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# Performance Evaluation of the Angle of Arrival of LoRa Signals under Interference

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***Abstract*—Tracking objects in indoor is always a challenge for a variety of Internet of Things (IoT) applications. Nowadays, many indoor tracking applications use Low-Power Wide-Area Networks (LPWAN) for Machine-to-Machine (M2M) communication. LoRa is a promising LPWAN radio communication technology designed for wide-area coverage and low-power embedded IoT devices. The objective of this paper is to evaluate the performance of the Angle of Arrival (AoA) direction finding approach in an indoor environment. The AoA performance of the LoRa signal is evaluated using different modulation settings, including Channel Bandwidth (BW) and spreading factor (SF). We measure the AoA accuracy of the LoRa signal using an individual Universal Software Radio Peripheral (USRP) B210, Software Defined Radio (SDR) receiver with the help of the GNU radio software development toolkit. In addition, a new approach to measure the AoA of LoRa signal under interference is investigated. We show that by using the Autocorrelation function combined with our direction finding algorithm, the detection and measurement of two simultaneous receptions is possible. The entire experimental setup was implemented in our indoor office environment.**

***Index Terms*—Long-Range (LoRa), Low-Power Wide-Area Networks (LPWANs), Software Defined Radio (SDR), Angle of Arrival (AoA).**

## I. INTRODUCTION

Direction of Arrival (DoA) finding techniques for signal processing have been used in a wide range of wireless sensors and communication applications such as signal detection and localization. DoA consists of measuring the Angle of Arrival (AoA) from which a received signal was transmitted. Several DoA techniques have been developed and proposed in the literature to determine the location of a node based on AoA. The most common DoA techniques include spectral-based techniques such as the Capon Beamforming method [1], typical techniques such as Maximum Likelihood (ML) [2], and subspace decomposition methods. Subspace decomposition methods include the Multiple Signal Classification (MUSIC) [3] technique and the Estimation of Signal Parameters via Rotational Invariance Technique (ESPIRIT) [4]. However, the implementation of these techniques is complex and expensive because it requires multiple receivers, as well as a synchronization between these receivers.

Our previous research work [5] showed that a direction finding system can be successfully implemented by measuring the AoA of a Long-Range (LoRa) signal using a Software Defined Radio (SDR). This method involves determining the phase difference of the signal received by two antennas spaced a set distance apart. The AoA can be measured in real time using a single SDR Universal Software Radio Peripheral (USRP) B210 receiver.

This paper presents a performance evaluation of the DoA method developed in [5]. The AoA accuracy of the LoRa signal is evaluated using different modulation parameters including signal bandwidth (BW) and the spreading factor (SF). In addition, we study the AoA accuracy of simultaneously receiving two LoRa signals configured with the same modulation parameters.

The rest of the paper is organized as follows. In section II, we discuss the advantage of SDR and USRP hardware to measure the AoA of LoRa signal. Section III describes the design and implementation of the proposed algorithm. In section IV we evaluate the performance of the algorithm based on experimental results. Section V concludes the paper.

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## II. RECEIVING LORA SIGNALS USING SOFTWARE DEFINED RADIO

### A. The USRP Hardware

Software Defined Radio (SDR) is a radio communication system in which the modulation and demodulation of the signal is performed by software on a personal computer [6]. The philosophy behind the SDR concept is that the software should run as close to the antenna as possible and on a general purpose device or computer. The SDR consists of two parts: a hardware part and a software part. In the hardware part, the RF front end convert the received signal from its carrier frequency to an intermediate frequency. Then, the resulting signal is converted into digital data by an analog-to-digital converter (ADC). After that, the signal processing is done by the software part which includes filtering, decimation, modulation/demodulation, coding/decoding.

SDR plays an important role in the development of radio direction finding engineering, providing new opportunities to study existing and create new direction finding algorithms. Various SDR direction finding systems are described and presented in the literature. Most SDR direction finding systems use the USPRs development platform to capture the RF signal and measure the AoA [6, 7, 8]. In [6], the authors proposed a DoA estimator using 4-element uniform linear array. The uniform 4-element linear array consists of 4 independent RF receivers that require phase synchronization between the receivers. The estimator use the MUSIC algorithm to estimate the DoA. Another direction finding approach is implemented in [7] using 4 USRP2 platforms. The 4 RF boards are synchronized using an external 10MHz reference clock signal. In [8], a low-budget direction finding system is implemented using a single two-channel SDR platform based on the USRP N200. The average absolute error between the real AoA and the estimated AoA is 3 degrees for angles in the range of [-30, +30] degrees. The above direction finding systems use computationally intensive algorithms or multiple USRP devices to estimate the DoA. However, providing an accurate and inexpensive direction finding system remains a challenge.

In [5], we proposed a low-cost direction finding system that uses a dual-channel USRP B210 device. The choice of the USRP B210 is motivated by its two RX input channels with fully coherent Multiple Input Multiple Output (MIMO) capabilities. The direction finding system can measure the AoA of a LoRa signal using the radio Interferometric algorithm [9]. The phase difference between the signals received by two antennas is used to measure the AoA. Unlike other direction finding systems, we proposed a direction finding system that is based on a single USRP B210 device and a fast phase difference algorithm that does not require high computational power. In addition, our algorithm can accurately measure the AoA with a maximum error of about 5 degrees in the range of [0, 180] degrees. Taking advantage of our previous research work, we propose to study the AoA accuracy of LoRa signal under different modulation parameters including channel bandwidth (BW), spreading factor (SF), and simultaneous receptions. In the next section, we describe the application of the SDR software to LoRa signal.

### B. Gnuradio Software and LoRa Libraries

LoRa is a low-power, low data rate radio communication technology developed by Semtech and designed for IoT applications. LoRa [10] is a physical layer that uses Chirp Spread Spectrum (CSS) modulation operating in the lower Industrial, Scientific and Medical (ISM) bands (EU: 433 MHz and 868 MHz, USA: 915 MHz). Thanks to its CSS modulation technique, LoRa use the entire allocated bandwidth to transmit a signal. As a result, the signal is more resilient to noise, interference, multi-path fading and Doppler effect.

There are not enough references and open source documentation for the LoRa physical layer. The investigation of the LoRa PHY remains a challenge for the research community. In recent years, a lot of research are centered on the LoRa PHY using the SDR platform [11, 12, 13, 14]. These works focus on the reverse engineering process to implement the LoRa physical layer. The reverse engineering process involves identifying the communication protocol used in the network. [11] and [12] provide a detailed description and documentation of the LoRa Physical layer. The first implementation [11] involves a modulation and encoding technique of the LoRa PHY. An open source software implementation named *gr-lora* was presented. *gr-lora* is an open source implementation of the LoRa physical layer using the GNU Radio software development toolkit. It defines signal processing blocks for the reception and transmission of LoRa signals using the reverse engineering methods. However, this implementation only supports reception and transmission of signals with spreading factor (SF) 8, code rate (CR) 4/8, and all bandwidths. The failure of all spreading factors and code rates is due to the fact that the whitening sequences are not handled properly. In the second implementation [12], a Multi-channel Software Decoder for the LoRa physical layer was implemented using the SDR platform and the GNU Radio framework. A reverse engineering algorithm based on real hardware LoRa transceivers was presented by the authors. The algorithm consists of 3 steps: detection, synchronization, and decoding LoRa frames in Real time using SDR. The decoder of this implementation named *gr-lora* can decode LoRa frames from multiple channels simultaneously in real time. The authors show that the decoder can decode frames for all possible combinations of spreading factors and code rates, and is able to communicate with existing LoRa transceivers such as SX1272, RN2483 and RFM96.

In this paper, the implementation of the LoRA PHY presented in [12] is used to detect, decode and measure the AoA of LoRa signals. The LoRa decoder will be used in conjunction with our direction finding system that we developed previously [5]. A performance evaluation of our direction finding system using different LoRa modulation parameters will be discussed in detail in the next section.

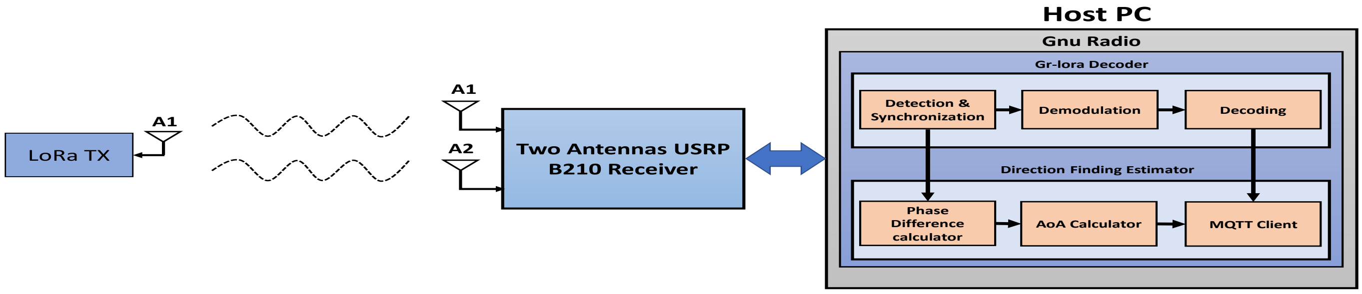

Fig. 1. USRP B210 direction finding system - block digram

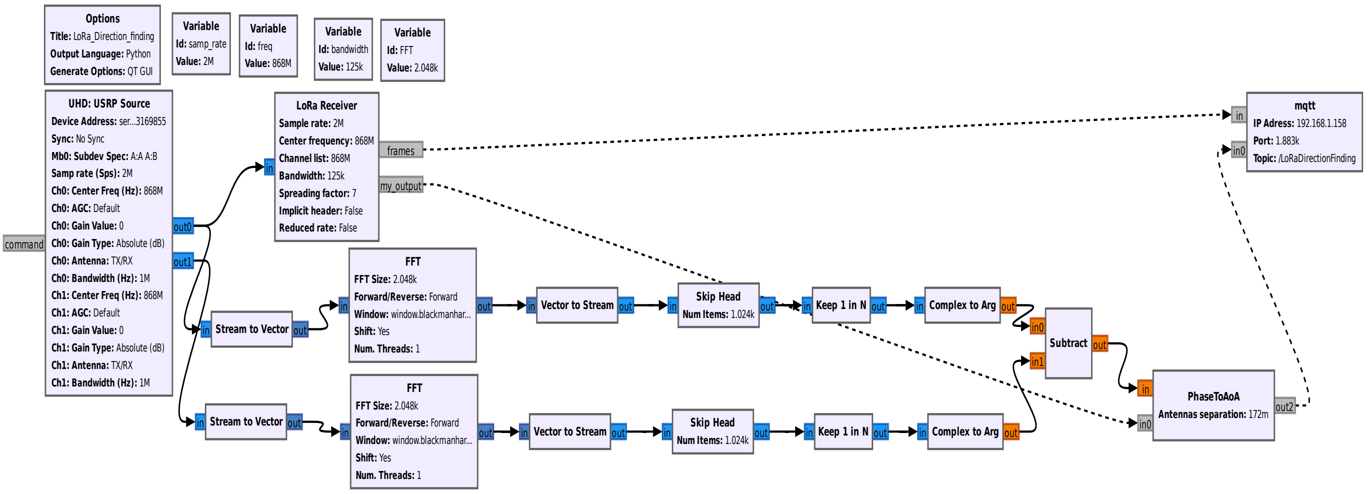

Fig. 2. USRP B210 direction finding system - GNU Radio Flowgraph

## III. LORA ANGLE OF ARRIVAL AND INTERFERENCE

### A. Syloin: an Indoor Positioning Project

The Syloin project is an indoor positioning system whose architecture is composed of a set of SDR/LoRa gateways deployed in a logistics warehouse in order to measure AoA from various places in the building. A triangulation function is then carried out leading to a set of lines intersecting close to each other and resulting in the coordinates calculation of LoRa objects deployed in the area. The objective of these connected objects, linked to a single battery is to transmit low-power signals towards the gateways in order to increase lifespan as much as possible. the number of connected objects in the warehouse must allow scaling up without saturating the radio channel. A good management of collisions and interference should allow this.

### B. LoRa Signal Detection and Angle of Arrival

In our system, the direction finding is determined by measuring the AoA of a LoRa signal received by a two-antenna SDR-based receiver. To measure the AoA, the direction finding system must be able to detect the phase of the signal as it arrives at both antennas. Once the phase of the signal is detected at each antenna, the AoA can be obtained by measuring the phase difference between the signals received at the two antennas [5].

As shown in Figure 1, the proposed system consists of a USRP B210 platform and a LoRa TX transmitter. The signal received at each antenna of the B210 is converted by the RF front-end from its carrier frequency to its baseband frequency. Then, the analog-to-digital converter (ADC) converts the signal to the modulation bandwidth. On the other hand, the processing of the converted signal can be done in the GNU Radio software. The GNU Radio part is divided into two paths. The first path consists of the *gr-lora* decoder which is responsible for the detection and synchronization, demodulation and decoding. To decode a LoRa frame, the decoder must know the beginning of the frame. Each LoRa frame is composed of a preamble of a few symbols (mainly eight up-chirps). Once the frame preamble is detected, the first path of the direction finding system informs the second path that a LoRa signal has been detected. Therefore, the second path will calculate the phase difference and the AoA of the detected signal. The communication between the two paths is based on a communication protocol called *Message Passing* which is a publish/subscribe communication protocol. The first path and the second path publish the decoded data and the AoA to the MQTT client block, respectively. Message Queuing

Telemetry Transport (MQTT) is a publish/subscribe network protocol that transports messages between the devices. This protocol is based on the TCP/IP communication protocol. The MQTT client block publishes data to an MQTT server where we can view the data in real time. The complete implementation of the direction finding system in GNU Radio is shown in Figure 2.

The next section discusses the case where two LoRa signals are received simultaneously with the same modulation characteristics.

### C. LoRa Signal Interference and Autocorrelation

LoRa technology uses the spread spectrum technique to encode the signal. Thus, LoRa introduces several spreading factors, typically 6 SF (from 7 to 12) that allow orthogonal transmissions to avoid interference and signal collisions. Interference occurs when two or more LoRa signals are received simultaneously on the same channel and with the same SF. Simultaneous reception of two or more LoRa signals on the same channel and with same SF leads to the loss of one packet if there is a stronger signal than the other and leads to the loss of all packets if the two signals have the same power [15, 16, 17]. The *gr-lora* decoder used in our direction finding system is able to decode only one signal from concurrent LoRa signals as long as they are on different SF and cannot manage two signals being received simultaneously on the same channel with the same SF. Improving the decoding step is not in our contribution scope. To our knowledge, there is no previous work on receiving two LoRa signals simultaneously with the same modulation parameters. This work concerns detecting and measuring AoA of two concurrent LoRa signals with same received power, on the same channel and with the same SF.

*Contributions:* In the section, we describe the GNU Radio SDR implementation of the Autocorrelation function of two LoRa signals received simultaneously at the two-antennas SDR Receiver.

The Autocorrelation function is a mathematical tool used to determine the degree of similarity between a given time series and a lagged version of it. The Autocorrelation of a signal is the correlation of a signal with its delayed copy. Suppose we have a discrete signal *x(n)*, *n = 1,2,3,..,N*, where N is the number of samples. The Autocorrelation function of *x(n)* is given by:

$$ACF(x) = Corr(x,x)_k \Leftrightarrow X(f)X^*(f) \equiv |X(f)|^2 \qquad (1)$$

Where *ACF(x)* is the Autocorrelation function of the signal *x(n)*, $X(f)$ is the Fast Fourier Transform (FFT), and $|X(f)|^2$ is the Power Spectral Density (PSD) of the signal. *ACF(x)* reaches its maximum value at the lag=0 and is always symmetric around zero. It is possible to detect and measure the AoA of two simultaneously received signals, using the Autocorrelation property functions and the two-antennas direction finding system.

## IV. EXPERIMENTATION AND RESULTS

Our direction finding system was evaluated in our ground floor office environment. The tests were performed using the USRP B210 as the SDR receiver, and the RFM95 LoRa module as the transmitter. The transmitter and receiver were configured with a carrier frequency equal to 868 MHz.

### A. Experiment 1: Performance Evaluation of Angle of Arrival using various LoRa Modulation Characteristics

In the first experiment, we evaluated the performance of our direction finding system with *gr-lora* decoder. The transmitter was programmed to transmit a LoRa signal with different SF (7 to 12) and BW (125 kHz, 250 kHz and 500 kHz). For each BW, we measured 500 AoA points with SF ranging from 7 to 12. Figures 4, 5 and 6 show the angular deviation error with three different BWs and for all SFs, respectively. We can clearly notice in Figure 4 that using a BW equal to 125 kHz, the algorithm gives the best performance for SF equal to 7, 8 and 9 respectively, and can accurately measures the AoA with a deviation error less than 10 degrees for SF equal to 7. However, the angular deviation error increases exponentially as SF increases from 9 to 12. Figure 5 shows that when the BW is equal to 250 kHz, the deviation error starts to increase for SF equal to 7, and decreases for SF equal to 10, 11, and 12. It can also be seen that the deviation error is not significantly affected when the SF is equal to 8 or 9 for both Bw 125 kHz and 250 kHz. Finally, for a BW equal to 500 kHz, the algorithm gives a better performance for the largest SF (10, 11, and 12) and a poor performance for the smallest SF (7 and 8). From these results we can conclude that the AoA accuracy is better when a small SF is combined with a smaller BW, or when a higher SF is combined with a larger BW.

### B. Experiment 2: Identification of Two Angles of Arrival under interference between Two Transmitters

In the second experiment, we aim to validate our contribution for the identification of two AoA received simultaneously at the receiver. The proposed method consists in using Autocorrelation function described in Section III. For this purpose, two LoRa RFM95 transceivers are configured to transmit simultaneously on the same spreading factor (SF = 7) and channel bandwidth (125 kHz), the same packet. Both transmitters send data at a carrier frequency of 868 MHz and a transmit power of +14 dBm. The two transmitters are placed at 45 degrees and 135 degrees from the receiver, respectively.

On the USRP B210 side, the sampling frequency is equal to 2 MHz, and the FFT length is equal to 2048 bins. The complete implementation of the Autocorrelation function with GNU Radio is illustrated in Figure 3. The Autocorrelation result as shown in Figure 7 consists of a maximum peak at the lag=0, and a few number of sub-peaks around the lag=0 which reveals two different periodic signals. Thanks to the LoRa up Chirp modulation, it is possible to distinguish the two transmissions. Our solution is to detect the maximum peak frequency and the sub-peaks frequencies and measuring the AoA of each detection. The result of this measurement is

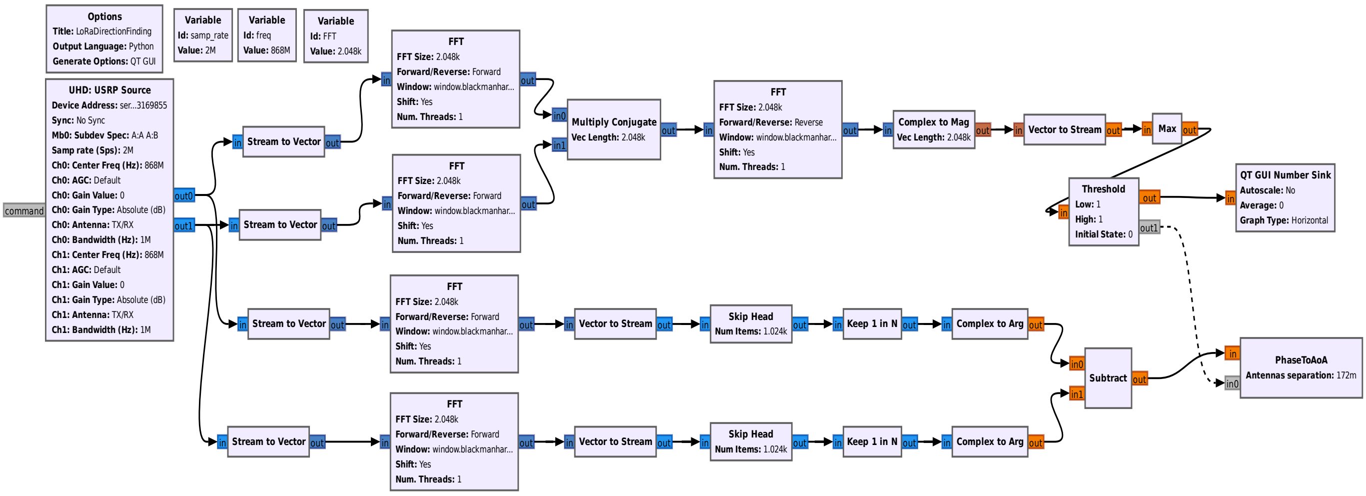

Fig. 3. USRP B210 direction finding system using Autocorrelation - GNU Radio Flowgraph

illustrated in Figure 8. Figure 8 shows the values of the AoA of two simultaneous receptions (45 degrees and 135 degrees). The x-axis represents the values of 25 real AoA. The 25 real AoA correspond to the measured angles of 25 detection peaks, including a maximum peak frequency at the lag=0 and 24 sub-peaks frequencies around the lag=0. We can clearly notice from Figure 8, that our algorithm can measure the AoA of the two simultaneous reception.

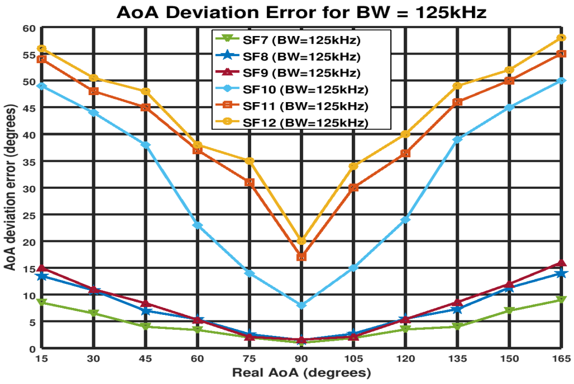

Fig. 4. AoA accuracy for BW = 125 kHz

## V. Conclusion

We presented the performance evaluation of our LoRa Angle of Arrival (AoA) direction finding system in an indoor environment using a Software Defined Radio (SDR) receiver. The measurements show that the best AoA accuracy is achieved when a smaller Spreading Factor (SF) is combined with a smaller Channel Bandwidth (BW) or when a higher Spreading Factor (SF) is combined with a larger Channel Bandwidth (BW). In addition, we provide an Autocorrelation function for measuring the AoA of two simultaneous LoRa receptions at the SDR receiver. Our Autocorrelation-based direction finding approach shows that is possible to detect and measure the AoA of two LoRa nodes located at different locations. We demonstrate that our solution is scalable even with a large number of connected objects that will sometimes generate interference, but our two-antenna SDR/software will be able to measure the AoA of each simultaneous signal.

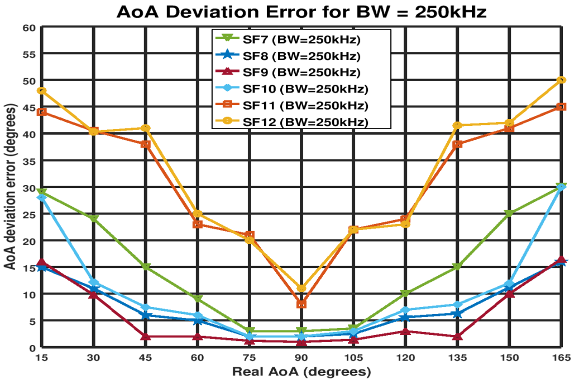

Fig. 5. AoA accuracy for BW = 250 kHz

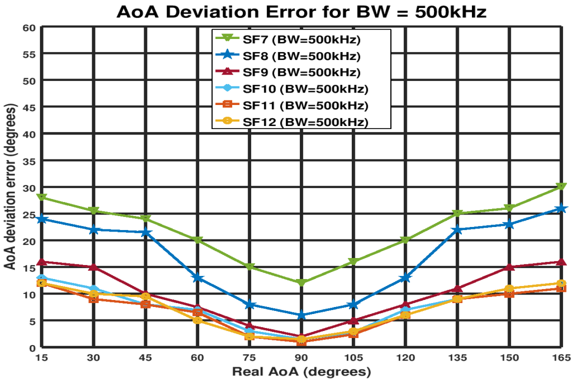

Fig. 6. AoA accuracy for BW = 500 kHz

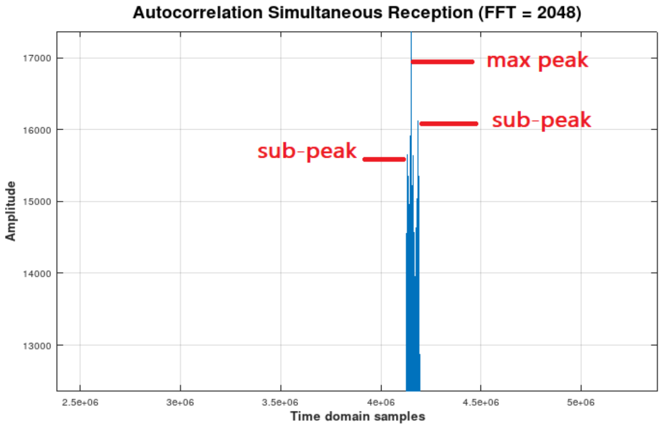

Fig. 7. Autocorrelation peaks detection

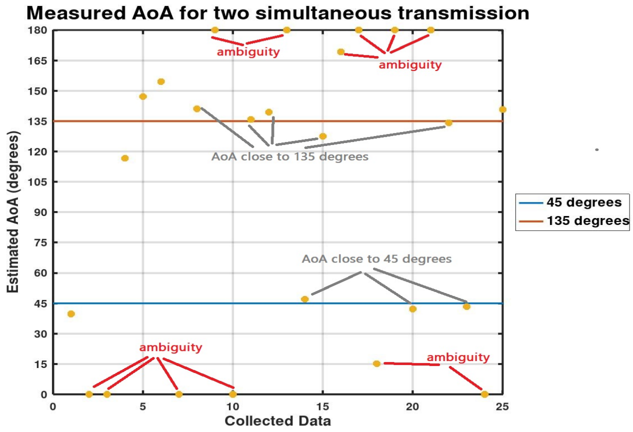

Fig. 8. AoA for two simultaneous receptions

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