Experimental Performance Evaluation of Location Distinction for MIMO Channels

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Abstract

Location distinction is defined as determining whether or not the position of a device has changed. We introduce methods and metrics for performing location distinction in multiple-input multiple-output (MIMO) wireless networks. Using MIMO channel measurements from two different testbeds, we evaluate the performance of temporal signature-based location distinction with varying system parameters, and show that it can be applied to MIMO channels with favorable results. In particular, a 2x2 MIMO channel with a bandwidth of 80 MHz allows a 64-fold reduction in miss rate over the SISO channel for a fixed false alarm rate, achieving as small as $4 \times 10^{-4}$ probability of false alarm for a $2.4 \times 10^{-4}$ probability of missed detection. The very high reliability of MIMO location distinction enables location distinction systems to detect the change in position of a transmitter even when using a single receiver.

I. INTRODUCTION

Location distinction is defined as determining whether or not the position of a device has changed. In the context of a wireless network, this means detecting when a transmitter changes its position via measurements made at one or more receivers, or vice versa.

Location distinction is fundamentally different from localization, in that location distinction is not concerned with the position of the transmitter, only whether or not it has moved. Location distinction should work under two use cases: (1.) when a wireless device is continuously moving; and (2.) when a wireless device and access point are stationary for a long time and suddenly a transmission with the same claimed identity is sent from a new location. Under use case (1.) the algorithm should detect a new location with each transmission, while under use case (2.) the algorithm should decide the new transmission is from a different location.

The ability to perform location distinction provides several benefits, including an improved capability to monitor the positions of radio-tagged objects, better energy conservation in radio localization systems, and a means to detect impersonation attacks in wireless networks [1], [2]. Location distinction has been shown to be useful in detecting the Sybil attack [3], [4]. Other work has also shown that characteristics of the physical layer of wireless networks, such as received signal strength (RSS), channel impulse response (CIR), or channel frequency response can be exploited to detect changes in transmitter/receiver positions [5], [6], [7], [8].

Multiple-input multiple-output (MIMO)-capable devices represent the state-of-the-art in wireless networking and have enabled significantly improved spectral efficiencies in wireless networks. Many new wireless standards, such as 802.11n, WiMax, and 4G cellular, take advantage of MIMO technology. Enhancing these standards with the capability to perform location distinction would offer extra security against impersonation attacks. For example, the 802.11n standard is vulnerable to impersonation and
denial-of-service attacks because the MAC addresses of network clients are sent over the air unencrypted and may be eavesdropped on and used by an attacker in order to masquerade as a legitimate client.

Previous work has suggested using channel measurements gathered between a single transmitter and multiple receivers in order to perform location distinction \([5, 1, 7, 4, 9]\). However, in typical WiFi networks, adjacent access points are set to operate on different channels in order to reduce interference and a client operates on a single channel. This makes collecting channel data at multiple access points difficult. Extending location distinction to MIMO allows robust location distinction to be performed with a single receiver.

![Location distinction measures link signatures from received packets, and then raises an alarm if the current measurement differs greatly from those in the history.](image)

This paper evaluates the performance of the general location distinction algorithm shown in Figure 1, in which channel impulse response measurements, called link signatures, are measured over time for a given link, and each new link signature is compared to those in a history of previous measurements in order to detect changes in position. To the authors’ knowledge no implementation and experimental evaluation of MIMO-based location distinction has been performed. We present the following work in order to characterize the performance of temporal signature-based location distinction in the context of a MIMO channel:

1. We introduce MIMO temporal link signatures for quantifying the state of the MIMO channel.
2. We perform two measurement experiments with two different experimental testbeds in order to evaluate location distinction under two distinct use cases.
3. We evaluate spatially dense channel measurements in order to study the spatial evolution of temporal link signatures.
4. We evaluate several trade-offs between system design parameters and performance, including: link signature history size, bandwidth, complex vs. magnitude-only signatures, use of delay between measurements, and number of antenna elements.

The results show that MIMO location distinction algorithms perform well in a variety of experimental conditions. For example, we achieve a \(4 \times 10^{-4}\) probability of false alarm for a \(2.4 \times 10^{-4}\) probability of missed detection using a 2x2 MIMO channel with a bandwidth of 80 MHz, and a \(3 \times 10^{-4}\) probability of missed detection for a false alarm rate of 0.01 using a 1x2 SIMO channel with a bandwidth of 20 MHz. Additionally, we show that:

1. In the context of spatially dense link signature measurements (inter-measurement distances < \(\lambda\)), it is necessary to introduce a delay between past and current measurements in order to reliably perform location distinction. The size of delay depends on the spatial density of the measurements.
2. The number of link signatures to store in the history depends on the amount of temporal variation in the link signatures when the wireless device is stationary.
3. The most significant performance gain for MIMO vs. SISO location distinction occurs in the move from SISO to 2x2 MIMO. Further increasing the number of antenna elements offers diminishing returns.
4. When random phase shifts due to imperfect synchronization are removed, complex link signatures lead to better performance than magnitude-only link signatures.
5) Increasing the bandwidth of the link signatures offers diminishing returns after about 20 MHz. In fact, higher bandwidth measurements are more susceptible to synchronization errors.

This paper is organized as follows. In Section II, we describe the link signatures, metrics, and MIMO location distinction algorithm. In Section III, we discuss two measurement experiments, which we will refer to as Experiment I and Experiment II. In Section IV, we present testing results and analysis of the MIMO location distinction algorithm. We discuss related work in Section V. Conclusions and future work are presented in Section VI.

II. METHODS

In this section, we first describe the link signatures we use for location distinction and the difference metrics we use to quantify changes in them. Next, we present a real-time location distinction algorithm and the framework for testing this algorithm.

A. Link Signatures

We define the \( n \)th complex temporal link signature (CTLS) calculated for the \( c \)th transmitter/receiver antenna pair as

\[
\mathbf{f}_c^{(n)} = [h_c^{(n)}(0), h_c^{(n)}(1T_s), \ldots, h_c^{(n)}((M-1)T_s)]
\]

(1)

where \( h_c^{(n)}(\tau) \) is the band-limited channel impulse response as a function of delay \( \tau \), \( M \) is the number of samples, \( T_s \) is the sampling period, and \( c \in S \), where

\[
S = \{1, \ldots, k_1\} \times \{1, \ldots, k_2\}.
\]

(2)

The number of transmitter and receiver antennas are represented by \( k_1 \) and \( k_2 \), respectively. We also define the \( n \)th temporal link signature (TLS) calculated for the \( c \)th transmitter/receiver antenna pair as

\[
\mathbf{g}_c^{(n)} = [|h_c^{(n)}(0)|, |h_c^{(n)}(1T_s)|, \ldots, |h_c^{(n)}((M-1)T_s)|].
\]

(3)

The MIMO channel measurements used in this paper are gathered using either a multitone probe or preamble-based channel estimation, both of which are described in Section III. In both cases, time-domain representations of the channel response are used for link signatures.

We let the \( n \)th MIMO complex temporal link signature (MIMO CTLS) be the concatenation of the set of complex temporal link signatures measured between the first \( k_1 \times k_2 \) transmitter and receiver antennas:

\[
\mathbf{F}^n = [\mathbf{f}^{(n)}_{c_1}, \ldots, \mathbf{f}^{(n)}_{c_k}],
\]

(4)

where \( c_1, \ldots, c_k \) is a list of the elements of \( S \).

Finally, we let the \( n \)th MIMO temporal link signature (MIMO TLS) be the concatenation of the set of temporal link signatures measured between the first \( k_1 \times k_2 \) transmitter and receiver antennas:

\[
\mathbf{G}^n = [\mathbf{g}^{(n)}_{c_1}, \ldots, \mathbf{g}^{(n)}_{c_k}].
\]

(5)

B. Difference Metric

In this section, we define the metric for measuring the difference between the current MIMO link signature the FIFO history of previous MIMO link signatures below. The FIFO history \( \mathcal{H} \) for the previous \( N \) MIMO link signatures is defined as

\[
\mathcal{H} = \{\mathbf{F}^n\}_{n=1}^N
\]

(6)

or

\[
\mathcal{H} = \{\mathbf{G}^n\}_{n=1}^N
\]

(7)
depending on the MIMO link signature being used. The difference metric we explore in this paper is
\[
\Delta(F^{N+D}, \mathcal{H}) = \frac{1}{\sigma} \min_{F \in \mathcal{H}} \|F - F^{N+D}\| \tag{8}
\]
where \(\sigma\) is the average distance between link signatures in the history, defined as
\[
\sigma = \frac{1}{(N-1)(N-2)} \sum_{F^m, F^n \in \mathcal{H}} \|F^m - F^n\| \tag{9}
\]
and \(D\) is a delay parameter. This delay is inserted to increase the time between the current link signature measurement and those in the history. As we show in Section [IV-A], \(D > 1\) helps detection performance under use case (1.). In the case of the magnitude-only TLS, the norms in (8) and (9) are the \(\ell_2\) norm; for the CTLS, these norms are the \(\phi_2\) norm, defined as
\[
\|g - h\|_{\phi_2} = \min_{\phi} \|g - he^{j\phi}\|_{\ell_2} = \|g\|^2 + \|h\|^2 - 2\|g^*h\|. \tag{10}
\]
The \(\phi_2\) norm removes the effect of random phase shifts that occur between subsequent CTLS measurements.

We examine various sizes for the FIFO history \(\mathcal{H}\) and the delay \(D\) in Sections [IV-B] and [IV-A] respectively. Changing these parameters dramatically affects the detection performance of the location distinction algorithm. The delay has the effect of increasing the difference between the latest link signature and those stored in the history. This is beneficial for location distinction under use case (1.). The FIFO history size is chosen to maximize the probability of detecting a change in receiver position, while minimizing the probability of misidentifying a stationary receiver as moving.

C. Real-time Location Distinction

A real-time location distinction algorithm is defined by the following steps:

1) Measure the current link signature.
2) Calculate the minimum difference \(\Delta\) between the current link signature and the link signatures in the FIFO history \(\mathcal{H}\).
3) Compare the minimum difference \(\Delta\) to a threshold \(\gamma\). If \(\Delta > \gamma\), raise an alarm to indicate that the receiver has moved since the last link signature was measured. If \(\Delta < \gamma\), do not raise an alarm, thereby indicating that the receiver has not moved since the last link signature was measured.
4) Add the current link signature to a FIFO delay buffer and add the oldest link signature in the delay buffer to the FIFO history \(\mathcal{H}\).
5) Return to step 1.

The process is illustrated in Figure 1. This is a real-time algorithm, but we note that in this paper, we first collect all of the link signatures, and then evaluate location distinction in post-processing.

D. Performance Evaluation

In this Section, we construct a framework used to apply the metrics described in Section [II-B] to the link signatures described in Section [II-A] in order to test the performance of MIMO location distinction. The performance evaluation is conducted using the following steps:

1) The output of the difference metrics
\[
E_f^{N+D} = \Delta(F^{N+D}, \mathcal{H})
\]
and
\[
E_g^{N+D} = \Delta(G^{N+D}, \mathcal{H})
\]
are recorded for stationary and moving receivers.
2) We identify the probability of false alarm $P_{FA}$ and probability of detection $P_D$ for each antenna subset in reference to a possible difference threshold $\gamma$. We define the null and alternate hypotheses, $H_0$ and $H_1$ as follows:

$H_0$: Receiver has not moved.

$H_1$: Receiver has moved.

We treat $E_f^{N+D}$ and $E_g^{N+D}$ as random variables and denote their conditional density functions under the two events above as $f_E(x|H_0)$ and $f_E(x|H_1)$. The $E_f^{N+D}$ and $E_g^{N+D}$ for a stationary and moving receiver are used to characterize $f_E(x|H_0)$ and $f_E(x|H_1)$ respectively. We calculate $P_{FA}$, $P_D$, and $P_M$ as:

$$P_{FA} = \int_{x=\gamma}^{\infty} f_E(x|H_0) dx$$

$$P_D = \int_{x=\gamma}^{\infty} f_E(x|H_1) dx$$

$$P_M = 1 - P_D$$

The $P_{FA}$ and $P_D$ as a function of $\gamma$ allow us to evaluate how well location distinction would have worked if a threshold of $\gamma$ was used in the real-time algorithm. Thus the set of possible $P_{FA}/P_D$ combinations provide a curve of feasible real-time detection performance.

III. MEASUREMENTS

We describe two MIMO measurement experiments. One is performed at Brigham Young University [10], and another is performed at the University of Utah. These datasets are used to evaluate the location distinction algorithm according to the framework described in the previous section.

These experiments provide an opportunity to examine the following two use cases for location distinction:

1) A wireless device sends packets while in motion so that each new packet is sent from a distinct location. In this case, the location distinction algorithm should detect the change with every new packet. Our Experiment I provides MIMO data to test the performance of location distinction in this use case. In fact, measurements are made with fine enough spacial resolution that it is necessary to delay inserting the most recent measurements into the history FIFO in order to ensure sufficient decorrelation between a current measurement and those in the history.

2) A wireless device sends packets while stationary for a long period of time. Then, a new packet is sent from a distinct location, either because the wireless device has moved, or because a second wireless device is attempting to impersonate the first from a different location. In either case, the location distinction algorithm should detect the change. Our Experiment II provides MIMO data to test the performance of location distinction for this use case.

Under both use cases, in order to simulate MIMO antenna arrays of different sizes and examine the associated performance of temporal signature-based location distinction, we compile the MIMO link signatures, as in (4) and (5), from the subsets of the SISO link signatures, CTLS and TLS, measured with $1 \times k$ and $k \times k$ antenna arrays, where $k \in \{1, \ldots, 8\}$. At the MIMO receiver, channel measurements are made with a period $T_r$. For each measurement taken at the receiver, we calculate the link signatures defined in Section II-A. The number of channel measurements varies with the receiver position. For Experiment I, if there are $n+1$ measurements at a given receiver location, the $n$th measurement is taken at $t = nT_r$, and the $n$th link signatures are associated with this measurement time. In Experiment II, $T_r$ varies slightly around a nominal value of 3.0 s, but we have the exact position of the transmitter and receiver for each measurement.
A. Experiment I

The first experiment is conducted at Brigham Young University by Wallace et al. [10]. MIMO channel data are collected using an 8x8 MIMO channel sounder in which a multi-tone baseband signal is mixed with a carrier frequency of 2.55 GHz and transmitted to stationary and moving receivers. The transmitter is stationary for these measurements. The multi-tone signal is constructed as follows:

\[ x_B(t) = \sum_{i=0}^{B} \cos(2\pi f_i t + \theta_i) \]  

(11)

where \( B = 39 \) and

\[ f_i = (i + 0.5) \text{ MHz} \]  

(12)

and \( \theta_i \) is a fixed random phase shift between 0 and \( \pi \) included for each tone in order to spread the signal energy in time [11]. The signal \( x_B(t) \) is multiplied by a Gaussian window to combat artifacts generated by switching the signal on and off.

The transmitter and receiver each use a uniform circular array of eight monopole antennas. These arrays have a nominal element spacing of \( \lambda/2 \) (where \( \lambda \) is the wavelength) and are well synchronized in both carrier frequency and phase. The wideband channel frequency response \( H(f) \) for each antenna pair is computed by dividing the Fourier transform of the measured signal by the Fourier transform of the known transmit signal and separating the results into bins which correspond to the tones in the transmitted signal. The wideband channel impulse response is calculated as

\[ h(n) = F^{-1}\{H(f)\} \]  

(13)

where \( F^{-1}\{\cdot\} \) represents the inverse discrete-time Fourier transform. Channel measurements are collected at eight different receiver locations on a single floor of an office building. Figure 2 is a diagram showing the first three receiver locations. The circled numbers represent each location.

In this experiment the receiver is in motion while the transmitter is stationary. We discussed in Section I applications which detect a moving transmitter using stationary receivers, and the reciprocity of the radio channel allows us to view these measurements as if this were the case [12], [13].

In the cases where the receiver is moving, it moves with a speed of 31.75 cm/sec. At each receiver location, between 390 and 585 measurements are made. In the measurements made with a moving receiver, the multi-tone probe is sent every 3.2 ms, or given the receiver speed of 31.75 cm/sec, every 1.016 mm. These dense (spatially and temporally) measurements are the reason we delay (D) inserting the most recently measured link signature into the history \( \mathcal{H} \). As we show in Section IV, the performance of location distinction improves when this delay is increased, or equivalently, when the current location of the receiver is further from its location during the measurement of the most recent link signature in \( \mathcal{H} \).
B. Experiment II

The second experiment is performed at the University of Utah. Channel measurements are made using a MIMO-OFDM transceiver implemented with a National Instruments vector signal generator (VSG) and vector signal analyzer (VSA) and Labview software.

The transmitted signal is designed to emulate the IEEE 802.11n standard [14]. It is an OFDM signal and has 64 subcarriers contained in a total bandwidth of 20 MHz (312.5 kHz per subcarrier). These include four null subcarriers over which the channel is not estimated (subcarrier indices -32, -31, 0, and 31). Each data symbol is 4.0 µs long consisting of a 3.2 µs data symbol and a 0.8 µs cyclic prefix.

The frame (timing) synchronization, carrier offset recovery, and channel estimation are aided by a preamble. We use the greenfield preamble described in the physical layer specification of the IEEE 802.11n standard, but we omit the high throughput signal field. This field is normally used to convey MAC information regarding the coding, modulation scheme, etc., and isn’t necessary for the channel estimation required by this experiment. The preamble consists of an 8.0 µs periodic signal with a short period (0.8 µs) for coarse carrier acquisition and coarse frame synchronization. This is followed by 8.0 µs of a periodic signal with a long period (3.2 µs) used for fine carrier acquisition and fine frame synchronization. Moose’s method is used for frame synchronization and carrier recovery [15], [16].

The MIMO channel state is estimated using mutually orthogonal sequences. After the long period signal, the transmitter sends to each antenna mutually orthogonal sequences of symbols generated with Walsh-Hadamard codes for each subcarrier. Each of these sequences has a duration of 4.0 µs, which includes a 0.8 µs cyclic prefix. A minimum mean-squared-error (MMSE) channel estimation algorithm with a structure derived from the MMSE estimator in [17] is employed. Compared to the estimator in [17], we increase the number of transmit symbols used for estimating the channel from two symbols (for a 2x2 system) to four symbols.

At the receiver, following carrier acquisition and frame synchronization, the mutual orthogonality of the symbol sequences allows the receiver to quickly invert the received signal information at each subcarrier by performing a single matrix multiplication per subcarrier. This provides an estimate of the channel response for each pair of antennas at each subcarrier, which are the estimates used for this analysis.

![Diagram of Experiment II](image-url)

Fig. 3. Diagram of Experiment II. Circles represent receiver locations, diamonds represent transmitter locations. The outer line represents the wall of the room. Channel measurements are made at each transmitter/receiver location. Desks, equipment, and other scatterers are present, but not depicted in this diagram.

The data are collected in the Wireless Communication Lab at the University of Utah, an open plan office.
lab containing desks, bookcases, chairs, and measurement equipment. We take measurements at eighteen different receiver locations and four different transmitter locations, as shown in Figure 3, resulting in a total of 3600 measurements of 72 distinct radio links. We choose a center frequency of 2.42 GHz and use whip antennas separated by 15.24 cm for the transmitter and receiver antenna arrays, placed at height of 0.91 m.

**IV. RESULTS AND DISCUSSION**

We present and discuss the results of Experiments I and II in the context of four link signature characteristics.

**A. Spatial Distance**

The results of both experiments show that differences in spatial location between link signatures are more significant than the temporal variations in link signatures measured for static receivers. In other
words, changing the position of the transmitter/receiver has a significant effect on the measured link signatures. Figure 4 shows the magnitudes of the 1x1 TLS measured at a stationary or moving receiver in Experiment I. The variation of the signatures for the moving receiver is more significant. In the case of the MIMO TLS, the same effect can be seen in the empirical distributions of the difference metric $E$. These distributions are shown in Figure 5(a). The mean difference metric is much higher in the case of a moving receiver. The same result can be seen in the empirical distributions of the difference metrics calculated for Experiment II. These distributions are shown in Figure 5(b).

Figure 6(a) shows the average $\ell_2$ and $\phi_2$-distances between 8x8 MIMO CTLSs as a function of receiver separation where the $\phi_2$ distance is defined in (10). The average $\ell_2$-distance reaches a maximum at a separation of approximately $\lambda/2$, and then oscillates with a period of $\lambda$. This result agrees with a result of the Clarke fading model, which assumes incoming multipath are uniformly distributed about the receiver $\lambda$.[18]. The average $\phi_2$-distance peaks at a receiver separation of about $\lambda$ and the oscillation is mitigated by the phase rotation inherent in the $\phi_2$-distance. Figure 6(b) shows the average difference metrics $E$ as a function of receiver separation. These results indicate that the difference metrics perform best in the case where the receiver has moved a wavelength or more between measurements. In the context of an impersonation attack, this is typically the case.

### B. History Size

The size of the history buffer $\mathcal{H}$ is a parameter which should be chosen in order to provide the best location distinction performance. For this work, we select a range of history sizes to examine in both experiments and identify the best size heuristically. However, the optimal number of signatures to include in the history is a function of the the difference metric being used and the distribution of the differences measured under $\mathbb{H}_0$ and $\mathbb{H}_1$. Because of the minimum operator in $E$, increasing the history size can only lower the average difference metric under both hypotheses.

Figure 7(a) shows the receiver operating characteristic (ROC) curve of the location distinction algorithm for the 8x8 MIMO CTLS and various history sizes. In this case, the best performance corresponds to a history containing fifteen previous link signatures. Figure 7(b) shows the ROC curve of the location distinction algorithm for the 2x2 CTLS of Experiment II and various history sizes. In this case, a history size of five offers the best performance.

The differences measured under $\mathbb{H}_0$ in Experiment I have a significantly higher mean/variance than those measured under the same hypothesis in Experiment II, indicating that the temporal variations of
the link signatures measured for a stationary receiver in Experiment I are more prominent than those in Experiment II. Therefore, a larger history size is necessary in Experiment I in order to capture the temporal variations of the stationary receiver.

C. Number of Antennas

The results show that as the size of the MIMO antenna array is increased, the performance of the location distinction algorithm improves. This is consistent with the simulation results of [8], which used ray-tracing simulations to show that the average miss rate in a location distinction system decreases with the number of antenna elements.

Figures 8(a) and 8(b) show the location distinction ROC curves for the data from Experiment I and different sized MIMO antenna arrays. Figures 8(c) and 8(d) show the ROC curves for the same experiment, but using SIMO arrangements. The trend in these figures is toward better location distinction performance with the increase in size of the MIMO antenna array. Figure 9 shows miss rates for a given false alarm rate and various SISO, SIMO, and MIMO arrays. The miss rates appear to follow the inverse power law

$$P_M = \frac{b}{(k_1k_2)^m}$$  \hspace{1cm} (14)

where $b$ and $m$ are parameters that define the rate that the probability of missed detection approaches zero with the number of MIMO channels. A least-squares approximation yields $b \approx 10^{-1.44}$ and $m \approx 0.93$ for the data in Figure 9. As a rule of thumb, the achievable miss rate for a constant false alarm rate is approximately inversely proportional to $k_1k_2$, the number of channels.

| $(k_1, k_2)$ | MIMO TLS $P_M$ | MIMO CTLS $P_M$ | CTLS/TLS Improvement | MIMO TLS $P_M$ | MIMO CTLS $P_M$ |
|--------------|----------------|----------------|----------------------|----------------|----------------|
| (1,1)        | 0.032          | $\leq 0.00024$| $\geq 133x$         | 0.0323         | 0.0092         |
| (2,2)        | 0.0005         | $\leq 0.00024$| $\geq 2x$           | $\leq 0.0003$ | $\leq 0.0003$ |

MIMO Improvement $\approx 64x$ N/A $\geq 108x$ $\geq 31x$
Fig. 8. ROC curves for (a) MIMO TLS (b) MIMO CTLS (c) SIMO TLS and (d) SIMO CTLS for various antenna array sizes. Location distinction performance improves with the number of antennas and the MIMO CTLS performs better than the MIMO TLS. The SIMO signatures nearly match the performance of the MIMO signatures.

Fig. 9. Experiment I: Probability of missed detection for a $2 \times 10^{-3}$ probability of false alarm vs. $k_1k_2$ for different SISO, MIMO, and SIMO arrays.
The most drastic improvement in the miss rate occurs in the change from a SISO channel to a 2x2 MIMO or 1x4 SIMO channel. Table I shows the improvement of the location distinction algorithm in a 2x2 MIMO channel over the SISO channel in Experiment I. There is as much as a 108-fold reduction in the miss rate for a constant false alarm rate when changing from SISO to 2x2 MIMO.

D. MIMO CTLs and TLS

In comparing Figures 8(a) and 8(b), it is also apparent that the MIMO CTLs and its associated difference metric leads to better performance than the MIMO TLS in Experiment I. Table I shows the improvement of the location distinction algorithm when using the MIMO CTLs instead of the MIMO TLS. Using the MIMO CTLs results in as much as a 133-fold reduction in miss rate for a constant false alarm rate.

This result is also confirmed in Experiment II, as shown in Table I. In Experiment II, the 1x1 CTLs results in a 3.5-fold improvement in miss rate over the 1x1 TLS. The 2x2 TLS and 2x2 CTLs both reach the lowest measurable miss rate in Experiment II.

E. Link Signature Bandwidth

Another crucial parameter in both experiments, and typically a limiting factor in radio design, is system bandwidth. We examined the performance of the location distinction algorithm over a range of bandwidths by varying the number of tones included in the IFFT of the frequency-domain measurements from Experiment I. This is similar to varying $B$ in (11).

![Fig. 10. Location distinction miss rate vs. link signature bandwidth for a $7 \times 10^{-4}$ false alarm rate in Experiment I. Increasing bandwidth offers diminishing returns.](image_url)

Figure 10 shows that performance typically improves with bandwidth, but it does so with diminishing returns. This is consistent with the simulation results of [8], which show that the miss rate of a location distinction system decreases with system bandwidth, but that the performance gain of MIMO over SISO also decreases, because at high bandwidths the SISO link signatures offer more decorrelation.

However, at high bandwidths the algorithm is more sensitive to timing-synchronization errors that might be hidden by lower bandwidth signatures. Figure 11 shows an example of two consecutively measured link signatures that exhibit this effect. These errors cause small drops in performance. The higher bandwidth of the link signatures measured in Experiment I (80 MHz) allows for better location distinction performance, but the results for the 2x2 MIMO link signatures of Experiment II (20 MHz) still offer a $3 \times 10^{-4}$ probability of missed detection for a $7 \times 10^{-3}$ probability of false alarm.
V. RELATED WORK

The papers discussed in this section have contributed to this work in different aspects. The most closely related work is that of Patwari et al. [1] and Zhang et al. [7]. In these two papers, a temporal link signature is defined to be used in the context of multiple transmitters/receivers and then refined to include phase information. We compliment that work by showing that a single MIMO transmitter/receiver pair can be used to perform reliable location distinction, and that lower false alarm rates are possible using a single receiver, when the communication system is a 1x2 or 2x2 MIMO system. In [7], the authors report a $9 \times 10^{-3}$ miss rate for a 0.01 false alarm rate using three receivers. For the same false alarm rate, we are able to achieve a $3 \times 10^{-4}$ miss rate using a single receiver and the 2x2 MIMO CTLS with less bandwidth. This net reduction in system complexity may enable location distinction in future wireless networking systems.

In [7] a complex temporal link signature is defined which allows for the exploitation of the phase information in the CIR. However, not all of the phase information represented by the link signature is due to the channel. Some phase shifts occur due to a lack of time and/or frequency synchronization between the transmitter and receiver. The distance between two link signatures which minimizes the contribution of random phase shifts corresponds is shown to be $\phi_2^2$. Zhang et al. call this the $\phi_2$-distance. It is not necessary to apply (10) to the data gathered in Experiment I, because it is phase-synchronous, but we do apply it to the data from Experiment II.

In [8], Xiao et al. present ray-tracing simulation results for MIMO location distinction in defense of impersonation attacks in an office building. They assume that channel measurements made in the frequency domain are distributed as complex Gaussian random variables and derive ideal change metrics based on this assumption. We extend this work by offering an experimental validation of MIMO location distinction using two MIMO testbeds.

In [6], Li et al. propose some of the underlying ideas of this work, namely, that characteristics of the radio channel (rapid de-correlation in space, time, and frequency) can be exploited to secure wireless networks. They offer methods of probing the channel in order to determine, based on the channel gains between transmitters and receivers, whether or not communications are coming from an authentic user or a would-be attacker. Using the USRP/GNU Radio and a simple change-point detector, they show that they are able to detect a change in the wireless link via channel gains and thereby detect a possible spoofing attack.

In [5], Faria and Cheriton utilize similar principles in designing a method for identifying a transmitter by
its signalprint, which consists of a vector of RSS values. These RSS values are gathered using wireless access points as sensors and a central authentication server for cataloging and comparing signalprints. Their results show that a stationary transmitter will produce a consistent signalprint and thereby allow for discrimination between authentic users and attackers whose signalprints will vary significantly because they are located in a different position in the multi-path fading channel. The signalprint is limited in that it may be unable to detect attackers located near authentic transmitters, because they may have a similar signalprints.

VI. CONCLUSION AND FUTURE WORK

In this paper we show that techniques for location distinction can be applied to a MIMO channel. Using two distinct measurement sets, we show that a simple linearization of the link signatures for each transmitter/receiver antenna pair can be used to form MIMO link signatures, and that difference metrics can be used to determiner whether or not a wireless device has changed position. Our results show that the presented MIMO location distinction framework can be used to discern a stationary transmitter from a moving transmitter with accuracy better than any previously reported experimental results. We also show how the adjustment of the parameters of the location distinction algorithm (history size, spatial separation, complex/magnitude-only signatures, and number of antennas) affect the performance of the algorithm.

In addition to the promising results we have shown, it will be beneficial to further characterize the link signatures used for location distinction and explore other difference metrics. For instance, our current difference metric uses the minimum Euclidean or $\phi_2$-distance between the most recent link signature and those in the history $H$. This tends to increase the miss rate in the context of noisy measurements. A weighted average of distances, such as the Mahalanobis distance may offer better performance. A broader experimental analysis of link signatures and their temporal and spatial variations will facilitate the design of better difference metrics.

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Link Signature Bandwidth (MHz)

Loc. Dist. Miss Rate

2x2 TLS

2x2 CTLS

Loc. Dist. Miss Rate

Link Signature Bandwidth (MHz)