PhaTrack: Fine-Grained Motion Tracking with (a Pair of) COTS Wi-Fi Phase value

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ABSTRACT

Previous COTS WiFi based work of wireless sensing (citation) extract human movements (keystroking, activates) from Amplitude with training. Phase is noisy, the main noises are introduced by Sampling Frequency Offset (SFO), Carrier Frequency Offset (CFO) and Packet Detection Delay (PDD). As a result, there will a dynamic random linear increased phase shift along the subcarriers across the antennas, and make it hard to extract the motion information from the Channel State Information (CSI). This paper shows that we can leverage the information hidden in Phase value for more Fine-Grained motion tracking. We leverage the assumption that mutip-path for indoor environment contains certain static paths (such as reflection from wall or static furniture), and we use these static path to calibrate the phase value of CSI. Then we can extract the dynamic paths due to human movements to detect motions.

(accuracy:WiDeo less than 7cm.)(ours?)

1. INTRODUCTION

Human motion tracking is one of the core technologies that enhancing the Human-computer interacting ability and enable a wide ranging of application such as health care, smart home, security. A massive works had exploited the possibility of using RF and other signals (e.g. acoustic signal, visual light signals) for motion tracking. FingIO use acoustic signal for finger movement tracking. WiDeo use SDR to show the possibility of fine-grained motion tracking with WiFi technology, but it will be more challenging to dealing with noise of cheap WiFi NIC card we mentioned in the abstraction. And recently works (CARM, Wikey) use CSI tools [] of COTS WiFi NIC for keystroking, activity recognition through merely training amplitude of CSI data to classification, but such method are not time and environment consistent. As they give up phase value because of phase noise. Training based method cannot disentangle two different motions at the same time. WiDraw harnesses the Angle-of-Arrival values of incoming wireless signals at the mobile device to track the user's hand trajectory with APs surround the mobile device based only on AoA, WiDraw's experiment with 30 Tx/Rx is not practical in real scenario. We summarize the related works in

Works:	Need Training	SDR/COTS	Use Phase	AoA/ToF
WiDeo	no	SDR	yes	both
SoptiFi	no	COTS	yes	both
breath	yes	COTS	no	Non
CARM/ Wikey	yes	COTS	no	Non
WiDraw	no	30 COTS	yes	AoA

Table 1. Comparison of Related works

table I and compare them with our work. Our work use COTS, leverage both AoA&ToF to build application of device-free motion/human activity tracking. Our work is inspired by SpotiFi, Which use MUSIC to decompose the multi-path taps with smoothed CSI of COTS WiFi for indoor device localization. We can use SpotiFi's Super-Resolution AoA Estimation algorithm, however we cannot adopt its Sanitizing algorithm for our motion detection application. As SpotiFi are dealing with the static paths only and can easily find the best linear fit of the unwrapped CSI phase to eliminate the phase noise. In application of motion tracking, the CSI is compose of static paths and dynamic paths, thus we cannot align the phase values of two packets at all with SpotiFi's algorithm. Instead we observed that spots of static path …

~~Device based localization, Device free motion/objects tracking.~~

~~SDR/COTS, phase/amplitude, localization/tracking~~

Conference'10, Month 1–2, 2010, City, State, Country.

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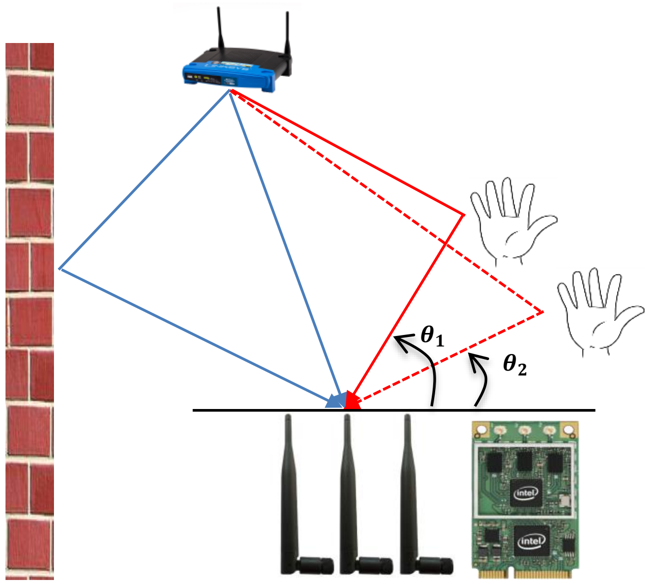
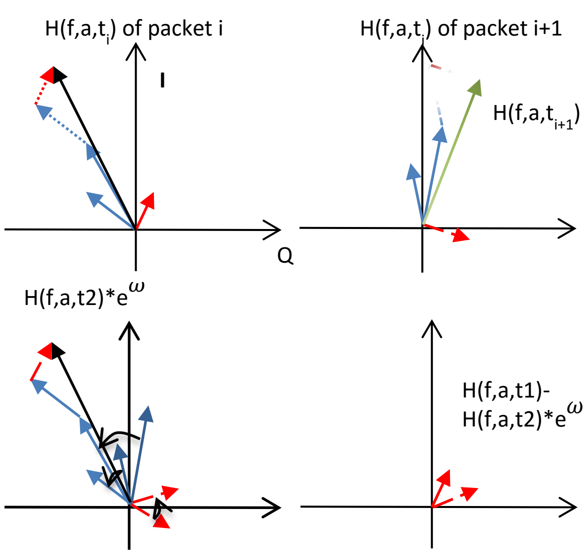
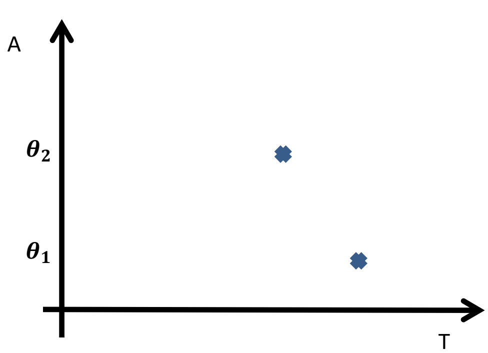


(a) Multipath presentation of hands movement



(b) Calibration of phase



(c) Decompose moving path

Figure1. System overview.

Here we briefly describe the challenges of use COTS WiFi for device-free motion tracking and our solutions:

1. The first challenge of COTS WiFi compare with SDR is the present of CFO (fig 2.). CFO value is time variant across different devices. It will shift the same random phase across subcarriers and antennas. So as a result, it will not distort the estimated AoA and ToF, instead it will add the same phase rotation on every individual path. Based on the realistic assumption, the path gain of static paths should no change across different packets. We can derive the CFO through compare path gain of the static path between two packets (Figure 1c). . As illustrated in Fig.1 b through the static path we can know the CFO difference between two packets is ω.

2. The second major challenge is the phase noise due to SFO & Packet detection delay (PDD). As showed in fig.2. It will add a linear increased phase addition across subcarriers. And as a result it will added a constant on the ToF across the paths for that packet. So as solution to calibrating this noise, we derived the phase difference by compare the ToF of the same static path between two packets.

3. The third one is because of strong signal power of static path, which makes it is hard to extract the week path signal due to the human movements. We cannot really have resolve of every path of the channel, the final path resolution may mix the dynamic with one of the static path in a single tap. Our method is by subtracting two calibrated CSI from two packet to eliminate the strong static paths, and thus we can find the path due to human movements. Then through MUSIC we can resolve the dynamic path without interference from the static path as illustrated in Fig1.c.

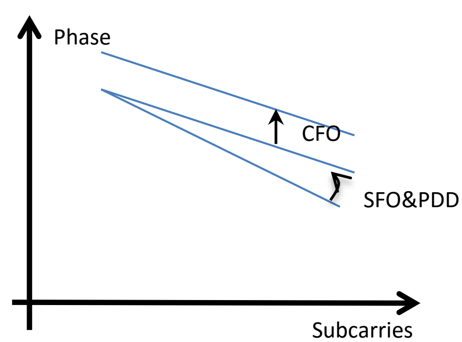


Figure 2. Phase noise presentation

To surmised our contributions:

We calibrating the COTS WiFi phase noise through comparing the parameters of the static paths in different measurements. Our contribution is that we propose to use the statics of environment to calibrate the handware noise.

We use phase difference as detector of movements. Averaging the packs that are considered as in one static duration.

We subtract the signal before feed to the MUSIC, thus to get rid of effect because of strong static path.

First work to show fine-grained motion recognition of COTS WiFi without training.

2. OBSERVATIONS AND STUDIES

We Use MUSIC algorithm like SpotFi to decompose the multiple path of indoor environments with COTS WiFi. Before we describe the details of our system and algorithm, we give the studies of how phase noises will take effects on MUSIC algorithm when decompose paths of CSI.

Observation I: How sensitive the phase difference could be even for COTS Wi-Fi? Through measurement the phase different between antennas as showed in Fig 3, we can clearly observe the how phase changes according human breath, hands movements.

All these measurements give a good sign that phase actually provides more stable and accurate indication for even stubble movements like breath. If it is in the static environments, phase difference is stable, and we can also use this value as detector of any movements.

During the static period, the paths are all static, …?

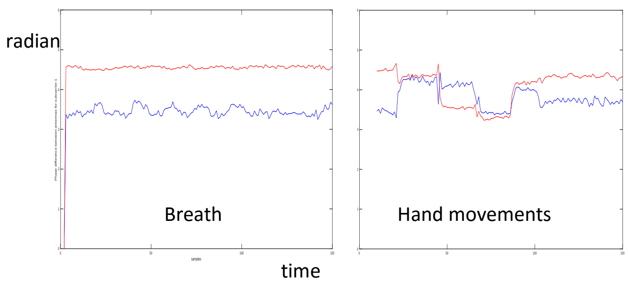
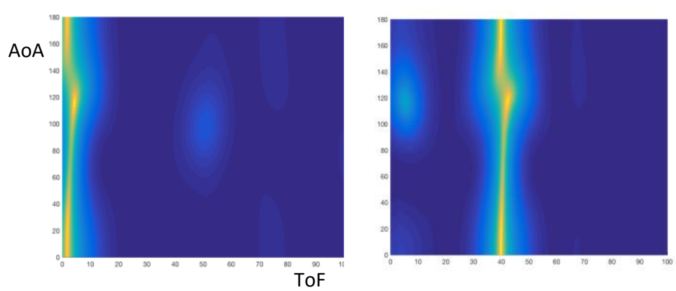


Figure 3. phase difference

Observation II: Fig4 is the AoA/ToF maps of multipath resolutions of two packets in the same static period. So these two packets have the same static paths.

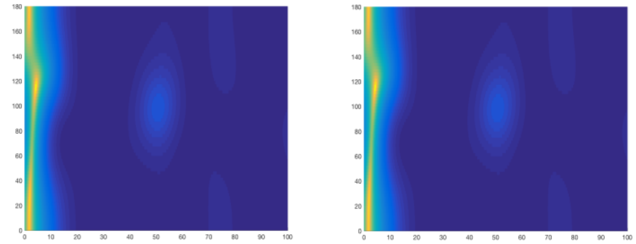
the SFO will only shift the path on ToF but not change the relative positions in the AoA&ToF 2D map. So through calculate the shift…



(b) CSI (a) CSI*exp()

Figure 4. effects of SFO on AoA/ToF

Observation III; CFO will not affect the AoA&ToF 2D map at all. But only add a phase value on all the path gain by a certain degree.



(c) CSI*exp()

Figure 5. Effects of CFO on AoA/ToF

3. SYSTEM DESIGN

According to the above observations: we design our system in following steps:

1. Detecting motion by monitoring the phase difference between antennas.
2. Calculate the SFO according the the AoA&ToF maps
3. Calculate the CFO by comparing the path gain of static path.
4. Subtracting two different measurement to eliminate static path.
5. Feed CSI differenc to MUSIC to calculate the dynamic paths due to human motion.

Before we describe the details of each steps, we briefly give a summary of how Spotifi's decompose multipath by apply MUSIC in MIMO OFDMA WiFi system.

3.1 MUSIC Algorithm with MIMO&OFDMA

We exploit the channel state information (CSI) provided by intel 5300 WiFi NIC for motion tracking. As [] provides CSI tools for extracting the CSI information for 3 antennas and 30subcarriers. So for each packet the raw data we have is a 3 by30 CSI matrix.

To utilize this CSI information to resolve the multipath, it is necessary to understand the multipath effects to form the CSI matrix. The paths direction and distance effects the signal on antenna domain (Angle of Arrival) and frequency domain (Time of Fly) respectively.

If k[th] path is coming from directionθ_k, and the path length is l_k , then the phase shift due to AoA of this propagation path is:

$$\Psi(\theta_k) = e^{-j2\pi \times d \times \cos(\theta_k) \times f/c}. \quad (1)$$

and the phase shift due to its ToF is:

$$\Phi(l_k) = e^{-j2\pi f \times l_k / c}. \quad (2)$$

Spotifi developed algorithm to resolve multipath with AoA & ToF.

So the AoA with L path matrix with 3 antenna is:

$$1 \quad \Phi(\theta_k) \quad \Phi(\Theta_k)^2$$

~~Figure~~ for smoothed CSI sensors:

$$CSI = \begin{bmatrix} csi_{1,1} & \cdots & csi_{1,30} \\ csi_{2,1} & \cdots & csi_{2,30} \\ csi_{3,1} & \cdots & csi_{3,30} \end{bmatrix} = \Psi' * \Phi \quad (3)$$

With smoothed MUSIC algorithm adopted from SpotiFi we could reconstruct, for CSI of each packet it constructed 32 measurement of 30 sensors.

$$\begin{bmatrix} csi & & \\ c & & \\ c & c & \\ c & c & \end{bmatrix}$$

the steer vector for

X=AF+W

X is smoothed CSI, A is steer matrix, F is path gain vector and W is noise.

Covariance MATRIX of smoothed CSI value can be presented as:

$$R = XX^H = AFF^H A^H + WW^H$$

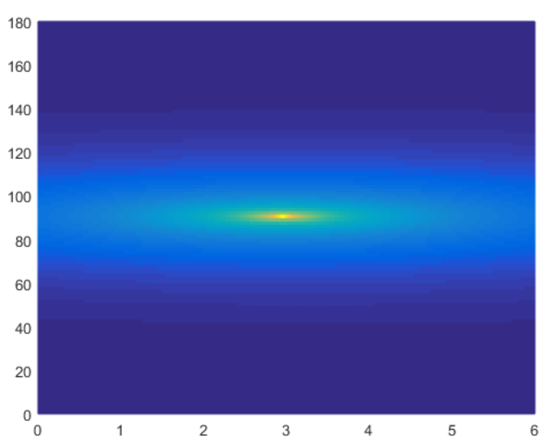
Here is the brief of the MUSIC algorithm with covariance matrix R as the input. And first compute the Eigen value, and find the Eigen vectors corresponding to the M smallest Eigen value as the noise space. Then calculate the distance of every possible steer vector from the noise space, Pick L peaks as vectors in A.

After finding steer matrix A, path gain can be derived:

$$FF^H = (A^H A)^{-1} A^H (R') A (A^H A)^{-1} \qquad (6)$$

But such algorithm can not directly used to tracking motion. In Figure 7, there is a hand movement between CSI2 and CSI1, but we can not directly inferring the motion through decompose paths by MUSIC. The reason is that the strong static path are not orthogonal with dynamic path and the dynamic path are absorbed into a path tab with one static path.

Resolution for AoA/ToF MUSIC decompose algorithm:



3.2 Calibrating SFO

For motion tracking purpose, we cannot use SoptiFi's algorithm to sanitize the SFO noise. Instead we developed our algorithm.
From observation II, we know the SFO only shift the whole plot back or forth on ToF direction, but not change the relative positions. So what we can do is find the static path between the packets/measurements. And compare to check how much static peak points is shift and calculate the SFO difference between packets, as we do not need to calculate the true ToFs, because we only need to align the SFO of two packets for subtraction the static path off the CSI.

Besides, for motion tracking we only need to calculate the relative path change because of hands motion.

As figure 4a.b shows :

Algorithm I:

Found the direct path first,

Find the static paths (peaks that have the same relative postions in two different packets)

Calculate the SFO phase shift by minimize stand sqt.

3.3 Calibrating CFO

As argued in CARM[5] "the phase sanitization method introduced in SpotiFi could not work for our case because the phase sanitization process also removes the phase shifts caused by body movements." After Calibrating the SFO, the static peak points are matched with each other. But when we do subtraction in the next step as described in 3.4 we can not … that is because of CFO introduce a phase rotation on each path. Although we aligned the steer vectors of static paths but have not align the coefficient yet (path gain).
Let us consider two CSI1 CSI2 from two packets. With CFO phase shifting difference Ω. And both these two CSI contains one same static path with parameter of path direction, path length, and path gain (θ_s, l_s, g_k) CSI1 contain no dynamic path $\cancel{(\theta_1, l_1, g_1)}$ while CSI2's dynamic path change to (θ_2, l_2, g_2). So the smoothed CSI for

SCSI1 $= \mathrm{V}(\theta_s, L_s, g_k)$,

SCSI2 $= (\mathrm{V}(\theta_s, L_s, g_k) + \mathrm{V}(\theta_2, l_2, g_2)) \times e^{j\Omega}$,

So the subtraction result of two CSI even after SFO calibration would not eliminate the static path:

SCSI1-SCSI2= $\mathrm{V}(\theta_s, L_s, g_k) \times (e^{j\Omega} - 1) + \mathrm{V}(\theta_2, l_2, g_2)$,

~~Also use standard lest squal???~~

So how can we self calibrating the CFO, this is old topics wireless communication for distributed MIMO, so we think our algorithm can also benefit the distributed wireless MIMO system. The assumption here is that the path gain for static path is stable and does not change during relative long period.

Through the MUSIC algorithms, we not only get the AoA &ToF, we can also get the path gain for each individual path with equation (6).

So the path gain is real value of square of path gain. dose not contain the information of CFO phase rotation.

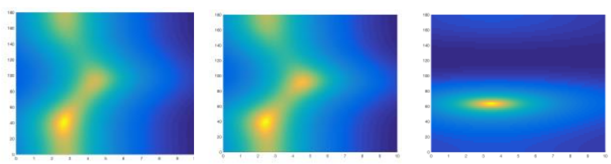
But we can reconstruct the signal with our estimated parameters (path gain, AoA, Tof) to reconstruct the signal and find the phase that minimizing the difference of measured signal and reconstructed estimated signal. After all of these, we compare the phase difference between the same static paths of two measurements.

3.4 CSI subtraction

WiDeo use full duplex tech to cancel interference from strong static signals. Such technology is not available in COTS WiFi. “If these reflections are stronger than the reflections from the moving object that WiDeo wishes to trace by more than the dynamic range of the radio, all information about the moving object will be lost in the quantization error of the ADC at the receiver. ”

So to eliminate the strong static path, our method is to subtract the CSI value between two packets after both SFO and CFO calibration.

Figure for two AoA/ToF estimation with same static paths. By only the two AoA/ToF map of two packets, we cannot notice that there is a dynamic path in CSI2 compare with CSI1. As this dynamic path is mixed in the static path, so the AoA/ToF map of CSI2 looks the same as CSI1. However after subtracting between the calibrated CSI2 and CSI2, the static path is eliminated and only the dynamic path was left.



CSI1 of packet1   CSI2 of packet2   CSI2-CSI1

Figure 7. AoA/ToF estimation of CSI1, CSI2 and CSI2-CSI1

~~3.5 Movement modeling~~

~~To construct the trajectory of movements:~~

~~…~~

~~choose a long period as reference frame.~~

~~Figure. Measurement 1, measurement2, subtrack.~~

3.6 Enhancing with more measurements on static period.

The noise could be further improved by detecting static period and average CSI values among packets (~~or low pass filtering???~~) .

Figure here:

4. EXPERIMENTAL EVALUATION

We implemented our system using off-the-shelf Intel 5300 WiFi NICs. We employed Linux CSI tool [68] to obtain the PHY layer CSI information for each packet. The Intel 5300 have three antennas and we place them as $\lambda/2$ ULA. And we set channel as 40 MHz. Currently we implement our system using matlab, so the computing is time consuming and can only work offline. So in our evaluation we did not do real-time experiment but collect data first, then do motion track off-line.

Experiment I (not fully experimented): in this experiments we checking how accuracy COTS WiFi could be for motion tracking. The assumption here is that we know the direct path length,
We place a hand one to two meters away from the receiver and estimated the hand relative movements with our system.

Error CDF figure:

Initial results shows path direction accuracy is less than 8 degree?

Experiment2 (not done yet): Wideo’s experiments is performed in controlled setup of connecting the Rx chains with wires from the transmitted chain (SDR).

1. Number of motions can be tracking simultaneously?
2.

(Need to compare with the related works, Wideo, Widraw)

~~We can achive close accuracy as Wideo(SDR), Widraw(30 transmitters) with a pair of cheap COTS WiFi NIC.~~

5. CONCLUSION

In this paper we exploit the possibility of fine grained motion tracking using COTS WiFi. The major barrier prevent the COTS WiFi adopt the advanced wireless sensing technology is it’s WiFi NIC’s frequency unlocked oscillator, it introduced sampling frequency offset and carrier frequency offset and make phase too noise for extract motion from CSI. And we proposed to calibrate the phase value with static wireless channel path reflection by static objects (such as walls). To extract the weak dynamic path we further eliminate the static path by subtract calibrated CSI of two packets.

Currently we did not run our algorithm in real-time for its time costing, for future work we will improve the efficiency of our algorithm to make suable for real-time applications.

For further impartments?:

1. Checking how much fast hopping could improving the accuracy.
2. Exchange the CSI between the TX/RX pair.

6. ACKNOWLEDGMENTS

7. REFERENCES

[1] Spotifi siggcom 2016.

[2] WiDeo NSDI 2015.

[3] Widraw mobicom 2015.

[4] WiKey mobicom 2015

[5] CARM mobicom 2015

[6] Tracking Vital Signs During Sleep Leveraging Off-the-shelf WiFi, MobiHoc 2015.

[7]

[8]

[9]

[10] MUSIC 1986

[11] Power delay Profile COTS, mobicom 2015