival
has applied MUSIC in the spatial (bearing to AP) domain [8], but
we note that MUSIC can also be applied in the time domain [2].
The multipath indoor radio propagation channel is usually mod-
eled as complex impulse responses as:
\[ h(t) = \sum_{k=1}^{D} c_k \delta(t - \tau_k) \]  
(1)
where \( D \) is the number of paths, \( c_k \) and \( \tau_k \) are the complex attenuation
and propagation delay of the \( k \)th path. Processing starts with
sub-carrier channel response of Equation 1 in the frequency domain:
\[ x[n] = H[f_n] + w[n] = \sum_{k=1}^{D} c_k e^{-j2\pi (f_n + \delta) \tau_k} + w[n] \]  
(2)
where \( w[n] \) denotes additive white noise with mean zero and variance
\( \sigma_n^2 \); \( f_n \) and \( \Delta f \) are the carrier frequency and subcarrier bandwidth.
Taking the DFT of the received 64-sample long training symbols in
the preamble we obtain the subcarrier frequency response \( x[n] \). In
802.11a/g, 52 out of 64 subcarriers are used and we employ all of
them for Synchronicity. The correlation matrix is defined as:
\[ R_x = E\{x[n]x[n]^*\} \]  
(3)
The time steering vector \( a(\tau) \) is defined as:
\[ a(\tau) = \begin{bmatrix} 1 \\ \exp(-j2\pi\tau\Delta f) \\ \vdots \\ \exp(-j2(M - 1)\pi\tau\Delta f) \end{bmatrix} \]  
(4)
Suppose \( D \) signals \( s_1, \ldots, s_D \) arrive at different time \( t_1, \ldots, t_D \) at
\( M \) (\( M > D \)) frequency domain subcarriers. The array correlation
matrix \( R_{\text{xx}} \) at AP will then have \( M \) eigenvalues associated respect-
ively with \( M \) eigenvectors \( E = [e_1, e_2, \ldots, e_M] \). The eigenvalues
are sorted in non-decreasing order, the smallest \( M - D \) correspond
to the noise while the next \( D \) eigenvalues correspond to the
\( D \) incoming signals. Based on this process, the corresponding
eigenvectors in \( E \) can be classified as noise or signal:
\[ E = \begin{bmatrix} \frac{E_N}{e_1} \ldots \frac{E_N}{e_M-D} \frac{E_D}{e_M-D+1} \ldots \frac{E_D}{e_M} \end{bmatrix} \]  
(5)
We refer to \( E_N \) as the noise subspace and \( E_D \) as the signal subspace.
The MUSIC time of arrival (ToA) spectrum is then computed as:
\[ P(\tau) = \frac{1}{a(\tau)^H E_D E_D^H a(\tau)} \]  
(6)

2.1.1 Algorithm
Synchronicity includes a new super-resolution scheme which em-
ploy the signal subspace \( E_D \) instead of the noise subspace \( E_N \), then
applies the matrix pencil [5] method to obtain the ToA information.
The traditional Matrix Pencil scheme is applied to the raw channel
response data. However, we notice that with Matrix Pencil applied
to the noiseless signal-space eigenvectors, we are able to achieve
even better performance than either MUSIC or traditional Matrix
Pencil although the computational load is a little bit higher. We
define two matrices \( E_{51} \) and \( E_{52} \) using the first \( M - 1 \) rows and the
2nd to \( M^{th} \) rows of \( E_D \) respectively:
\[ E_{51} = [I_{M-1}, 0_{M-1,1}] E_D \]  
(7)
\[ E_{52} = [0_{M-1,1}, I_{M-1}] E_D \]  
(8)
where \( I \) and \( 0 \) are the identity matrix and the zero matrix respectively.
We then obtain ToA information by finding the generalized singular
values for the matrix pencil \( E_{51} \) and \( E_{52} \).

2.2 Spectrum accuracy determination
We now describe the processing that happens on the ToA profile
computed in §2.1. When the lengths of a line-of-sight path and a
reflected path are too close to each other, MUSIC is unable to resolve
the two signals correctly in the time domain on the pseudospectrum.
This leads to either inaccurate pseudospectrum peak positions or
multiple peaks merged into one. However, Synchronicity leverages
the insight that we can still retrieve useful and accurate information
from these inaccurate pseudospectra.

![Figure 1: Synchronicity high-level view. Each pair of AP antennas (A1, A2, and A3) measures time difference of arrival (TDoA) to generate a possible location whose locus is a hyperbola. A third AP generates another hyperbola, and hence the intersection is identified.](image-url)
We see from the figure that MUSIC is able to resolve both paths we fix the distance between the direct path signal and reflected signal once the distance between the two signals is decreased to around 2.7 m propagation delay in the air). The ground truth path length delays are denoted with dotted lines.

Figure 2: Testing MUSIC’s ability to resolve two paths with decreasing path length difference. The ground truth path length delays are denoted with dotted lines.

Figure 3: Peak error (translated and shown in meters) on the pseudospectrum when two signals are too close for MUSIC to resolve.

### 2.2.1 Microbenchmark characterization

**MUSIC super-resolution capability.** To determine when line-of-sight and reflected paths are too close to each other for MUSIC to resolve at 20 MHz, we use RF splitter-combiners to split a signal into two, delay one branch, and then combine the other branch and the delayed copy, thus simulating multipath propagation with one reflection path in a controlled manner. We use different cable lengths to control the relative path lengths, and attenuators to control the respective path signal strengths to the same level.

Decreasing the path length difference from 13.5 m gradually to 2.7 m results in the MUSIC pseudospectra shown in Figure 2. We see from the figure that MUSIC is able to resolve both paths quite accurately when their lengths are sufficiently different, but once the distance between the two signals is decreased to around six meters, MUSIC is not able to generate accurate pseudospectra anymore. This fundamental limit to all the super-resolution scheme is determined by the sampling rate (bandwidth).

**Effect of path attenuation.** Most of the time, the direct path and reflection path signals don’t have the same amplitude. We observe that even when the two peaks are too close for MUSIC to resolve, the larger peak on the pseudospectrum corresponding to the larger signal is still quite accurate compared to the smaller peak.

We demonstrate this observation by the following experiments: we fix the distance between the direct path signal and reflected signal as 5.4 meters with the help of different length cables. Then we tune the relative signal strength ratio of the direct path and reflection path from 3 dB to 9 dB and show the peak position error in Figure 3. We see clearly that when the direct path signal is stronger, although MUSIC is not able to resolve both of them correctly, the error of the direct-path peak is quite small (less than 0.5 meter). On the other hand, the smaller reflection path peak has a much larger error, so we can still extract relatively accurate information from the MUSIC spectrum in these scenarios as we only care the direct-path peak.

Next, we show that when the two signals are even closer (separated by 2.7 meters) and the two peaks actually merge into one as shown in Figure 2 bottom subplot, as long as the direct-path signal is stronger, the error is still small. We vary the relative strength ratio from 22 dB to −7 dB and show the error results in Figure 4. We can see that the error is well under one meter as long as the direct-path signal is stronger. The error increases significantly when the reflection path is stronger.

2.2.2 Algorithm (Spectrum identification)

As shown in the preceding microbenchmarks, useful and accurate information can still be retrieved even when MUSIC fails to resolve all the signals correctly as we only care about the direct-path peak. A critical step for Synchronicity is to identify useful pseudospectra; the algorithm is as follows:

**Step 1.** We take the first two peaks on the pseudospectrum as input to the algorithm. If the two peak positions are separated by less than half the sample period, they fall into the zone that MUSIC is not able to resolve accurately and we proceed to Step 2.

**Step 2.** Next, we compare the relative amplitudes of the two peaks. From the above microbenchmarks, we know that as long as the direct path signal is stronger than the reflection path signal, the direct-path peak position will be accurate. So if the amplitude of the first peak is greater than the second peak, we mark the spectrum as useful. Otherwise it’s discarded. Referring to Figure 5, we identify the spectrum in the upper figure as useless and the lower as useful.

**Step 3.** Then we check whether the first peak is a single-signal peak or a merged peak. A single-signal peak is much thinner compared with a merged peak. The difference is apparent when we compare the higher peak in Figure 5 (lower) with the peaks in Figure 6. We measure the peak lobe width at 90% of the peak amplitude and compare it with a predefined value $W_i$. (This value is stable at a particular bandwidth) to make the decision. If it’s a single-signal peak, we identify this spectrum as useful and keep it for localization. If it’s a merged peak, we proceed to the next step.

**Step 4.** Now we check the direction of the peak’s skew. We measure the width of the lobe with respect to the peak position as shown in Figure 6. Here the width of the green part is much larger than

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1 Because of lower transmission speed in cable, we translate cable length to equivalent air propagation distance. (The delay of a 1.8 m RG-58 cable is equivalent to 2.7 m propagation delay in the air).

2 We will investigate using the second moment (variance).
In the last stage of TDoA localization, the measured TDoAs are converted into corresponding distance differences and used to estimate the mobile’s location. Each pair of APs yields one TDoA estimate in the shape of half a hyperbola. Thus three APs are able to localize the client at the intersection of two hyperbolas. We propose the following two algorithms to handle this very challenging scenario.

The purple part so it’s identified as useless. The lower plot shows a spectrum skewing earlier in time (merged towards the direct-path peak). In this case the peak has a reasonably small error, and can thus still be employed for localization.

Step 5. After the above steps, only the useful peak remains. Then we calculate the relative ToA corresponding to the useful peak from the generalized singular values with outputs derived from Equations 7 and 8 and thus the TDoA between a pair of APs.

2.3 Multi-AP data fusion

In the last stage of TDoA localization, the measured TDoAs are converted into corresponding distance differences and used to estimate the mobile’s location. Each pair of APs yields one TDoA estimate in the shape of half a hyperbola. Thus three APs are able to localize the client at the intersection of two hyperbolas.

Occasionally, the direct-path signal may be totally blocked, with only reflection signals existing. We propose the following two algorithms to handle this very challenging scenario.

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3. EVALUATION

We implement Synchronicity on the WARP platform. In our current evaluation, we use four antennas attached to the WARP to serve as four synchronized APs and distribute them with equal-length cables in a large, cluttered 20 × 30 m office (Figure 9). We place the clients at 16 randomly-chosen locations denoting their positions as red dots on the floor plan. Half of the chosen clients locations are not in the same room as the APs, with at least one to two walls in between.
We compare the following schemes:
1. MUSIC, picking the first peak in each spectrum as the direct-path peak, deriving TDoA information from the MUSIC spectrum.
2. MUSIC with spectrum identification (SI, §2.2.2) and the triangle inequality (TI, §2.3.1), deriving TDoA information from the MUSIC spectrum.
3. Synchronicity, including SI and TI, deriving TDoA information from generalized singular values (§2.1.1).
4. Synchronicity with neither SI nor TI, but deriving TDoA information from generalized singular values.

3.1 End-to-end location accuracy
We show location accuracy results in Figure 10. The CDF is composed of 160 measurements, 10 at each location measured at different times. With only a 20 MHz sampling rate, we are able to achieve around 1.6 meters median accuracy, significantly better than both the naive spatial resolution of 15 m and MUSIC’s spatial resolution of approximately 6.5 m. With Synchronicity’s SI scheme, the modified version of MUSIC is also able to achieve around 1.75-meter location accuracy. Note that we include all the schemes described in §2 except clustering and outlier rejection, simply averaging all the location estimates across each triplet of APs. With more APs, we expect cluttering and outlier rejection to further refine the accuracy of Synchronicity’s location estimate. We plan to run more through evaluations at higher bandwidth and with outlier rejection to improve Synchronicity’s accuracy in near-term future work.

If we exclude our spectrum identification and triangle inequality schemes, how will MUSIC and Synchronicity perform? From Figure 10, we can see that the median error is around 2.8 m and 3.6 m for Synchronicity and MUSIC respectively. We notice that MUSIC without TI & SI has a particularly long tail mainly caused by not detecting a blockage of the direct client-AP path, and employing inaccurate peak without SI when the sampling rate is not high enough to accurately resolve all signals in the spectrum.

3.2 Impact of time-synchronization error
In our current setup, the four antennas serving as APs are fully synchronized and connected to a WARP. In a distributed MIMO system, there will be time synchronization errors between APs, leading to a performance degradation for Synchronicity. We evaluate the effect of time synchronization error on Synchronicity in Figure 11. We borrow the time synchronization error data from SourceSync [3] and incorporate it into our TDoA estimation for Synchronicity. We can see that, with 5 ns and 10 ns 95th percentile time synchronization error, Synchronicity is still able to perform reasonably well, achieving a median localization error below two meters. With 20 ns time synchronization error, a larger location error is found. However, as long as we can keep this error below 10 ns, location accuracy remains mostly unaffected. We expect to minimize this synchronization error in our future work when we push Synchronicity to work on larger bandwidth for greater accuracy.

4. CONCLUSION
Synchronicity is an indoor localization system that pushes the accuracy envelope with very few antennas and APs, and relatively narrowband wireless channels. Synchronicity is able to achieve 1.6 m median accuracy at 20 MHz bandwidth. We expect to realize centimeter accuracy localization at the 160 MHz bandwidth of 802.11ac. We also leave the use of multiple antennas at each AP in Synchronicity to further improve accuracy as future work. Multiple antennas at each AP can bring angle-of-arrival information as well as enhancing ToA information at the AP, thus potentially improving the location accuracy performance.

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6. REFERENCES