Calibrating Phase Offsets for Commodity WiFi

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***Abstract*—The calibration of phase offsets between RF chains on commodity WiFi chips has been an key obstacle for many WiFi-based applications. In this paper, we conduct extensive experiments to explore the characteristics of the phase offsets. The real experimental results reveal that the phase offsets are actually deterministic. We explain such a phenomena via the circuit design of WiFi chips. We also show that the phase offsets are even the same among different chips. With extensive experiments, we obtain and report the measured phase offset values for the commodity Intel 5300 and Atheros AR9380 WiFi chips. With the observation illustrated in this paper, the calibration of the phase offsets can be simplified greatly.**

***Index Terms*—Phase offset, commercial WiFi, AOA estimation, phase calibration.**

I. Introduction

With the release of 802.11n CSI tool [1], [2], indoor applications such as indoor localization, passive sensing and position tracking with commercial WiFi devices have drawn more and more attentions in recent years. On the other hand, array signal processing (ASP) techniques, which focus on extracting information with an organized sensor array, have been well investigated in the past decades. Utilizing the multiple antennas equipped on the commodity WiFi device, existing works have demonstrated that the ASP techniques are reliable solutions for the aforementioned indoor applications [3]–[8].

Despite of many advantages provided by the ASP techniques, the key obstacle which prevents it from practical deployment for WiFi devices is the phase offset between RF chains in WiFi chips. In WiFi chips, received signals from different antennas are fed into different RF chains to perform down-conversion. Since the signal phases in different RF chains are not synchronized perfectly, the measured CSI will be distorted by the phase offsets between RF chains. Note that rather than estimating the initial phase offset on specific RF chains, the main focus of the paper is dealing with the difference of the initial phase offsets on different RF chains. Previously, the offset is recognized as a constant when the WiFi system locks to a specific frequency but varies randomly every time the system restarts [4]. Since the ASP techniques require accurate phase synchronization between antennas, the calibration is essential. Xiong and Jamieson in [3] proposed to calibrate the phase offsets using cables and splitters, which is reliable but requires lots of human efforts. Gjengset et al. in [4] proposed to calibrate the phase offsets by transmitting signals from known locations, which requires multiple transmitters and exhaustive search over all possible values with limited accuracy. What is worse, the calibration needs to be invoked every time the system restarts due to the randomness of the offset, which further limits the practical applications. As discussed in [13], the phase offset has been a troublesome problem for researchers to reproduce previous works.

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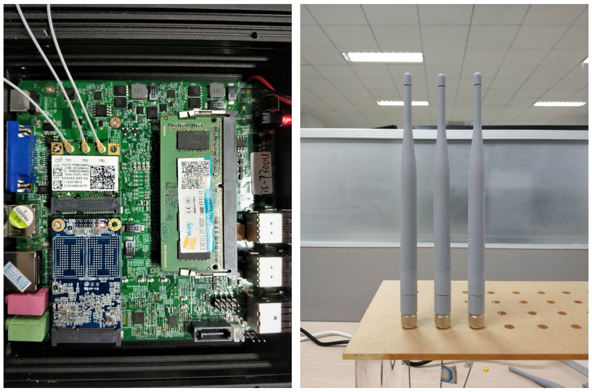
Although the calibration of the phase offsets is critical for building practical array systems using WiFi chips, to the best of our knowledge, the characteristics of the phase offsets have not been investigated neither by rigorous theory nor extensive experiments. In this paper, we conduct extensive experiments to explore the characteristics of the phase offsets. The empirical results show that the phase offsets are semi-time-invariant with two possible values. The relationship between the two values is known, which indicates that the phase offsets are actually deterministic. The typical design of 802.11 WiFi chips also indicates that the phase offsets are introduced by the fixed delay in the internal circuit, which should be deterministic in theory. The real experiments also show that the phase offsets are even the same among different WiFi chips. Based on such observations, we propose a simple phase offset calibration method, i.e., transmit signal from a known location and select the phase offset values which could give accurate estimation of the Angle of Arrival (AOA). We show that with such a simple calibration method, the AOA estimation performance is comparable with the state-of-the-art method, which validates the correctness of the phase offset calibration. Note that such a simple calibration makes it possible for practical deployment of array systems using commodity WiFi chips. The reported results may also benefit other systems which require accurate phase synchronization between antennas such as fingerprint localization system.

The rest of this paper is organized as follows. In section II, the problem is described in detail. Then, experiments and analysis are illustrated in section III. The applications are discussed in section IV and conclusions are drawn in section V.

II. Problem Description

The channel state information (CSI) obtained from the commercial WiFi chip characterizes the frequency response of the wireless channel, which contains several kinds of phase distortion introduced by the imperfect inertial circuits. With all known phase distortions [9], [10], the CSI can be expressed as

$$\begin{aligned} H(t,m,k) &= e^{-j2\pi(f_{CFO}t + k\Delta f(\tau_{SFO}(t)+\tau_{PDD}(t))} \\ &\quad e^{j\varphi_m}\sum_{i=1}^{L}\alpha_i e^{-j2\pi f_k \tau_i^m}, \end{aligned} \tag{1}$$



(a) (b)

Fig. 1: The device and array used in experiments: (a) the mini computer and Intel 5300 half mini NIC; (b) the three-antenna array.

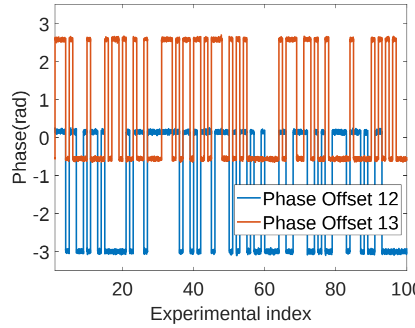


Fig. 2: Phase offsets between antennas.

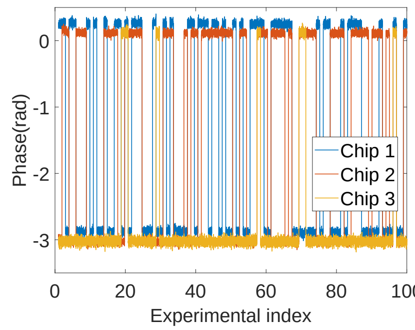


Fig. 3: Phase offsets on different chips.

where t, m and k denote the index of time, antenna and subcarrier, respectively, Δf denotes the frequency interval between subcarriers, L denotes the number of propagation paths, α and τ denote the attenuation coefficient and time of flight (TOF) of the signal, respectively, f_{CFO} denotes the carrier frequency offset (CFO), τ_{PDD} and τ_{SFO} denote packet detection delay (PDD) and sampling frequency offset (SFO), respectively, and φ denotes the phase locked loop (PLL) initial phase. Note that [10] proposes a solution to remove IQ imbalance, while this paper focuses on dealing with phase offsets among different RF chains. Therefore, the main scopes of [10] and this paper are different.

The CFO, PDD, and SFO do not cause catastrophic problem to the ASP algorithms since they are the same among different RF chains. However, the PLL initial phase is different among RF chains. The calibration of PLL initial phase difference, $\varphi_{m_1} - \varphi_{m_2}$, is the main scope of this paper. Considering that three antennas are generally equipped with the commodity WiFi, there are three different initial phases on the corresponding RF chains φ_1, φ_2 and φ_3. The phase offset $\varphi_{12} = \varphi_2 - \varphi_1$ and $\varphi_{13} = \varphi_3 - \varphi_1$ must be compensated to perform ASP algorithms.

The objective of calibration is to measure φ_{12} and φ_{13}. In previous works, φ_{12} and φ_{13} are treated as constants when the WiFi chip locks to a specific frequency and vary randomly every time the WiFi chip restarts [4] [7]. In [7], the phase difference between antennas was empirically measured for 20 times as the chip powers on/off, and the results showed the randomness of the phase difference. As a result, the system requires re-calibration every time it restarts. However, previous calibration methods suffer from lots of human efforts [3], [12] or limited accuracy [4], which limits the practical deployment of ASP systems. To solve this problem, we have noted that the characteristics of phase offset have not been well investigated. To fill this gap, in this paper, we investigate the characteristics of phase offset through extensive experiments and analyze the corresponding results based on the design of 802.11 WiFi chips.

III. Experiments and Analysis

In this section, we will conduct extensive experiments to evaluate the characteristics of the phase offset. As shown in Fig. 1 (a), we use mini computers equipped with Intel 5300 NIC as transmitters and receivers. In total, 21 Intel 5300 NICs are tested. The Linux 802.11n CSI Tool [1] is installed on the Ubuntu desktop 14.04 LTS OS for both the transmitter and the receiver. We randomly choose the channel 62, i.e., 5.31GHz carrier frequency with the 20MHz bandwidth, as our experiment band. The transmitter and receiver work in the "monitor mode". Although the experiments in [7] showed the randomness of the phase difference between antennas, since the signal propagates in the indoor environment and even human breath would affect the signal phase significantly [8], [12], the measured phase difference is not only the phase offset, but also the environment changes. To avoid the influence caused by the environment changes, the receiver and transmitter is connected through coaxial cables and splitters. The measured phase offset may also contain the constant phase offsets introduced by cables and splitters. However, with the same coaxial cables and splitters, such additional offsets remain the same during experiments, and will not affect the result. The elimination of these offsets will be illustrated at the end of this section.

The phase offsets on the 30 subcarriers are averaged to give the final result of measurement. We perform 100 experiments, and in each experiment 100 packets are transmitted and received within one second. Power off, system reboot, and driver reload are performed among experiments to simulate the daily operations on computers and WiFi chips. To determine whether there are any offset drifts with time, it spends 48 hours to finish all the experiments. The measured φ_{12} and φ_{13} are shown in Fig. 2. It can be seen from the figure that the phase offsets are not the same among experiments. However, there are only two possible values for each phase offset φ_{12} and φ_{13}. To confirm that the observed phenomenon is not an individual case, we conduct similar experiments on all other 20 Intel 5300 chips. The only difference is that the experiment time on each chip is compressed to 2 hours. It spends totally more than 5 days to finish all experiments on the 20 Intel 5300 chips. The results are the same with the case shown in Fig. 2, which proves that the phase offset is actually semi-time-invariant with two possible values. Combing all the measured data, we have noticed that the relationship of these two values is given by

$$|\varphi^{'}_{m_1m_2} - \varphi_{m_1m_2}| \approx \pi, \tag{2}$$

where $\varphi_{m_1m_2}$ and $\varphi^{'}_{m_1m_2}$ denotes the two possible values, respectively. m denotes the antenna index and $|.|$ denotes the absolute value.

This unknown phase rotation may caused by the bug in released CSI tool as reported in [14]. As a result, it can be concluded that the phase offsets are actually constants and may rotate π due to some uncertain problems.

In order to explain the observed phenomenon, we explore the internal circuit design of the WiFi chip. Although Intel has not published any papers to describe the design of Intel 5300 NIC, we can infer its inner structure by the typical designs of 802.11 WiFi chips. As shown in [15], signals from antennas are fed into different slave chips which contain the RF chains to perform down conversion. To avoid time-varying offsets, all slave chips actually share the signal from the same PLL. As a result, the only phase offset is introduced by the fixed delay in the circuit, which is determined by the length of the cable on the chip. Thus, the phase offset between two RF chains can be expressed

$$\varphi = 2\pi f\tau, \tag{3}$$

where τ denotes the fixed delay between RF chains.

Since the delay in Eq. 3 is determined by the length of cables which are carefully designed and precisely manufactured on chips, it should be approximately the same among different WiFi chips. To verify this conjunction, we perform experiments using the 20 WiFi chips again. To avoid phase offsets between experiments caused by the cables and splitters, we use the same cables and splitters for the corresponding RF chains in all experiments. The measured φ_{12} on three different chips are shown in Fig. 3. It can be seen from the figure that the phase offsets are approximately the same for different chips. Due to the limited space, only results on three chips are shown while all the results on other chips are the same. The overall variance of the phase offsets on 20 different chips is 0.0257.

Based on the aforementioned experiments, the phase offset has been proved to be semi-deterministic. The value of phase offset may rotate π due to some unknown problems. It is approximately the same among different chips. As a result, we can measure all the possible values and build a table for calibration. For a three antenna WiFi chip, considering the phase rotation of π, there are totally four possible offset values. To eliminate the phase offsets introduced by cables and splitters and obtain the accurate measurement of φ_{12} and φ_{13}, we adopt the method in [3], which exchanges the external cables and splitters and averages the measurement results. More specifically, the measured φ_{12} with the offsets introduced by external cables and splitters can be expressed as

$$\varphi^1_{12} = \varphi_{12} + \varphi_{ex2} - \varphi_{ex1}, \tag{4}$$

where φ_{ex1} and φ_{ex2} denotes the phase offsets introduced by the external cables and splitters.

Then, we exchange the external path, the measured offset is given by

$$\varphi^2_{12} = \varphi_{12} + \varphi_{ex1} - \varphi_{ex2}. \tag{5}$$

The accurate estimation of φ_{12} can be given by

$$\varphi_{12} = (\varphi^1_{12} + \varphi^2_{12})/2. \tag{6}$$

Intel 5300	φ_{12}	φ_{13}
channel 38	-2.3762/0.7874 rad	-0.0065/3.1435 rad
channel 46	-2.3372/0.8225 rad	-0.0051/3.1399 rad
channel 54	-2.3415/0.8108 rad	-0.0193/3.1226 rad
channel 62	-2.3255/0.8131 rad	-0.0218/3.1151 rad
channel 104	-2.1536/1.0022 rad	0.0303/-3.1094 rad
channel 110	-2.0611/1.0827 rad	0.0233/-3.1197 rad
channel 118	-2.0597/1.0891 rad	0.0265/-3.1134 rad
channel 126	-2.0704/1.0740 rad	0.0482/-3.0442 rad
channel 134	-2.0419/1.0918 rad	0.0997/ -3.0359 rad
channel 151	-2.0398/1.1016 rad	0.0719/-3.0674 rad
channel 159	-2.0317/1.1031 rad	0.0347/-3.1014 rad

TABLE I: Measured Values of Phase Offsets on Intel 5300

Atheros AR9380	φ_{12}	φ_{13}
channel 38	-2.7717/0.3815 rad	-3.0813/0.0642 rad
channel 46	-2.8708/0.2515 rad	-3.1343/0.0045 rad
channel 151	2.4926/-0.7069 rad	2.4692/-0.7151 rad
channel 159	2.3658/-0.7888 rad	2.3399/-0.8254 rad

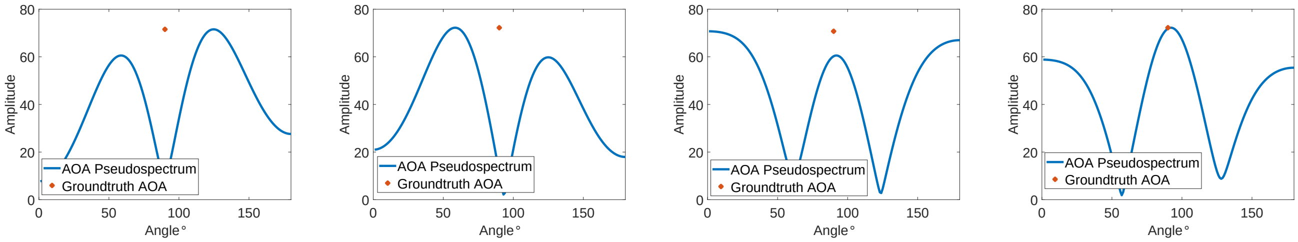
TABLE II: Measured Values of Phase Offsets on AR9380

We perform measurements using Intel 5300 WiFi chips on different channels and the results are summarized in Table I. It can be seen from the table that for Intel 5300 WiFi chips, the phase offset variation on different channels is relative small.

Besides the Intel 5300 WiFi chip, we also conduct extensive experiments on Atheros AR9380 WiFi chip using Atheros CSI Tool [2]. The results are very similar with experiments on Intel 5300. There are two possible phase offset values and their relationship is given by Eq. 2. The phase offsets are approximately the same among different WiFi chips. The only minor difference is that the phase offset variation on different channels is more significant. Since the Ubuntu version of Atheros CSI Tool does not support Monitor-Injection mode, we have to use AP-client mode and AR9380 can only act as AP in a small part of channels. We summarize the possible phase offset values on all available channels in Table II.

IV. Applications

In the previous section, we have reported all possible values of the phase offsets. The only problem left in practice is to



(a) (b) (c) (d)

Fig. 4: The AOA pseudospectrum with different phase offsets: (a) the result using phase offset 1 (wrong); (b) the result using phase offset 2 (wrong); (c) the result using phase offset 3 (wrong); (d) the result using phase offset 4 (right).

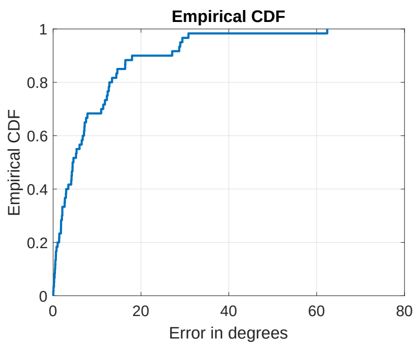


Fig. 5: AOA Estimation Error.

determine which values correspond to the actual ones. This problem can be solved by transmitting signal from a known location and then select the phase offset values which could give the accurate AOA estimation as in [4]. Since there are only four possible values for a three-antenna device, one transmitter with a known location is enough for the calibration. As shown in Fig 4, only the AOA pseudospectrum calculated using the actual phase offset values could give the accurate estimation of AOA.

To further verify the correctness of our results, we build a three-antenna system using the WiFi chip to estimate the AOA of transmitter. The system is equipped with three omidirectional WiFi antennas as shown in Fig. 1 (b). Note that the measurement results in Table I only contain the internal phase offsets. The cables connected to the antennas may introduce additional phase offsets. To avoid this, we use cables labeled the same length for all 3 antennas. We use the beamforming estimation method to jointly estimate the AOA and TOF [5]. We first verify whether we could obtain the right phase offset values by transmitting the signal from known locations. We directly select the phase offset values which could give the most accurate AOA estimation. The signal is transmitted from one transmitter, and we test at 40 different locations for the transmitter. With only one transmitter, the system could determine the right phase offset values with the accuracy of 85% without any additional computational cost. With 2 or more transmitters, the proposed method can achieve 100% accuracy.

After determining the right phase offset values, we then calibrate the measured CSI and perform the AOA estimation. The distance between the transmitter and receiver varies from 3m to 5m. The ground truth AOA varies from $45°$ to $135°$. We adopt the metric in [5] to determine the AOA estimation performance. The empirical cumulative distribution function is shown in Fig. 5. The performance is comparable to the results reported in [5], which validates the correctness of the calibration. Besides the proposed method, the calibration will be further simplified by combing inertial sensors [11], which is considered to be our future work.

V. Conclusions

In this paper, we investigated the characteristics of phase offsets between RF chains on commodity WiFi chips through extensive experiments and theoretical analysis. The phase offsets are introduced by the fixed delay in the internal circuit. They are the same among different chips. All the possible values of the phase offsets on the commodity Intel 5300 and Atheros AR9380 WiFi chips are reported in this paper. With the results reported in this paper, the calibration of the phase offsets can be simplified greatly.

References

[1] D. Halperin, W. Hu, A. Sheth, and D. Wetherall, "Tool release: gathering 802.11n traces with channel state information," *ACM SIGCOMM CCR*, 2011.

[2] Y. Xie, Z. Li and M. Li, "Precise Power Delay Profiling with Commodity WiFi," *ACM MobiCom*, 2015.

[3] J. Xiong and K. Jamieson, "ArrayTrack: A Fine-Grained Indoor Location System," *USENIX NSDI*, 2013.

[4] J. Gjengset, J. Xiong, G. McPhillips, and K. Jamieson. "Phaser: enabling phased array signal processing on commodity WiFi access points," *ACM MobiCom*, 2014.

[5] M. Kotaru, K. Joshi, D. Bharadia, and S. Katti, "Spotfi: Decimeter Level Localization Using WiFi," *ACM SIGCOMM*, 2015.

[6] M. Kotaru and S. Katti, "Position Tracking for Virtual Reality Using Commodity WiFi," *IEEE CVPR*, 2017.

[7] W. Gong and J. Liu, "RoArray: Towards More Robust Indoor Localization Using Sparse Recovery with Commodity WiFi," *IEEE Trans. Mobile Comput.*, 2018.

[8] D. Zhang, Y. Hu and Y. Chen, "Breath Status Tracking using Commodity WiFi," *IEEE GLOBECOM*, 2018.

[9] Y. Zhuo, H. Zhu, H. Xue, and S. Chang. "Perceiving Accurate CSI Phases with Commodity WiFi Devices," *IEEE INFOCOM*, 2017.

[10] H. Zhu, Y. Zhuo, Q. Liu and S. Chang "π-Splicer: Perceiving Accurate CSI Phases with Commodity WiFi Devices," *IEEE Trans. Mobile Comput.*, vol. 17, num. 9, pp. 2155-2165, Jan. 2018.

[11] K. Qian, C. Wu, Z. Yang, Z. Zhou, X. Wang and Y. Liu "Enabling Phased Array Signal Processing for Mobile WiFi Devices," *IEEE Trans. Mobile Comput.* , vol. 17, num. 8, pp. 1820-1833, Aug. 2018.

[12] D. Zhang, Y. Hu, Y. Chen and B. Zeng, "BreathTrack: Tracking Indoor Human Breath Status via Commodity WiFi," *IEEE Internet Things J.*, 2019.

[13] https://github.com/dhalperi/linux-80211n-csitool-supplementary/issues/124

[14] https://github.com/dhalperi/linux-80211n-csitool-supplementary/issues/23

[15] J. W. M. Rogers, F. F. Dai, M. S. Cavin and D. G. Rahn, "A Multiband $\Delta\Sigma$ Fractional-N Frequency Synthesizer for a MIMO WLAN Transceiver RFIC," *IEEE J. Solid-State Circuits*, vol. 40, no. 3, pp. 678-689, Mar. 2005.