Monopulse Switching to Cancel Phase Offset in Array Antenna Comprising Multiple COTS SDRs

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***Abstract*—This paper proposes a phase offset canceler for an array antenna, which comprises multiple low-cost commercial of the shelf (COTS) software defined radio (SDR) devices. The main challenge is the phase synchronization of SDR devices because each SDR devices has its own phase offset when it produces IQ stream. We devise a simple yet effective method to cancel the phase offset of individual SDR device using a double-pole, double-throw (DPDT) switch which is implemented between antenna and SDR device. The DPDT switch is controlled according to the frame timing of each IQ stream to produce two set of measurements, from which we can compute angle of arrival(AoA) with a simple signal processing. We refer this mechanism as "Monopulse Switching". We evaluated the working principle experimentally to reveal Monopulse switching successfully cancel phase offset to detect AoA without any initial calibration and achieves 2.8 degree measurement accuracy.**

***Index Terms*—Coherent receiver, Software Defined Radio, Array antenna, Complex monopulse**

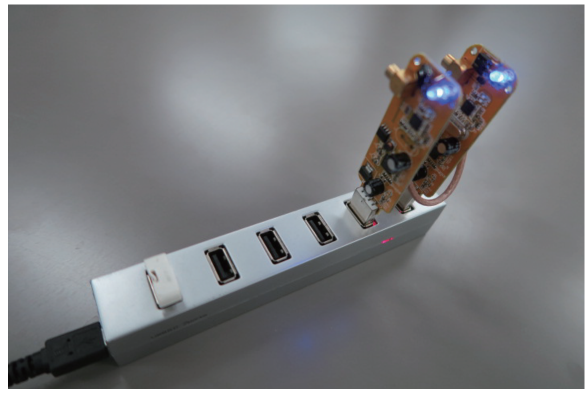

Fig. 1. Commercial low-cost digital TV tuner can be used as IQ receiver

I. Introduction

We have been observing the rapid deployment of short range wireless network, such as RFID, WiFi, Zigbee and Bluetooth. Those short range wireless devices are often attached to physical objects to collect sensor data, its locations and disposition to information system achieve services such as supply chain management, warehouse management system and manufacturing controls. This is the basic notion of Internet of Things. Almost all of such services, accurate localization of physical object is essential and demanded by industries.

Accordingly, we have many commercial products and researches on indoor localization system. Even when we only confine the survey in RFID, there are a number of commercial products and researches [1], [2], [3], [4], [5], [6], [7], [8], [9]. Existing technology can be classified into the following categories[3].

- use markers
- transmit power control
- antenna beam steering
- tag RSSI based
- tag phase based

Among the five categories, the phase based localization is, in principle, accurate but the measurement of phase demands dedicated commercial hardware[1], [2] or a coherent receiver [10].

Existing studies mainly target localization system with a set of geographically fixed reader/writer. But there are many available handheld RFID reader/writer in the market and extensively used for relatively small scale automatic identification needs particularly in baggage handling in logistics and the inventory management in apparel [11], [12], [13].

The authors have been working on a mobile localization system using multiple low-cost commercial off the shelf (COTS) software defined radio (SDR) devices. Our motivation is to make use of low cost commercial SDR platform such as a low-cost digital TV tuner shown in Fig.1.

Our typical use case is shown in Fig.2 [13]. In the figure, it is shown that a worker with a handheld reader/writer is looking for an object, which is applied an RF tag. The handheld reader/writer is equipped with a receiving only angle of arrival (AoA) detection module. The AoA detection module receives the signal from the target RF tag and calculates AoA and navigates the worker by means of, for example, a laser pointer. As the worker approaches the target object the resolution of AoA detection increases.

In the course of development of such mobile reader/writer, we encountered a fundamental problem of the use of multiple SDRs – synchronizations among SDRs. There are three types of synchronization, frame synchronization, timing (clock) synchronization and phase synchronization, all of which we explain in detail later. Among the three synchronizations, the most challenge is the phase synchronization. The phase synchronization is difficult to be achieved because the sampling and frequency conversion inside a SDR is done by individual circuitry and thus producing a phase offset. Because

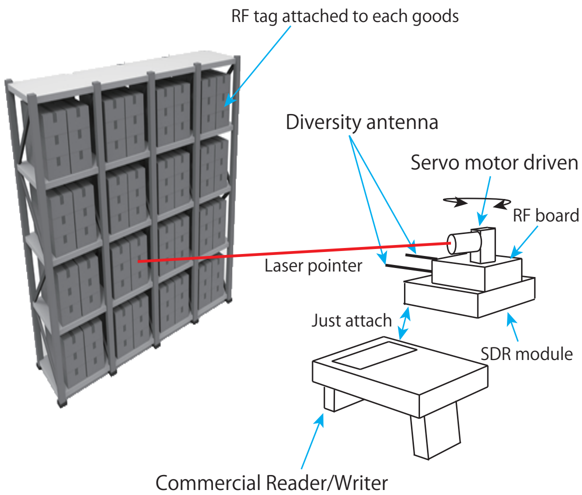

Fig. 2. A use case of handheld RFID reader/writer equipped with AoA detection module

of this phase offset, we are forced to perform an extensive calibration before a measurement. Alternatively we need to adopt a coherent receiver which is usually expensive. This leads to the scarce use of localization system in industrial deployments.

In this paper, we propose "Monopulse Switching " which makes use of an RF switch to produce two sets of IQ data from two antenna. By a simple signal processing, we can cancel the phase offset of SDR device. Although we focus our discussion to a complex monopulse based AoA detection[13], [14] in this paper, the core contribution of this study, cancellation of phase offset in SDR device, can be applied to other AoA detection principles and other applications such as interfering signal rejection.

We organize the rest of the paper as follows. In Section II, we explain the basic theory of AoA detection based on complex monopulse method and summarize the challenges to realize AoA detection with multiple low-cost SDR devices. In Section III, the idea of "Monopulse switch" is explained followed by experimental evaluation of the method in Section IV. Finally we conclude the paper in Section V.

II. Basic Theory of AoA Detection with Two COTS SDR Devices

In this section, we explain a principle of AoA detection based on complex monopulse and clarify the problem to implement with two SDR devices.

A. Principle of AoA detection based on Complex Monopulse method

Figure 3 is the basic technical component of AoA detection with two element antenna where θ and d denote the AoA and the distance between the two element antennas, respectively. Let λ and ϕ denote the wave length, and the phase difference

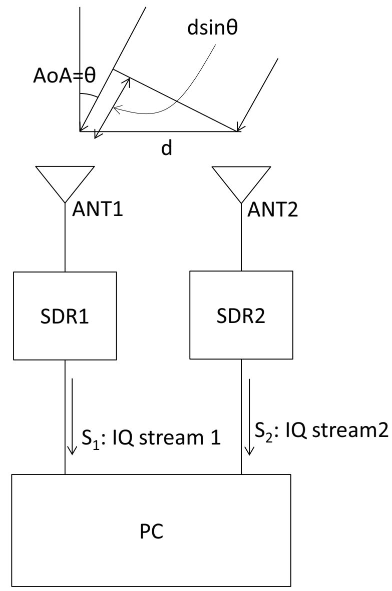

Fig. 3. AoA detection with monopulse of two element antenna

of the two antenna, respectively. The phase difference of two IQ streams, $S_1$and S_2, can be written as follows.

$$\phi = \frac{2\pi d \sin\theta}{\lambda} \tag{1}$$

There are fundamentally three monopulse principles. The first principle is to derive the amplitude of sum signal $S = S_1 + S_2$ and the differential signal $D = S_1 - S_2$ and is applied the following formula to derive the approximation of phase difference.

$$\phi = \tan^{-1}\frac{|D|}{|S|} \tag{2}$$

This looks simple and robust but suffers from fluctuation of amplitude, fading. The generation of the sum and the differential signals would be easy when we use an analog 0/180 degree divider as a front end. The second principle is to derive the phase difference directly from S_1 and S_2 such that

$$\boldsymbol{\phi = \angle S_1 - \angle S_2.} \tag{3}$$

This is invariant to amplitude fading but we need to synchronize the phase of two signals. The third principle is the complex monopulse[14], which takes the complex ratio such that

$$\frac{D}{S} = \frac{S_1 - S_2}{S_1 + S_2}. \tag{4}$$

The complex monopulse, difference of two signal divided by sum of two signals, can be expressed in the following simple form.

$$\begin{aligned} \frac{D}{S} &= \frac{e^{j0} - e^{j\phi}}{e^{j0} + e^{j\phi}} \\ &= \frac{1 - e^{j\phi}}{1 + e^{j\phi}} \end{aligned} \tag{5}$$

A graphical representation of Eq.5 is shown in Fig.4. The denominator of Eq.5 is a linear combination of 1 and $e^{j\phi}$

whose overall phase is denoted as α in Fig.4. The numerator, on the other hand, constitutes the phase angle β in the complex plane. Since both triangles ACO and BCO are isosceles triangles. $\alpha + \beta = \frac{\pi}{2}$, the division in Eq.5 falls on the imaginary axis if there is no multi-path. In other words, we just discard the measurement where an observed $\frac{D}{S}$ is NOT on the imaginary axis and thus, inaccurate.

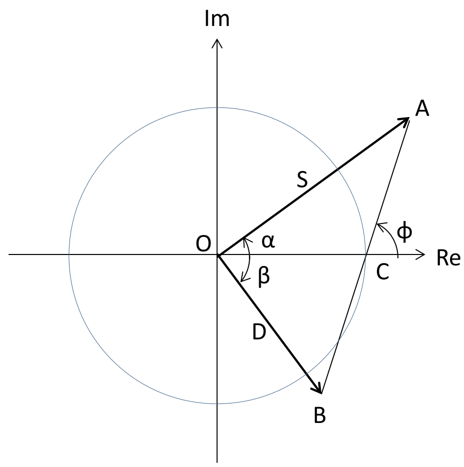

Fig. 4. Complex monopulse ratio shows up on imaginary axis on complex plane when there are no multi-path influence

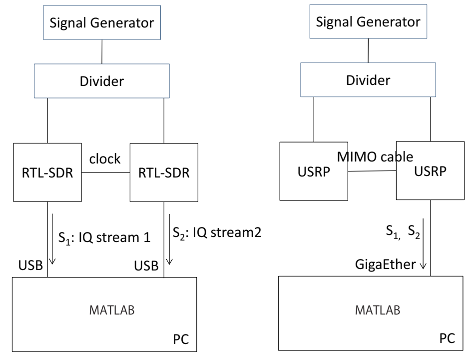

Fig. 5. Experimental setup to examine IQ streams from two sets of SDR devices

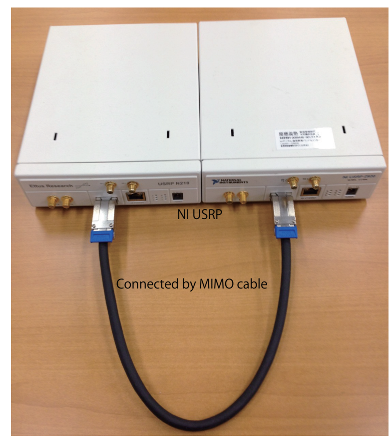

Fig. 6. Two USRP are connected with MIMO cable

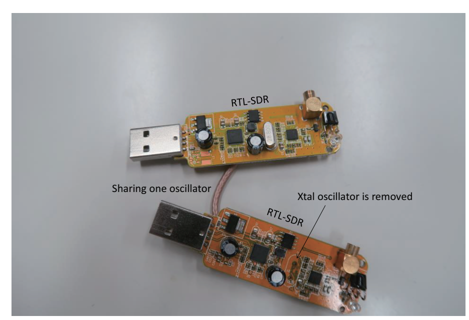

Fig. 7. Master oscillator of one is fed into the other

B. Problems of AoA detection with COTS SDR devices

Even if we have the same type of SDR devices, their clock frequency is different because they have their own oscillator. The difference of clock frequency can be corrected by providing single reference clock. But the absolute phase cannot be synchronized because of the phase offset which depends on the hardware and software of MCU and other electric circuits inside the SDR.

To quantitatively examine the problem, we set up an experiment shown in Fig.5 where an ASK modulated signal is equally divided and fed into two SDR devices to produce two IQ streams which is analyzed with MATLAB. We prepared two sets of SDRs. One set is USRP and another is RTL-SDR. The clock of two USRPs are synchronized with MIMO cable(Fig.6). The master oscillator of one RTL-SDR is fed into the other one after removing its own oscillator (Fig.7). Figures 8 and 9 show the results.

From the measurements, we identified the following challenges.

- Although we provide the same radio signal with a divider to the SDRs, there is a frame time difference, which can be observed by the difference of ASK timing. In case of USRP, the difference is about 0.1 msec. In case of RTL-SDR, it is about 0.3 msec. This frame delay stems from the timing delay to transfer IQ data to the processing computer.
- The clock timing can be synchronized both in USRPs and RTL-SDRs, by means of a MINO cable and a dedicated coaxial cable, which can be observed by the recovered frequency, the slope of phase, of two SDRs coincides; If there is a difference of clock, the frequency cannot be the same.
- Even after we synchronize the frame by properly shifting the time sequence, we still observe phase offset between streams S_1 and S_2. This phase offset changes at every measurement. This problem stems from the timing of starting IQ sampling in the SDR device.

Since the starting timing depends on each hardware and software in SDRs, it is difficult to adjust the timing from MATLAB or other external software. Because of this phase offset, a mere subtraction on phase difference does not match

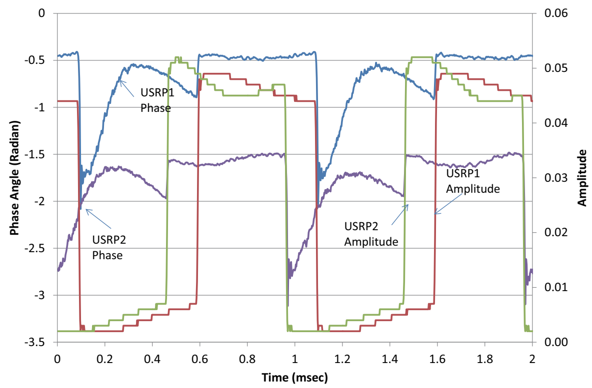

Fig. 8. IQ stream observation with two USRPs

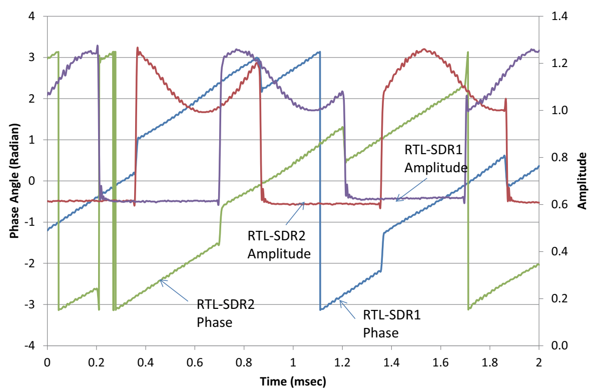

Fig. 9. IQ stream observation with two RTL-SDRs

the phase difference caused by AoA. To solve the problem, it is usual to calibrate before a measurement in which we layout the array antenna and a known source of radio located in a designated AoA. This is cumbersome in industrial usages particularly when we use a mobile reader/writer which is, in many cases, frequently power controlled to save battery consumption.

III. Cancellation of Phase Offset with Monopulse Switching

This section introduces a proposal to cancel phase offset. We insert Double-Pole Double-Throw(DPDT) switch between antennas and SDR devices, and acquire two set of phase differences with a DPDT switch. Figure 10 shows the proposed "Monopulse switch" system overview. The DPDT switch provides $SW1$ and $SW2$ states such that

- $SW1 : SDR1 = \phi_{01} + \phi \ and \ SDR2 = \phi_{02}$
- $SW2 : SDR1 = \phi_{01} \ and \ SDR2 = \phi_{02} + \phi$

where ϕ_{0i} denotes the phase offset of $\mathrm{SDR_i}$

The phase difference at SW1 state is $\Delta SW1 = \phi_{01}+\phi-\phi_{02}$ and the phase difference at SW2 state is $\Delta SW2 = \phi_{01} - (\phi_{02} + \phi)$. The subtraction of the two states yields the following.

$$\Delta SW1 - \Delta SW2 \quad = 2\phi \tag{6}$$

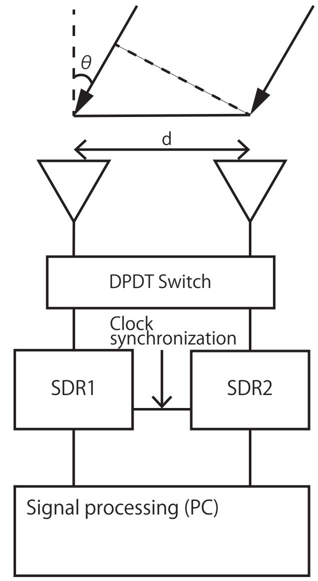

Fig. 10. Introducing a DPDT switch to conventional AoA detection system to cancel phase offset

Thus, we can cancel the phase offset $\phi_{o1} - \phi_{o2}$ and can derive the phase difference purely caused from AoA ϕ. In terms of IQ stream processing, it is simply

$$e^{j2\phi} = \frac{S_1^1 S_2^2}{S_2^1 S_1^2} \tag{7}$$

where we denote the stream i at SWj state as S_i^j. Since the switching response of commercial DPDT switch is usually less than 20 nsec, we can neglect the influence of even fast fading in "Monopulse switch" .

IV. Evaluation

This section introduces a prototype phase difference estimation system with complex monopulse switching with COTS SDR devices, experimental environment and the results of experiment evaluation. An schematic of the prototype system is shown in Fig.11. Since this is a functional experiment, the experiment was conducted by wired configuration rather than wireless AoA detection. We use Skyworks SKY13411-374LF which is less than 50 cents as a DPDT switch. A signal generator generates an RF signal at 918MHz with 1kHz ASK modulation. The signal is divided into two signals with a 3dB divider. We insert a phase shifter (Pastermack PE8244) to one of the two routes to apply a predefined phase shift. We shifted the phase of one route by adjusting PE8244. Since the phase shifter is dial type and there are no gauge, we used a network analyzer (HP 8753D) to accurately adjust the phase. This time, we applied four phase shifts, 0 deg, 30 deg, 60 deg and 90deg with PE8244 and measure the phase difference with a straightforward complex monopulse method and the proposed complex monopulse switching method. The two SDR devices which connected by MIMO cable are connected to a PC through Gigabit Ethernet cables, and IQ signals generated by SDR devices are processed by a custom made virtual

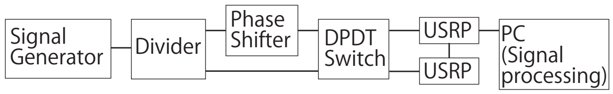

Fig. 11. Experimental setup schematics

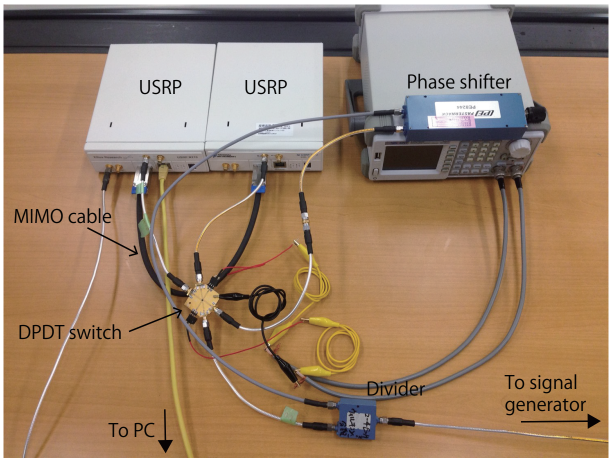

Fig. 12. Experiment set up of monopulse switching evaluation

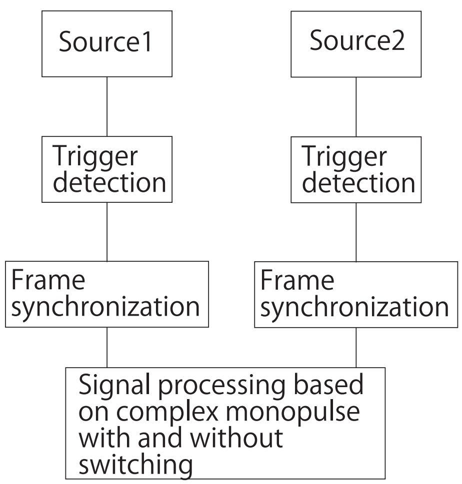

Fig. 13. The function flow of the developed virtual instrument of LabVIEW

instrument(VI) in LabVIEW. Figure 13 shows the schema of VI program.

A. Result of experiment

Figure 14 shows the result. It is shown Monopulse Switching can provide exact phase difference measurement by eliminating the phase offset. On the other hands, the straightforward complex monopulse produces erroneous phase difference. This is because every time we restart the SDR devices the phase offset would be different. The average phase measurement error of complex monopulse switching is 2.8 degree. This remaining error seems to be resulted from the imperfect frame synchronization. Figure 15 shows the occurrence probability of the measurements. Horizontal axis of the figure denotes the phase difference measurement error. The vertical axis is

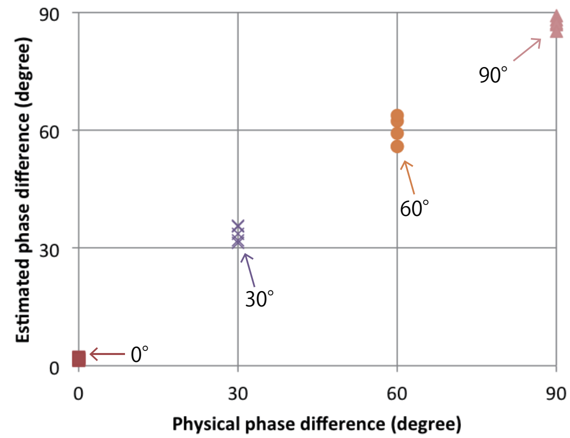

Fig. 14. Result of phase difference measurement with complex monopulse switching

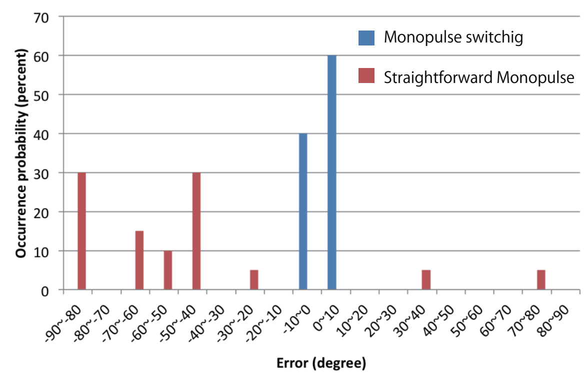

Fig. 15. Occurrence probability of measured phase difference

the occurrence probability of the corresponding error range. In Fig.15, it is clearly seen that the Monopulse Switching can provide stable and accurate measurements.

V. Conclusion

AoA detection with multiple COTS SDR devices is attractive particularly when we use a mobile reader/writer. But it suffers from the phase offset caused by the software and hardware in each SDR device. Therefore, calibrations before measurement are demanded in conventional AoA detection with non-coherent array antenna. We can cancel the phase offset with proposed Monopulse Switching, which can be implemented by using a low-cost DPDT switch and simple signal processing. An experimental evaluation reveals Monopulse Switching can achieve stable AoA detection with 2.8 degree error demanding no calibration before experiments.

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