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A Feasibility Study of Plug-in Type RF Tag Localization System for Handheld UHF RFID Reader/Writers

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Abstract—**This paper proposes a plug-in type RF tag localization system, using an Angle of Arrival principle, in UHF RFID, particularly targeting handheld reader/writers. Being a plug-in type, the RF tag localization system is receive-only, incurring no radio license requirement, small in size and can be built at low cost. Our fundamental idea is to employ a newly developed short-range mono-pulse method for the RF tag direction detection enabled with affordable software defined radio device and an analog front end. In this paper, we report an experimental evaluation with a functional prototype primarily on the detecting accuracy. It is shown that we can achieve about 3 degree accuracy for RF tags at 7.3 m distance from a 4 W EIRP reader/writer. Because the measurement in the direction of boresight is more stable than the other directions, the direction accuracy can be improved when we feed back the direction detection to the orientation of handheld reader/writer. We also confirm this feature experimentally.**

I. Introduction

Short range wireless system has been adopted in many industrial and also consumer products. Low cost wireless and battery-less terminals which can be embedded or attached to physical objects to collect the location and disposition are attractive to many applications and services. Passive UHF RFID [1] is a popular technique for such use. Usually, an object identification and observation event in an RFID system is stored in a database in conjunction with the reading point and business location, such as a shelf number or an alley number in a warehouse [2]. In the practical use of UHF RFID, the capability of physical object level location, not just the shelf location, would provide a significant operational efficiency. For this reason there have been number of researches and also commercial products to provide a localization capability in UHF RFID.

Commercial localization capable UHF RFID system are all fixed reader/writer system [3], [4] making use of multiple dedicated antenna and an advanced signal processing. Consequently, they usually demand a radio station licensing and a special preparation or calibration before the usage. On the other hand, there are a number of 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 [5], [6].

We found there are strong demands for object localization with handheld reader/writers. Since most of the business applications of handheld reader/writer is strongly tailored to the reader/writer interfaces and specs, replacing a handheld reader to new reader, which has a localization function, requires the in-operation business applications to be migrated to the new reader. This migration problem usually consumes lots of effort and cost, thus in many case, prohibitive. These requirements motivate us to build a plug-in type RF tag localization system. Being a plug-in type, the RF tag localization system is receive-only, incurring no radio license requirement, small in size and can be built at low cost.

There are many researches [8]–[14] on localization of UHF RFID. Nikitin [8], [9] classifies the principles into the following five methods.

- Makers: Use of reference readers and RF tags, the locations of which are known.
- Transmit power control: Estimate the distance from reader to RF tags by changing the transmission power.
- Antenna beam steering: Phase control of reader antennas provide read rate distribution. [3] is in this category.
- Tag RSSI based: Measure the RSSI from RF tag as the indication of distance.
- Tag phase based: Incoming backscatter phase is captured by multiple antenna.

Among those methods, the tag phase based methods, including the monopulse method explained later, have a number of variations and can provide good accuracy. Also we can leverage of the emerging low cost, Software Defined Radio (SDR hereafter) platforms, such as RTL2832U [**?**] since our target is to build a plug-in type RF tag localization system to handheld type UHF RFID.

An exemplary usage model of the proposal is shown in Fig. 1 where RF tag attached items are on a shelf and a worker holding a handheld reader/writer scans the inventory to locate the target item. The reader/writer implements a direction detector which consists of SDR module and RF board with a laser pointer driven by a servo motor controlled by the SDR. When the reader/writer inventories a target RF tag by specifying the pattern of its Identification Number (ID) , the two antennas set horizontally in RF board receive the backscatter signal from the RF tag. The SDR computes the angle of arrival (AoA) and controls the servo motor to orient

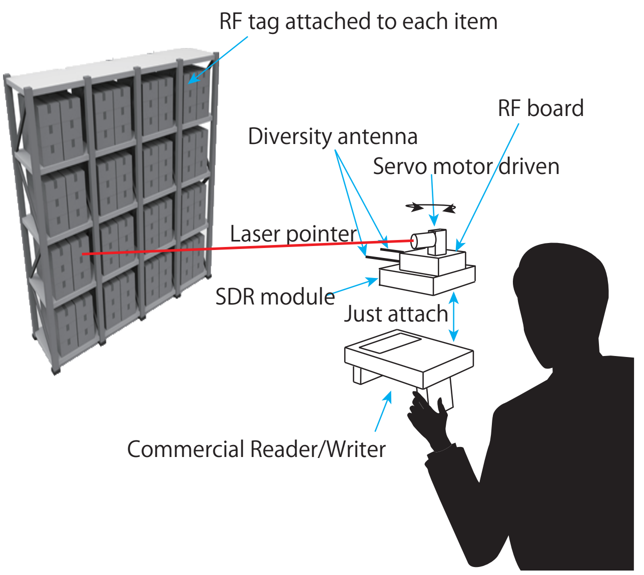

Fig. 1. Exemplary usage model of the target system. A localization function can be added to existing reader/writer without changing the in-operation business applications.

the laser pointer to the direction. As the worker orients the reader/writer following the inferred direction and comes close to the target, the direction detector provides improved inference and finally the worker can reach to the target item.

To achieve this goal, we think the following issues have to be studied and developed.

1) Working principle to determine AoA with affordable SDR with reasonably small form factor
2) Command analysis and timing synchronization with reader/writer transmission
3) Examination of stability of the feedback control

In this paper, we studied the first research issue. The expected problems stemming from affordable SDR are the low phase stability and narrow bandwidth (such as 3.2 Msps) and low bit-width of sampling (such as 8-bit IQ sample) while we need to capture an weak backscatted signal from RF tag which entails a carrier fluctuation.

The rest of the paper is organized as follows. In Section II, we explain the signal characteristics of UHF RFID and derive a fundamental working principle of localization based on a monopulse method. In Section III we examine the performance of the approach implementation on SDR. Section IV concludes the paper.

II. Principle of Angle of Arrival Detection

In this section, we first introduce the typical modulation and coding of UHF RFID tag backscatter. Then, we examine the working principle of AoA determination with affordable SDR.

A. UHF RFID tag backscatter

UHF RFID utilizes a modulated backscatter where RF tag is empowered by the continuous wave (CW) from the reader/writer and transmits signal by changing the antenna impedance. Since the reader/writer transmits the CW while it is listening to RF tags, the major noise in the tag-to-reader link is, in many practices, the phase noise of the reader/writer itself. To avoid the phase noise, most of UHF RFID uses a subcarrier modulation by superposing the baseband signal onto a constant sequence of switching on/off which is referred to as subcarrier frequency. By doing this, a modulated backscatter appears at the subcarrier frequency as shown in Fig. 2. Since the subcarrier frequency is produced by a low stability resonator of RF tag, the subcarrier phase fluctuates while it backscatters. As we examine later in this paper, this is the fundamental problem of AoA in UHF RFID.

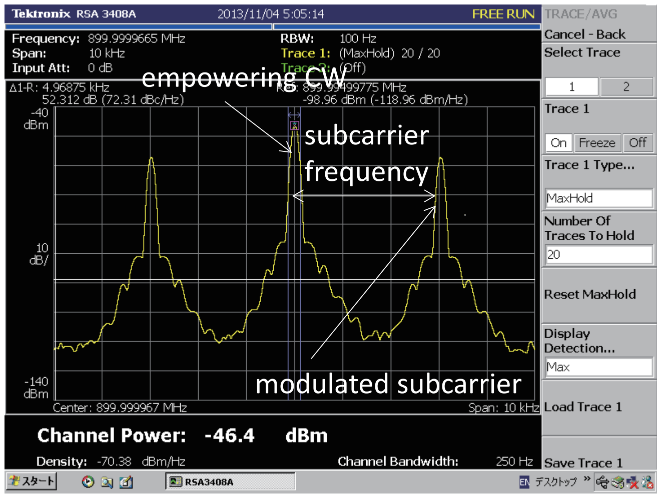

Fig. 2. XOR of a constant switching on/off and the baseband signal produces modulated subcarrier which is frequency-wise separated from the CW.

B. Direction detection with monopulse method

As shown in Fig. 3 where R, θ, λ, A and d represent the distance to the target RF tag, the direction of coming backscatter signal measured at the center of two antennas, the wave length, a path difference and the distance between two antennas, respectively. We use two receive-only antennas per horizontal and vertical axes to detect a direction of an RF tag. As also shown in the Fig. 3, we have element antenna gain G_1 and G_2 which might be different depending on the RF tag position and the difference of AoA to each antenna.

In most of conventional AoA, we presume the two arriving directions are parallel to yield

$$A = d \sin \theta. \tag{1}$$

and the phase difference is

$$\phi = \frac{2\pi A}{\lambda}. \tag{2}$$

The exact path length from the RF tag to one of the elemental antennas, denoted with a subscript A_i where i is either 1 or 2

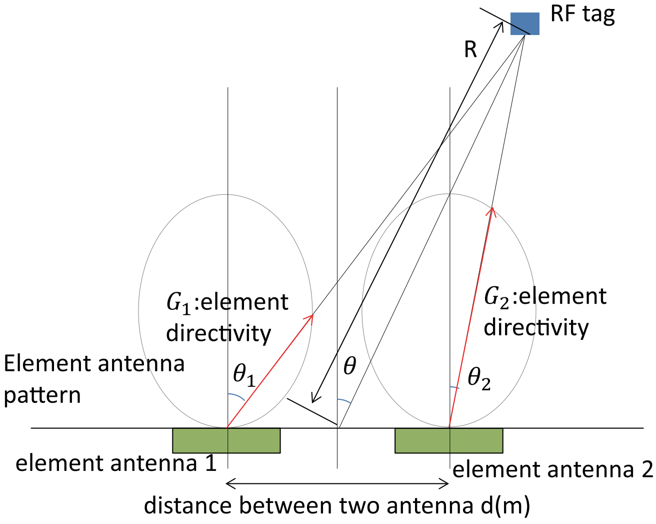

Fig. 3. Principle of direction detection.

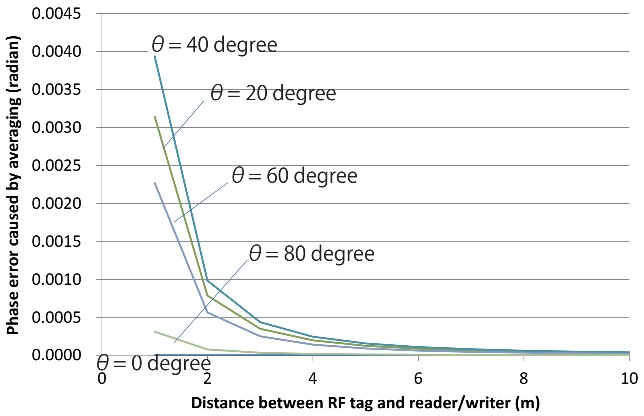

Fig. 4. Phase measurement error yielded by ignoring the difference of AoA at element antenna.

are as,

$$A_1 = \sqrt{\left(R\sin\theta + \frac{d}{2}\right)^2 + R^2\cos^2\theta}. \quad (3)$$

$$A_2 = \sqrt{\left(R\sin\theta - \frac{d}{2}\right)^2 + R^2\cos^2\theta}. \quad (4)$$

The calculated phase difference Φ is thus

$$\Phi = \frac{2\pi(A_1 - A_2)}{\lambda}. \quad (5)$$

Figure 4 shows the phase difference between the averaged case ϕ and the exact case Φ in various R and θ where we fixed d to be half wavelength to suppress grating lobes.

It is shown that there is marginal phase error in every distance and angle which means that we can use the simplified formula (1) to derive the AoA. It is interesting to see that the phase error at $\theta = 40$ degree is larger than that of $\theta = 20$ degree. This is reasonable because the phase difference at $\theta = 0, 90$ is zero in either case. Figure 5 shows the phase difference according to the AoA in case R is 5 m. It is shown

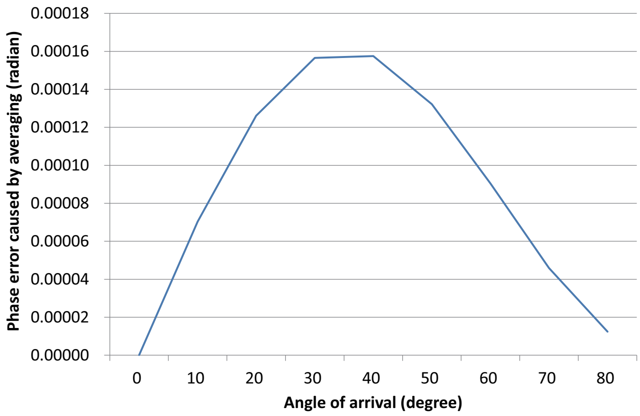

Fig. 5. Phase error caused by averaging is maximized when the AoA is about 40 degree. But the error is still marginal.

that the phase error is maximized when the AoA is about 40 degree. This enables us to eliminate the detailed geometry in AoA localization even in short-range wireless system such as RFID.

In order to normalize the signal intensity and to yield the phase difference from two sets of IQ data S_1 and S_2 obtained from two antennas, monopulse methods extensively used in radar area [16], [17] are examined. There are fundamentally two monopulse principles. The first principle is to derive the amplitude of in-phase signal $S_c = S_1 + S_2$ and anti-phase signal $S_a = S_1 - S_2$ and apply the following formula to derive the approximation of phase difference.

$$\Phi = 2\tan^{-1}\frac{|S_a|}{|S_c|}. \quad (6)$$

This is simple and robust but suffers from fading. The second principle is to derive the phase difference directly from S_1 and S_2 such that

$$\boldsymbol{\Phi = \angle S_1 - \angle S_2.} \quad (7)$$

This is invariant to amplitude fading but we need to synchronize the phase of two signals. There is a combination of amplitude and phase monopulse referred to as complex monopulse [18].

Since we would like to use a low cost SDR which usually does not have a capability to synchronize with other SDR device and we also expect unstable subcarrier whose power is significantly smaller than the empowering CW. It is expected to be challenging to use phase based method. We measured the phase stability of a IQ signal of an emulated subcarrier at 100 kHz produced with an RF switch and a saw resonator. The result is as shown in Fig. 6. It is shown that the both the phase angle and the frequency fluctuate. This observation leads us to employ the amplitude based monopulse method. However, we still need to have the exact phase match in two SDR devices to derive in-phase and anti-phase signals as in (6). For this reason we introduce an analog front end, which is simply a commercial 180 degree divider before SDR device as shown in Fig. 7.

The accuracy of the short range amplitude based monopulse method including the element antenna gain in

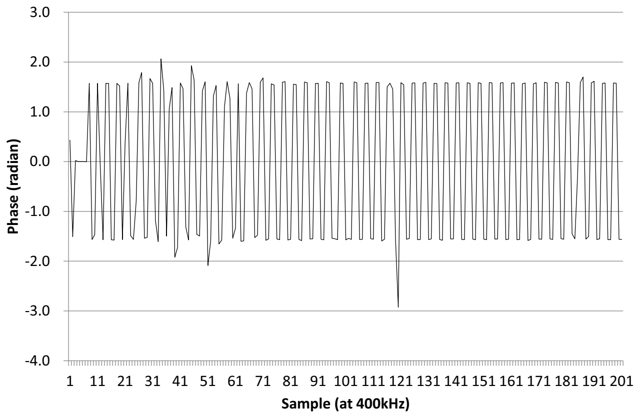

Fig. 6. Phase transition produced by an unstable resonator and an RF switch fluctuate over time both in time and phase angle.

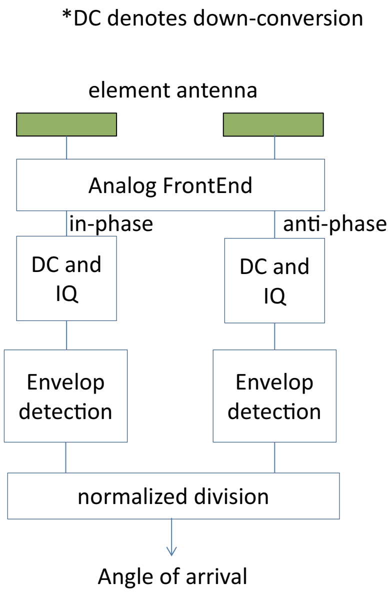

Fig. 7. An analog front end to facilitate the SDR processing.

1 m, 5 m and 10 m range are numerically simulated as shown in Fig. 8 It is shown that if we properly derive the amplitude of received signal from IQ data, the accuracy of amplitude monopulse is satisfactory except the AoA is over 80 degree. This is a strong advantage of the proposed short range monopulse method over existing proposals which confine the applicable AoA range depending upon the element antenna pattern.

The sensitivity of AoA determination against the phase measurement can be derived by taking the differential form of (2).

$$\Delta\theta = \frac{\lambda}{2\pi d\cos\theta}\Delta\Phi. \tag{8}$$

which reveals that the phase measurement error results in worse AoA accuracy when the AoA is large. It is, thus, expected that we can improve overall AoA determination accuracy by orienting the handheld reader/writer toward the inferred direction in order to match the boresight to align the AoA.

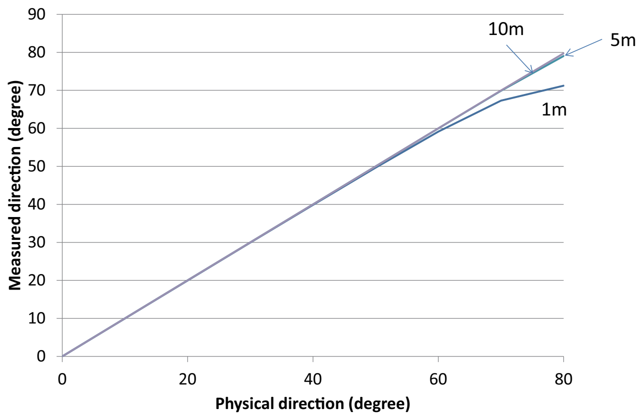

Fig. 8. Amplitude based monopulse method provides a good accuracy except the AoA is over 80 degree.

III. AoA Accuracy Evaluation

This section introduces a prototype plug-in type RF tag localization system on SDR, experimental evaluations and the results of experiment. An overview of the prototype system is shown in Fig. 9. As shown in Fig. 10 where θ represents the direction of coming backscatter signal. We denote the right side as positive value and the left side as negative value and move a tag from $-\theta = 50$ degree to $\theta = 50$ degree by 10 degree interval.

Backscatter signals received by each element antenna are input to SDR devices, NI USRP. The two SDR devices are connected to a PC through Gigabit Ethernet cables, and IQ signals generated by SDR devices are processed by a custom made virtual instrument (VI) in LabVIEW. The flow of the VI program is shown in Fig. 11. Since this is the functional evaluation, we use USRP and LabVIEW, in the future development we will replace them with affordable SDR equipment and embedded software.

A. RF tag localization system on SDR

We first examined the accuracy of the prototype RF tag localization system on SDR. We adjust the backscatter power to emulate the distance between the RF tag and the reader/writer to be from 1.8 m to 7.3 m for in 4W EIRP reader/write to examine the accuracy dependence on the communication range. This time we focus on only horizontal axes. Figure 12 shows the result. Each point in the figure represents the average of measured directions on each cases. The average of all errors is 2.2 degree. Even in case of the distance between the RF tag and reader/writer is long, the direction accuracy is satisfactory. However, we observe that the dispersion of measured direction increases as the AoA becomes large, which is in-line with our expectation on the error sensitivity in (8).

B. Feed back the direction detection result

As we mentioned earlier, there are dispersion of measurement on some cases. To solve the problem we turned element antennas toward the inferred direction as shown in Fig. 13. In this time we turn element antennas manually. We conducted an experiment focusing on $\theta = 30$ degree and $\theta = 50$ degree.

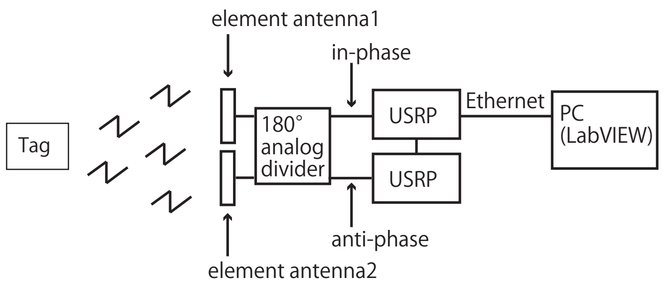

Fig. 9. The overview of experimental environment.

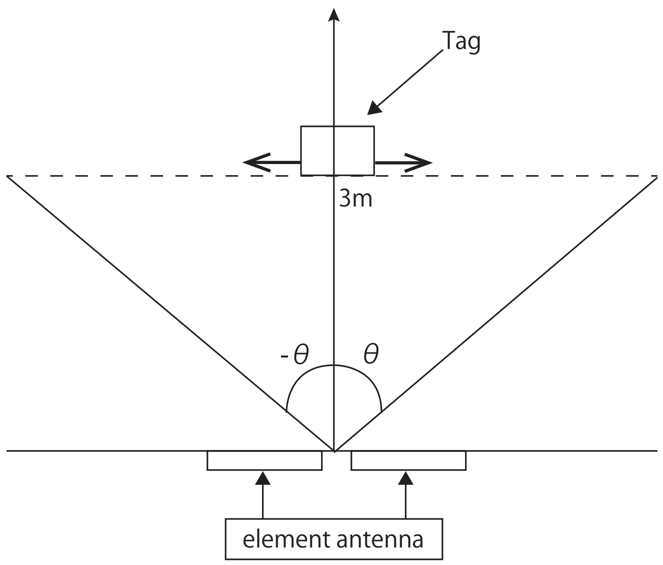

Fig. 10. Experimental environment of tag's position.

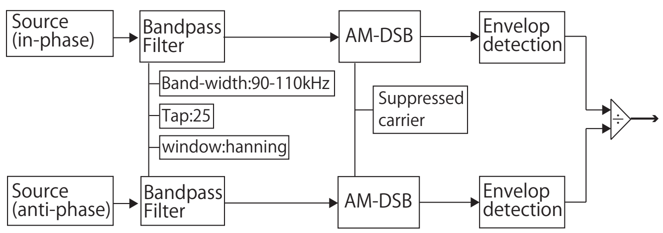

Fig. 11. A schema of VI program.

Figure 14 shows the result of before turning element antennas and after turning element antennas. After turning element antennas, there is less dispersion than before turning element antennas.

IV. Conclusion

A localization function in handheld UHF RFID reader/writer can be realized by a combination of low-cost SDR devices and a 180 degree analog divider. The achievable accuracy is about 3 degree, which is satisfactory for industrial applications. We confirm the performance in indoor experiments up to 7.3 m in communications range. Because the AoA determination in the boresight direction is more stable than the other directions, the direction accuracy can be improved when we feed back the direction detection to the orientation of handheld reader/writer.

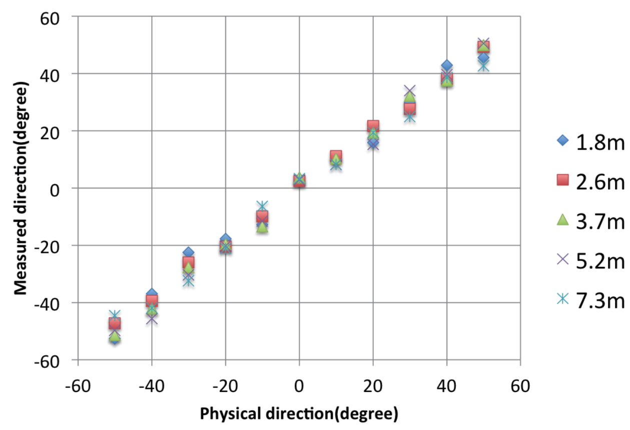

Fig. 12. Average of measured direction of coming backscatter signals on each amplitudes.

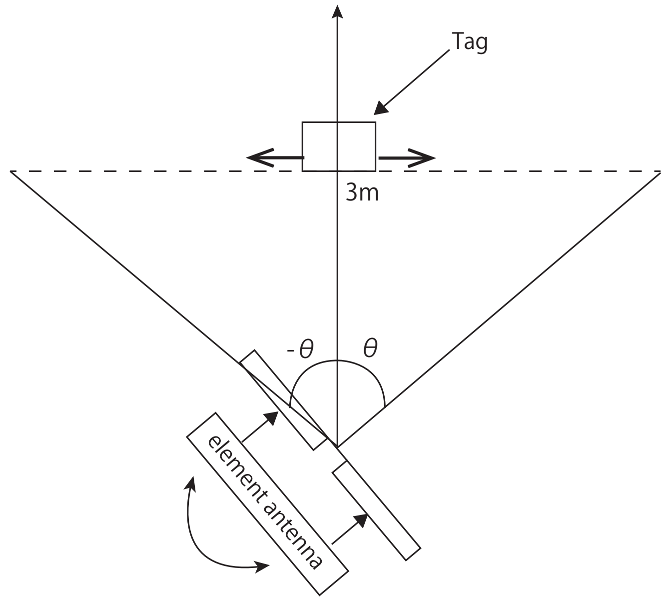

Fig. 13. Example of turning antennas toward calculated direction.

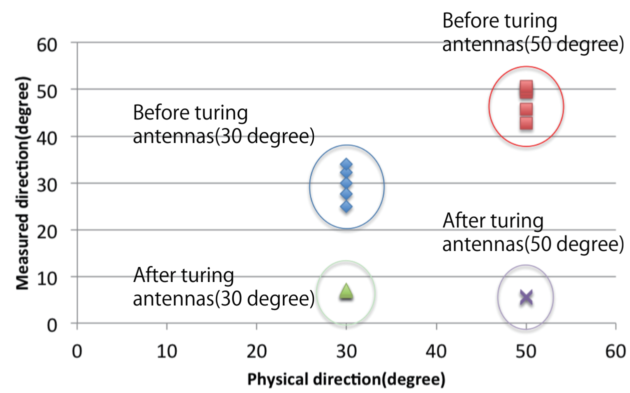

Fig. 14. Compared with measured direction after turning antennas and before turning antennas.

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