Poster: Improving Multipath Resolution with MIMO Smoothing

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ABSTRACT

Super-resolution subspace methods are popular in estimating multipath parameters such as angle of arrival and time of flight. However, they require decorrelation techniques to resolve coherent multipath components. The conventional decorrelation techniques reduce the effective aperture of the MIMO array, thus reducing the resolution and number of resolved paths. In this paper, we introduce *MIMO smoothing* as a new technique to bring decorrelation effect by leveraging the spacial and frequential diversity in MIMO transmitters and receivers. Via extensive experiments on WiFi links, we show that MIMO smoothing can increase the accuracy of multipath resolution.

KEYWORDS

MIMO smoothing, CSI, Multipath resolution, Spatial diversity

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1 INTRODUCTION

In wireless communications, signals from a transmitter arrive at the receiver in multiple paths after reflecting off the objects in the physical environment. Each of these paths have their own specifications which could be characterized by the Angle-of-Arrival (AoA), Angle-of-Departure (AoD), path delay or Time-of-Flight (ToF), and fading (shown in Figure 1). Many techniques have been proposed for estimating AoA in a MIMO array such as super-resolution subspace methods [4]. However, they assume that the received reflections are from different targets, thus uncorrelated with each other; while the wireless multipath reflections in indoor environments are emitted from a single source, thus phase-synchronized and highly correlated.

To address this issue, some signal processing methods such as spatial smoothing [5, 9] and forward-backward averaging [3] are proposed to decorrelate the multipath signals. However, they decrease the array aperture and the degree of freedom, resulting in lower accuracy and fewer number of resolved paths. Recent works try to overcome these limitations by developing joint estimation in both ToF and AoA dimensions [2, 8], but they still suffer from reduced effective aperture. In this paper, we propose a new smoothing algorithm called *MIMO Smoothing*, which leverages the recent advances in wireless techniques such as *MIMO-OFDM* to improve the accuracy of multipath estimation. MIMO arrays employ multiple transmitting antennas for emitting multiple data streams, and multiple receiving antennas for separating these signals. This results in spatial diversity both in transmitting and receiving antenna arrays. In addition, OFDM as a modulation format has been widely used in wireless communication for encoding data streams on multiple carrier frequencies, which provides frequential diversity due to multipath selective fading. MIMO smoothing combines the frequential and spatial diversity to accurately decorrelate coherent signals, without decreasing the effective aperture.

The basic idea in MIMO smoothing is that the signals transmitted from any of the transmitting antennas will be incident in any of the receiving antennas, provided they are in far field. However, each propagation path has to travel an additional distance if transmitted from the second antenna, introducing a constant phase shift on the received signal. Therefore, the propagation paths received from multiple transmitting antennas have similar steering vectors, while the superimposed received signals across receiving antennas are linearly independent. This is due to different phase shifts associated with multipath components from the transmitting antennas to the receiving antennas. As a result, the transmitting antennas could be successfully used to decorrelate the received signals and vice versa, which are explained in details in the next section.

To evaluate MIMO smoothing, we leverage the PHY layer Channel State Information (CSI) provided in off-the-shelf WiFi cards. The CSI values include the phase and amplitude shifts due to channel for multiple transmitting and receiving antennas at the granularity of OFDM subcarriers. We evaluate MIMO smoothing with 90 experiments in a large smart home lab with different link conditions. Our extensive analyses show that MIMO smoothing achieves higher

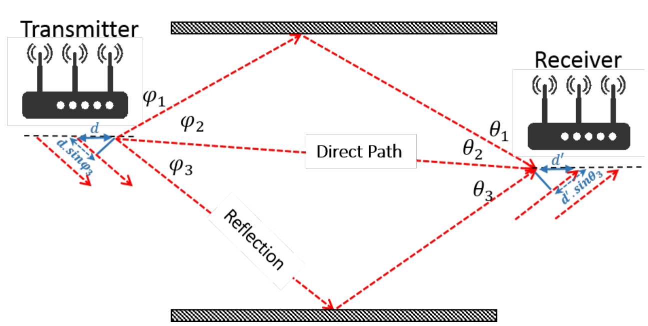

Figure 1: An illustration of multipath propagation in an indoor invironment

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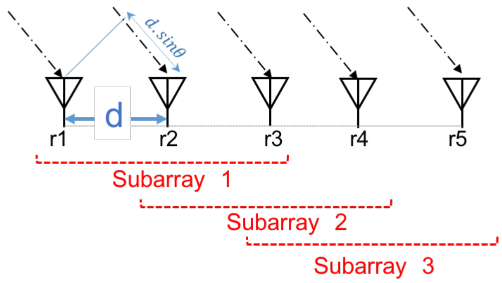

Figure 2: The Conventional spacial smoothing approach reduces the array aperture length and degree of freedom

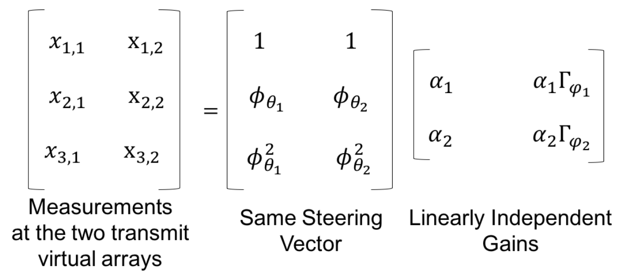

Figure 3: The transmit virtual subarrays share the same steering vector but linearly independent gains.

multipath resolution by achieving an average improvement of 6.9 degree in estimating AoA of the direct path between transmitters and receivers. In addition, its larger effective aperture resolves more paths compared to conventional sub-space methods.

2 METHODOLOGY

The super-resolution sub-space methods such as MUSIC [4] resolve multipath components by relying on extra phase shifts across sensor arrays due to additional travel distance. The introduced phase shift is a function of AoA and could be expressed as

$$\Phi(\theta_l) = e^{-j2\pi f d \sin(\theta_l)/c} \tag{1}$$

for l^{th} path due to AoA of θ_l, where d is the distance between antennas, c is the speed of light, and f is the frequency of the transmitted signal. Therefore, the received channel response X at the receiving antenna array can be expressed as

$$X(t) = [x_1(t), ..., x_M(t)]^T = a(\theta)s(t) + N(t) \tag{2}$$

where M is the number of receiving antennas, $s(t)$ is the received signal vector at the first antenna and $N(t)$ is the noise vector. $a(\theta)$ is called the steering vector and expresses the phase differences at the antenna array:

$$a(\theta) = [1, \phi(\theta), ..., \phi(\theta)^{M-1}]^T \tag{3}$$

The MUSIC algorithm calculates the eigenvectors of XX^H, and divides them into noise and signal subspace. Then, it searches for the AoAs whose steering vectors are orthogonal to the noise subspace. This method assumes that the incoming signals are from different sources and are uncorrelated with each other. However, the multipath signals are phased-synchronized, thus resulting in a reduction in the rank of the covariance matrix and superposition of coherent signals in the output of MUSIC. Therefore, a preprocessing scheme such as spatial smoothing [5] is required to convert the covariance matrix into a full rank matrix[5, 9]. In spatial smoothing, the receive antenna array is divided into a number of smaller overlapping sub-arrays as shown in Figure 2. Then, the covariance matrices of all sub-arrays are averaged. However, this smoothing method reduces the aperture of the sensor array from M to $M - r + 1$, where $r = L + 1$ is the size of sub-arrays and L is the number of coherent paths.

To address this problem, we leverage the presence of multiple transmit and receive antennas in MIMO systems. The idea is that the incoming signals from different transmitting antennas can define the virtual subarrays required in spatial smoothing. The intuition behind this idea is that the signals emitted from a linear transmit array will be received with a phase shift $\Gamma(\varphi)$, which is a function of AoD

$$\Gamma(\varphi_l) = e^{-j2\pi f d \sin(\varphi_l)/c} \tag{4}$$

where φ_l is the AoD of the lth path. Since each received signal from different transmitting antennas has its own AoD, the virtual subarrays are linearly independent, thus increasing the rank of the covariance matrix. A MIMO radar with M receiving and N transmitting antennas can resolve $L = min(M, N)$ coherent paths using MIMO smoothing, while the effective aperture of the sensor array remains M. For more clarity, let's consider an example, where $L = 2$, $M = 3$, and $N = 2$. As shown in Figure 3, $x_{i,j}$ shows the received signal at antenna i from transmitting antenna j. The measurements of the two virtual transmit subarrays can be written as a linear combination of the same steering vectors, but with linearly independent complex gains due to AoD phase shift. Therefore, we can successfully apply MUSIC on the averaged covariance matrix of multiple transmitting antennas, while increasing the rank of the coveraince matrix.

We further improve the multipath resolution, by combining MIMO smoothing with joint estimation of multipath characteristics. The current WiFi standards such as 802.11 leverage MIMO-OFDM technology, in which data streams are transmitted over multiple antennas and multiple subcarriers. Therefore, instead of just estimating AoA of each propagation path, we can jointly estimate AoA and ToF while applying MIMO smoothing. For two consecutive OFDM subcarriers, the lth path with ToF τ_l introduces a phase shift as bellow

$$\Omega(\tau_l) = e^{-j2\pi f_\delta \tau_l} \tag{5}$$

where f_δ is the frequency difference between two consecutive subcarriers. It should be noted that AoA and AoD do not introduce any phase shift across subcarriers because of the small frequency differences. However, we can measure the phase shifts across subcarriers based on ToF (because of the absence of speed of light factor in the denominator). Considering the sensor array as all subcarriers in all receiving antennas, the new steering vector per transmitting antenna is formed by phase shifts due to AoA and ToF as

$$a(\theta, \tau) = [1..\Omega^{K-1}(\tau), \Phi(\theta), ..., \Omega^{K-1}(\tau)\Phi(\theta), ..., \Phi^{M-1}(\theta), ..., \Omega^{K-1}\Phi^{M-1}(\theta)] \tag{6}$$

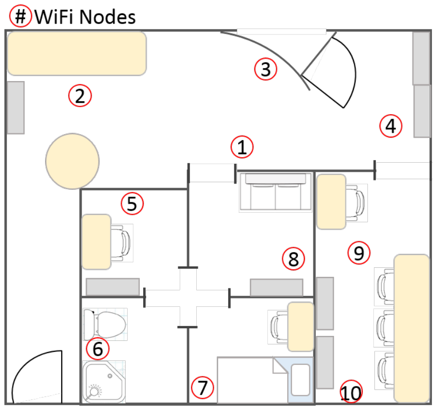

Figure 4: Floor plan and the experimental setup

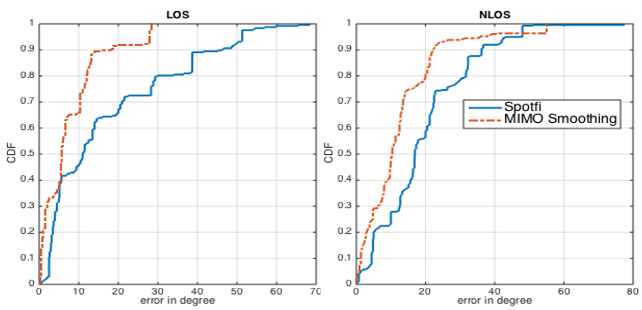

Figure 5: MIMO smoothing achieves an average improvement of 6.9 degree over SpotFi in AoA estimation

where M is the number of receiving antennas and K is the number of subcarriers. The new steering vector is of dimension $(MK) \times L$, and the measurement matrix X is of dimension $(MK) \times PN$, where P is the number of samples and N is the number of transmitting antennas. It should be noted that the MIMO smoothing could be applied for AoD-ToF estimation by defining virtual sub-arrays from receiving antennas.

3 PRELIMINARY RESULTS

Current commercial WiFi cards report the overall phase and amplitude shifts of the wireless channel as Channel State Information (CSI) for each subcarrier of each (tx-rx) antenna pair. Therefore, to evaluate MIMO smoothing, we use 10 mini-PCs that are equipped with Intel 5300 cards, CSI tool [1], and 3 antennas. Each of these nodes can work in transmitting or receiving modes. We conducted a round robin experiment in a smart home lab as shown in figure 4, where in each round one node is transmitting and the other nine nodes are receiving. The experiments are performed in the 5GHz frequency band by employing a 40MHz channel. The measured vector is of size 90×60 (or $(3 \times 30) \times (3 \times 20)$), for 3 tx and 3 rx antennas, 30 subcarriers, and 20 samples. Since we only have ground truth AoA for the direct path between the transmitter and receivers, we measure the accuracy of the AoA estimation as the minimum difference of the ground truth value and estimated AoAs. Figure 5 shows

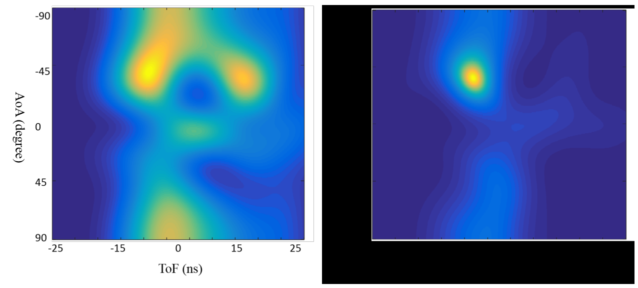

Figure 6: MIMO Smoothing (Left) can resolve more paths compared to SpotFi (Right)

the CDFs for AoA estimation error and compare MIMO smoothing with SpotFi which introduces a 2D smoothing for AoA-ToF estimation. In line-of-sight (LoS) cases, MIMO smoothing achieves median AoA accuracy of 7.1 degrees better than that achieved by SpotFi. In non-line of sight (NLoS) scenarios, we achieve an improvement of 6.8 degree in direct path AoA errors.

We further improve MIMO smoothing by combining it with SpotFi to define virtual arrays both from transmitting antennas and subcarriers, which results in a 45x48 matrix (or $(15 \times 3) \times (16 \times 3)$). Please refer to SpotFi paper [2] for more details. Our empirical analyses show that MIMO Smoothing can resolve more paths as shown in Figure 6. The higher resolution in addition to more accurate estimations provides the opportunity of using Wireless signals and commodity WiFi devices for reliable presence sensing [6, 7] and precise localization of people/robots in the physical environment even if the reflected signals from human body is so weak. However, to quantify the performance of MIMO smoothing in resolving more multipaths, the groundtruth of reflected paths are required which is not accessible with current techniques. In our future work, we address this requirement using synthetic data, and chamber analysis.

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