Application Note: Telink Position Solution Introduction

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Brief:

This document is the brief introduction for Telink Position Solution.

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Revision History

Version	Major Changes	Date	Author
1.0.0	Initial release	2019/5	HHL,YY,JF,TJB
1.1.0	Updated Section 3	2019/8	HHL,YY,JF,TJB
1.2.0	1. Updated Section 4.3.1 2. Updated Section 4.3.3	2019/9	YY,JF
1.3.0	1. Updated wording 2.Updataed Section 4	2019/10	HHL, YY
1.4.0	1. Update Section 3	2020/4	HHL
1.5.0	1. Updated RSSI 2. Updated ANT switch sequence	2020/4	YY,BY
1.6.0	1. update reference design 3	2020/5	HHL
1.7.0	1. update for 8278 chips	2020/7	HHL

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1 AOA/AOD

Telink Position Solution supports AOD/AOD features defined in Core 5.1. Client device is hereinafter referred to as “the LE radio that we want to get direction information”. Server device is hereinafter referred to as “the LE radio that set as the basepoint of the direction information”. Client device can get its direction information for a server device though AOA/AOD method. Using direction information from several server devices and profile-level information giving their locations, a client radio can calculate its own position.

Telink position Solution can provide estimated angle by its embedded MCU, provide 3 reference designs of antenna array, including PCB antenna.

1.1 Angle of Arrival (AOA) Method

Client device can make its angle of arrival (AoA) information available to server device by transmitting direction finding enabled packets using a single antenna.

Server device, consisting of an RF switch and antenna array, switches antennae while receiving those packets and captures IQ samples. The IQ samples can be used to calculate the phase difference in the radio signal received using different elements of the antenna array, which in turn can be used to estimate angle.

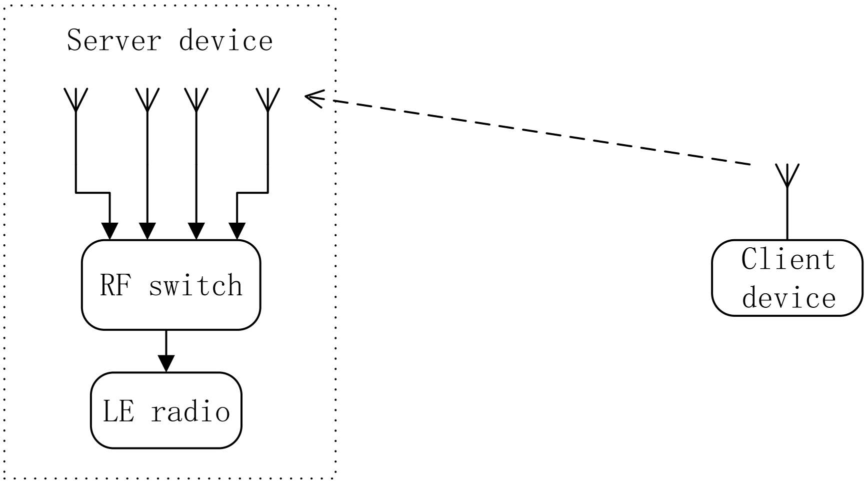

Figure 1-1 Angle of Arrival Method

1.2 Angle of Departure (AOD) Method

Client device, consisting of an RF switch and antenna array, can make its angle of departure (AoD) detectable by transmitting direction finding enabled packets, switching antennae during transmission.

Server device receives those packets and captures IQ samples. The IQ samples can be used to calculate the phase difference in the radio signal received using different elements of the antenna array, which in turn can be used to estimate angle.

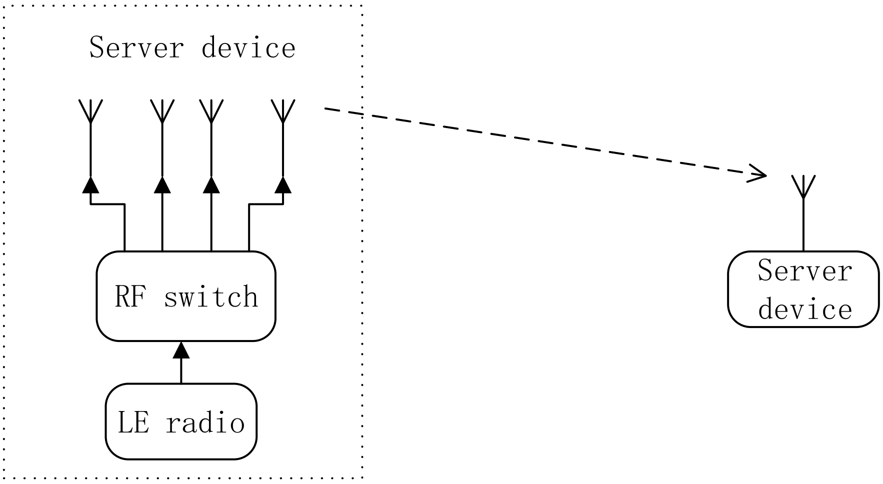

Figure 1-2 Angle of Departure Method

2 Packet Format

LSB MSB

Preamble (1 or 2 octets)	Access-Address (4 octets)	PDU (2-258 octets)	CRC (3 octets)	Constant Tone Extension (16 to 160 µs)

Figure 2-1 Packet Format

Telink Position Solution supports packet format specified for AOA and AOD feature: consisting of Preamble, Access-Address, PDU, CRC (Cyclic Redundancy Check) and Constant Tone Extension. Header in PDU contains controlling information of AOA AOD.

2.1 Constant Tone Extension

Constant Tone Extension is specified for AOA AOD feature. The Constant Tone Extension has a variable length; it is at least 16 µs and not greater than 160 µs.

The first 4 µs of the Constant Tone Extension are termed as the guard period and the next 8 µs are termed as the reference period. After the reference period, the constant Tone Extension consists of a sequence of alternating switch slots and sample slots, each either 1 µs or 2 µs long as specified by the Host. The structure of the Constant Tone Extension is shown in Figure 2-2 Constant Tone Extension Structure.

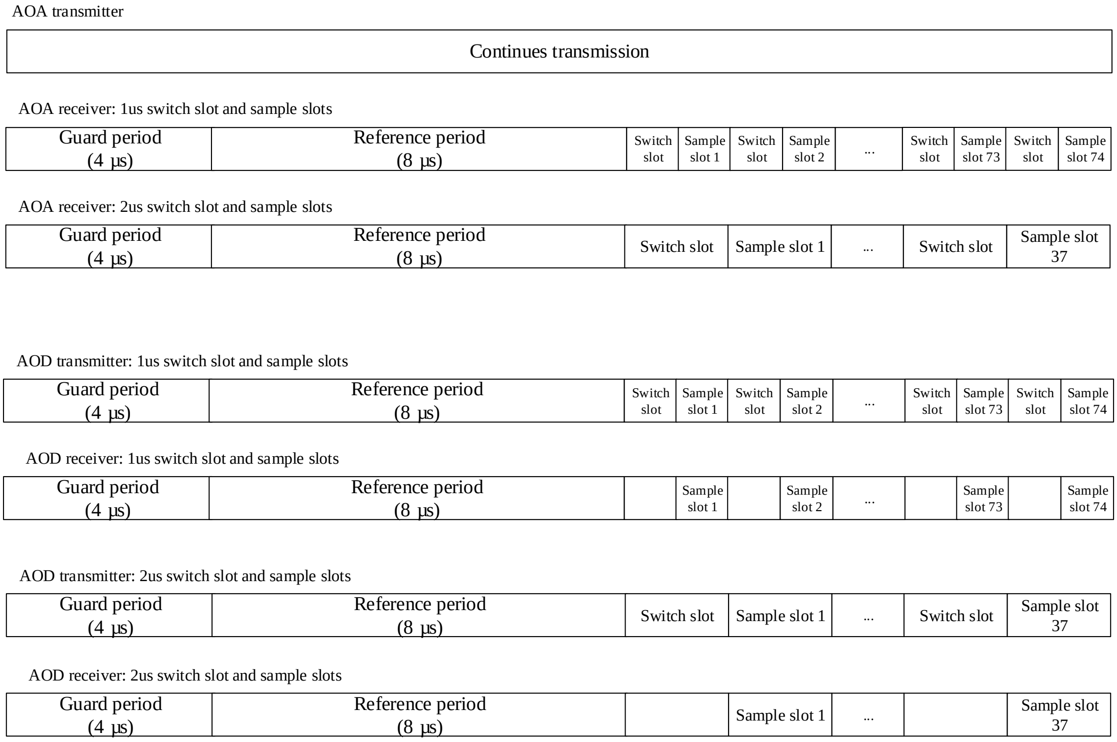

Figure 2-2 Constant Tone Extension Structure

2.2 Antenna Switch

The device switches between the antennae either while receiving the AoA Constant Tone Extension or while transmitting the AoD Constant Tone Extension. The switching takes place during time periods called switch slots. The first 4 µs of the Constant Tone Extension are termed as the guard period and the next 8 µs are termed as the reference period. The receiving Link Layer captures IQ samples during the reference period and during time periods are called sample slots.

The first antenna in the pattern will be used during the reference period. The second antenna in the pattern will be used during the first sample slot, the third antenna during the second sample slot, and so on. The same antenna ID may appear more than once in the pattern. The antenna in use will only be changed during the guard period and switch slots.

2.3 IQ Sampling

When receiving a packet that contains an AoD Constant Tone Extension, the receiver does not need to switch antennae. When receiving a packet that contains an AoA Constant Tone Extension, the receiver performs antenna switching at the rate and follows the switching pattern configured by the Host. In both cases, the receiver takes an IQ sample each microsecond during the reference period and an IQ sample each sample slot (thus there will be 8 reference IQ samples, 1 to 37 IQ samples with 2 µs slots, and 2 to 74 IQ samples with 1 µs slots, meaning 9 to 82 samples in total). The Controller reports the IQ samples to the Host. The receiver samples the entire Constant Tone Extension, irrespective of length, unless it will conflict with other activities.

2.4 RSSI

The receiver measure the RSSI of received packets on the antenna used for receiving the body of the packet (in both cases excluding any Constant Tone Extension).

3 Cable Test

We tested chip 8278 according to spec “RF-PHY.TS.5.1.1”. 8278 passes all AOA/AOD test cases. Here are some details about these test cases.

3.1 Antenna switching integrity

Chip 8278 implements 3 GPIO ports to control PA switch. The switch pattern is configurable by software. 8278 supports up to 8 antennas, 16 non-cycle switches.

3.2 IQ Samples Dynamic Range

In order to implement high order algorithm such as MUSIC, the IQ samples shall show different amplitude corresponding to the received signal strength. The test case in Spec. is transmit -52,-49,-57 and -62dBm signal to Antenna 1, 2, 3 and 4. The Spec. requires MEAN ANT4 < MEAN ANT3 < MEAN ANT 1 < MEAN ANT 2. ‘MEAN ANT n’ is IQ samples amplitude mean value of antenna n.

Chip 8278 outputs IQ samples with 8 bit precision. Figure 3-1 shows the mean and STD. value of IQ sample from different ports sample by sample, normalized by the reference signal. The resolution of amplitude is less than 1dB.

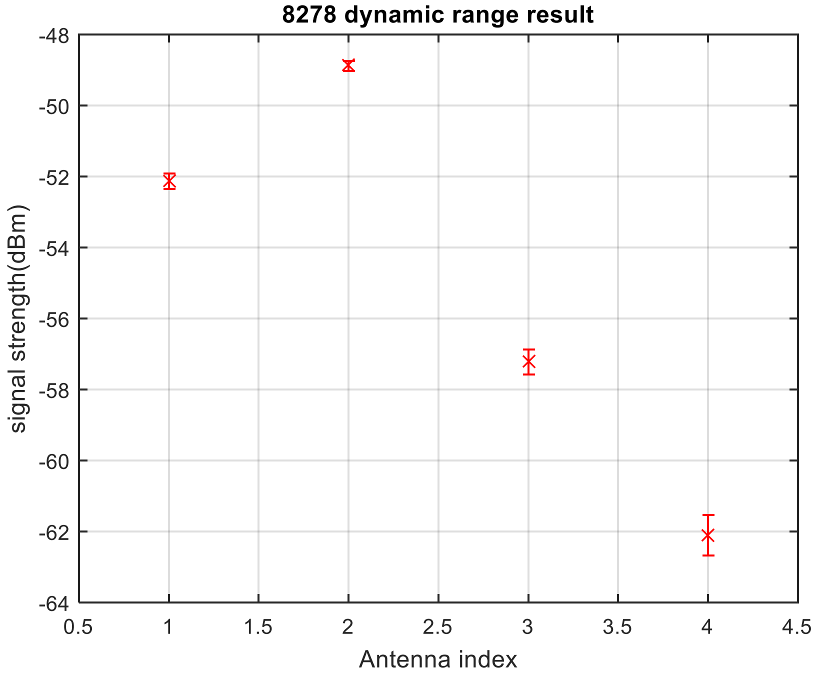

Figure 3-1 dynamic range result

3.2 IQ Samples Coherency

In order to calculate phase difference of signal from different antennas to derive angle, the phase of same antenna at different time shall be coherent, and the phase difference from different antennas at different time shall be coherent. See section 5.2 of Core 5.1 for requirement details.

Use power split to transmit signal to 4 ports of chip 8278, all packet attached with 160us CW, calibrated cable difference and power split difference, calibrated initial phase difference with reference signal. The spec requires phase variation (v-MRP) shall less than 0.52 for same antenna, and phase variation (MRPD) shall less than 1.125 between different antennas. The STD. value of phase from different ports across packets collected by 8278 are below 0.025 rad. Figure 3-2 is the phase of IQ samples from 4 ports.

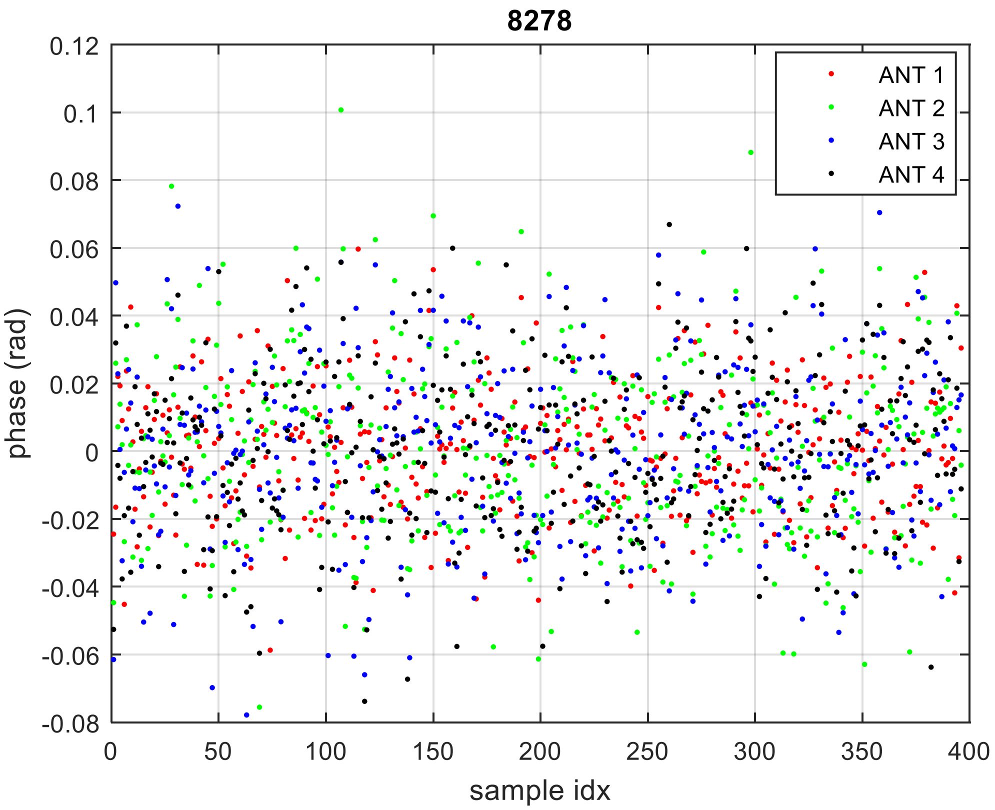

Figure 3-2 phase of different antennas

4 Hardware

There are 3 selections of reference design, reference design 1 for board on the wall and reference design 2 for board on the ceiling, reference design 3 uses PCB antennas as replacement of external antennas in reference design 2. The reference board design 1 is shown in Figure 4- 1. The Figure 4-2 shows the illustration of angle. The X axis points to 0 degree while the Y axis points to 90 degree. The reference board 2 design is show in Figure 4-3 and the illustration of angle see Figure 4-4. Set RF8-RF1 as x axis pointing to 0 degree while taking RF5-RF4 as y axis pointing to 90 degree. The reference board 3 design is show in Figure 4-5 and the illustration of angle is the same as reference board 2.

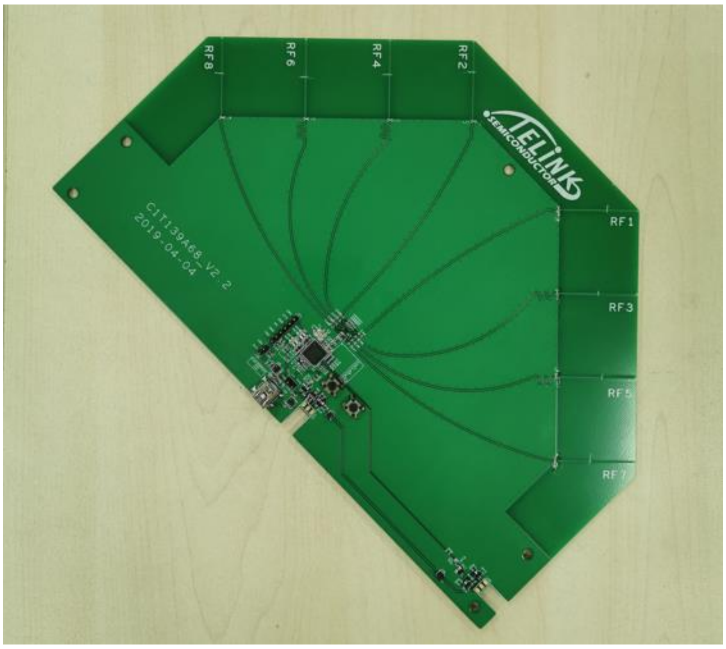

Figure 4-1 Reference Board Design 1

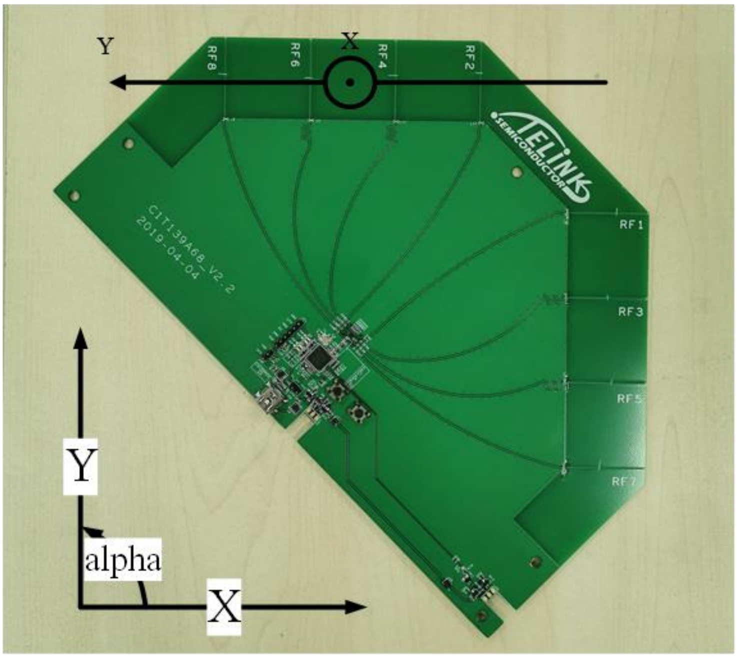

Figure 4-2 Illustration of Angle for Reference Board Design 1

Figure 4-3 Reference Board Design 2

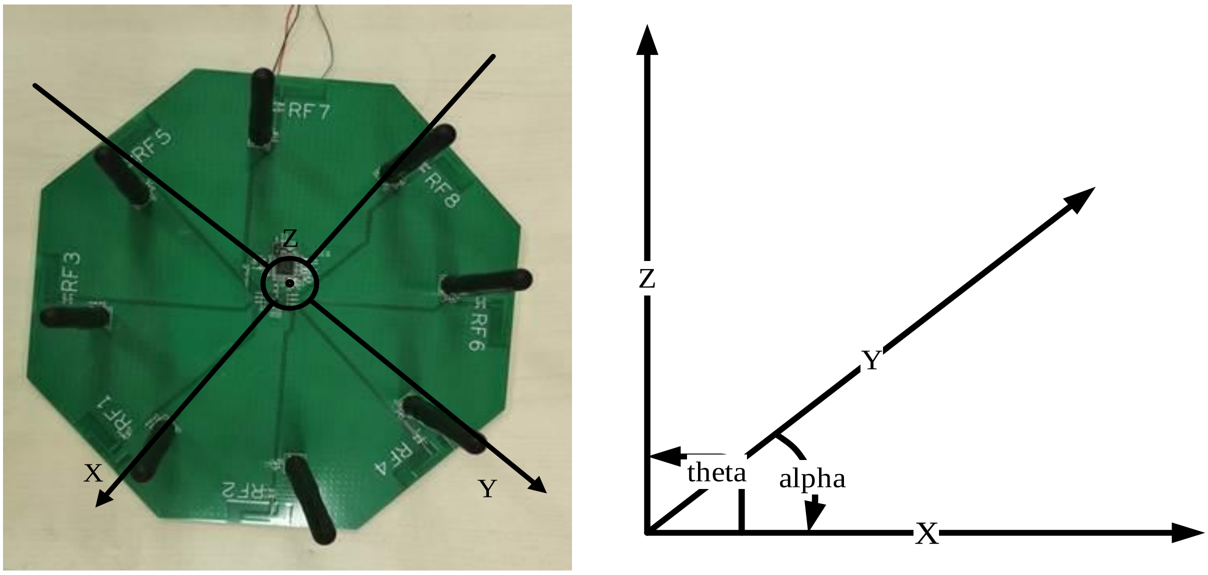

Figure 4-4 Illustration of Angle for Reference Board Design 2

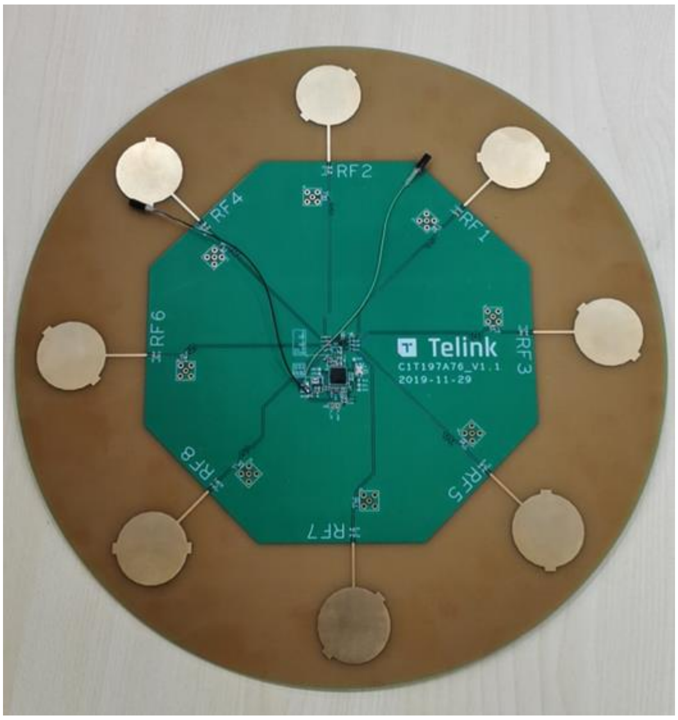

Figure 4-5 Reference Board Design 3

5 Firmware and API

For ease of use, we can provide calculated API and raw data. User can choose to call API to get input angle directly (calculated by our inner arithmetic) or get raw data to do other arithmetic. We also provide a Demo to help user realize AOA or AOD test.

5.1 API and Raw Data

aoa.c and aoa.h in driver include all necessary parts for aoa signal, thus user can add these two files to the project. Both angle-calculated API and raw data is provided in aoa.c.

User can call function get_input_angle (unsigned char *ptr_packet) or get_input_angle_for_polygon(unsigned char *ptr_packet) to get input angle as below:

```
char angle_value;
angle_value = get_input_angle (&rx_packet[0]);              //if use triangle board
angle_value = get_input_angle_for_polygon(&rx_packet[0]);   //if use polygon board
```

Then user can get a char parameter of angle and rx_packet in it should be received as buffer.

User can call function get_raw_data (unsigned char *data_table, unsigned char *ptr_packet, unsigned int number) as below to get raw data:

```
unsigned char raw_data[90];
get_raw_data(&raw_data[0],&rx_packet[0],90);
```

Then raw data is copied to raw_data[0],raw_data[1], raw_data[2] … raw_data[89], which stand real part of IQ0, image part of IQ0, real part of IQ1 …image part of IQ44. User need an unsigned char table which has at least 90 parameters because there are 45 sample data and each data includes real part and image part.

5.2 Demo

Demo of AOA transmitter and receiver is provided for reference. Download demo program to referenced hardware to realize transmitter continually sending data while receiver outputting angle through USB.

5.2.1 Demo Parameter

Variable parameters in drivers/8258/aoa.h:

```
#define RF_REAL_FREQ      2450                //set TX/RX frequency.here is 2450MHz
```

It defines transmit frequency.

Variable parameters in app.c:

```
/***************IO pin define*************************/
#define LED2                        GPIO_PA3
#define LED3                        GPIO_PA4
#define LED4                        GPIO_PB0
#define LED5                        GPIO_PB1
#define SW2                         GPIO_PC1
#define SW3                         GPIO_PC0

#define V1                              GPIO_PC6
#define V2                              GPIO_PC5
#define V3                              GPIO_PC7
```

It defines some GPIO as multiplex function to switch antenna and to debug.

```
/***************Choose TX or RX*************************/
#define TX            1
#define RX            2

#define RF_TRX_MODE            RX
```

It defines board as transmitter or receiver.

```
/***************Choose AOA or AOD**********************/
#define RF_AOA_MODE            1
#define RF_AOD_MODE            2

#define AOA_OR_AOD_MODE            RF_AOD_MODE
```

It defines board as AOA or AOD.

```
/***************Choose board and Ant**********************
[Brief Description]：
RF_triangle_1357: Using triangle board with ant 1.3.5.7,API output xy angle.            *
RF_triangle_2468: Using triangle board with ant 2.4.6.8,API output xy angle.            *
RF_eight_all_open:Using polygon board with all 8 ants,    API output xy angle.          *
*****************************************************/
#define RF_triangle_1357              1
#define RF_triangle_2468              2
#define RF_eight_all_open             3

#define RX_RF_ARRAY                       RF_eight_all_open
```

It defines board antenna.

```
/***************************TX/RX frequency**********************
[Brief Description]：
RF Frequency,In order to change frequency,please change RF_REAL_FREQ in drivers/8258/aoa.h
*************************************************************/
#define RF_FREQ                    RF_REAL_FREQ-2400   // TX/RX frequency
```

RF frequency should be verified in aoa.h,by changing RF_REAL_FREQ ,but not here.

```
/***************TX Power***************************/
#define RF_POWER                RF_POWER_P10p46dBm
```

It defines TX power , RF_POWER_P10p46dBm here is 10dbm.

```
/**************Connect access code*****************/
#define ACCESS_CODE                 0xfcaab2c1
```

It defines ACCESS_CODE.

```
/*******TX interval,16000000 equal 1 second********/
#define TX_INTERVAL                 400000
```

It defines transmition frequency. 16000000 means send packet per second.

5.2.2 User Guide

Software:

Telink IDE 1.3

Telink Burning and Debugging Tool (BDT)

Progress:

a. Change RF_TRX_MODE in app.c to TX, then use Telink IDE 1.3 build project to generate .\8258_AOA_Demo\ 8258_AOA_Demo.bin.
b. Connect single antenna board by usb or SW, download TX program.
c. Change RF_TRX_MODE in app.c to RX, then rebuild project to generate a new .\8258_AOA_Demo\ 8258_AOA_Demo.bin.
d. Connect multi-antenna board by usb or SW, download RX program.
e. Use usb connect multi-antenna RX board to supply power and communicate, then change BDT to usb log mode by View -> usb log as shown in Figure 4-0-1.

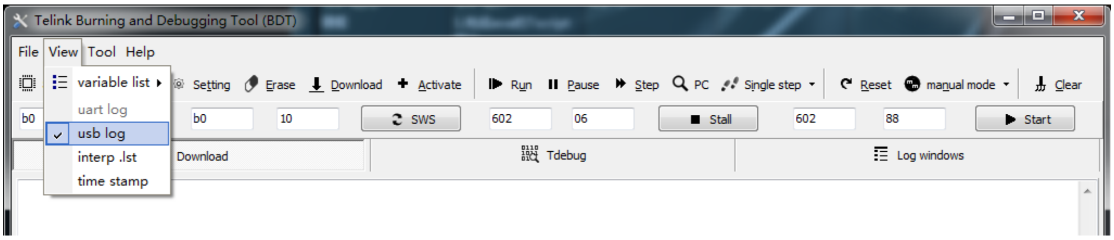

Figure 5-1 Change BDT to usb log mode

f. Open Log windows. Then user can see input angle once receive AOA packets. Make sure print it out if use print function in program, or program will come out unknown mistake.

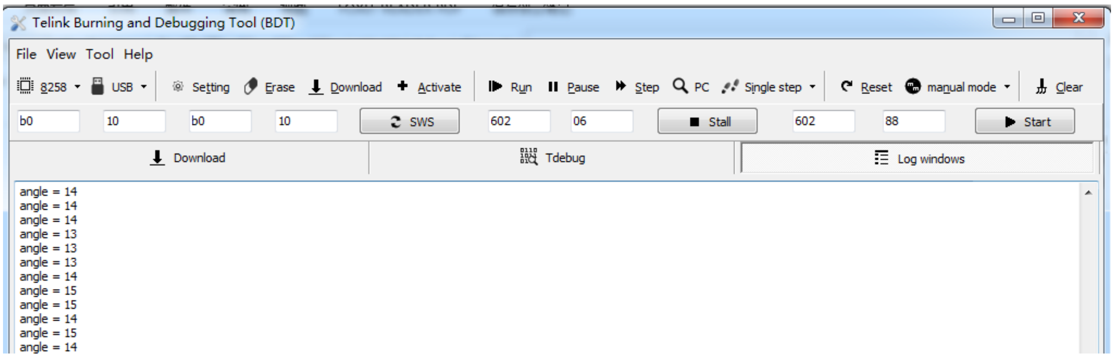

Figure 5-2 Enter Log Windows Interface

g. If user want to use UART to print , there are some definition need to be changed in drivers/8258/ printf.h. Change DEBUG_BUS as DEBUG_IO, set PRINT_BAUD_RATE and DEBUG_INFO_TX_PIN , then GPIO will emulate UART and print out message with bandrate up to 1000000.

```
#define  DEBUG_IO        1
#define  DEBUG_USB       2

#define  DEBUG_BUS       DEBUG_IO

#if (DEBUG_BUS==DEBUG_USB)
/**
 * @brief       This function serves to printf string by USB.
 * @param[in]  *format  - format string need to print
 * @param[in]  ...      - variable number of data
 * @return      none.
 */
void usb_printf(const char *format, ...);
#define  printf     usb_printf
#elif (DEBUG_BUS==DEBUG_IO)
#define PRINT_BAUD_RATE                     1000000      //1M baud rate,
#define DEBUG_INFO_TX_PIN                   GPIO_PB4
```

Figure 5-3 Enter Log Windows Interface

5.3 Telink Solution Release

Telink AOA/AOD solution is provided besides Demo. It is used to show AOA/AOD result and collect raw date with referred hardware. The solution includes bin file and debug tool - Tscript. The interface is as follows.

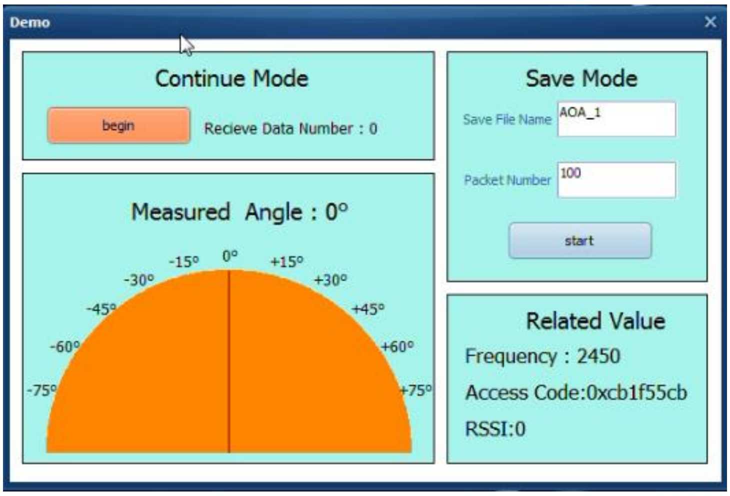

Figure 5-4 AOA/AOD Tool Interface 1

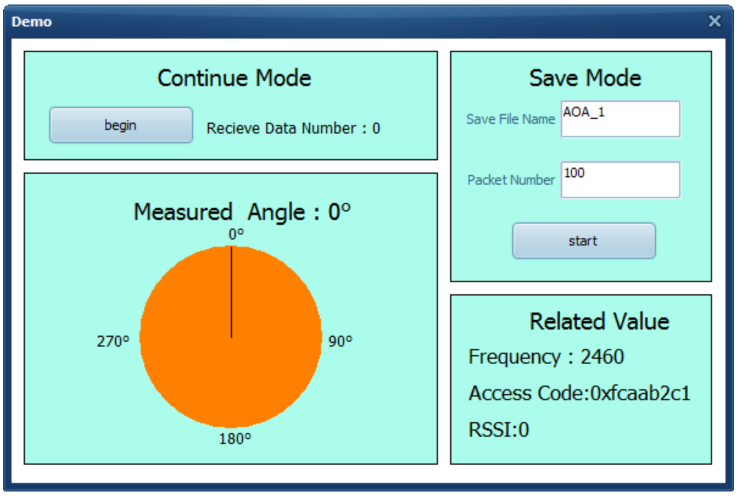

Figure 5-5 AOA/AOD Tool Interface 2

5.3.1 How to use

Step1: download specified bin file to the chip. Then connect board to computer with USB or SWS to power on and communicate. Connect polygon board to the computer through SWS especially when testing AOA with polygon board since there is no USB on the board.

Step2: open Tscript.exe, double click RF_AutoTest_Kite\AoA.lua as follows. Then interface is shown as the below Figure 4-0-2. Choose AoA_Sniffer_draw_by_sws_V1.4.lua or AoA_Sniffer_draw_by_usb_V1.4.lua according to the different connection mode between computer and board.

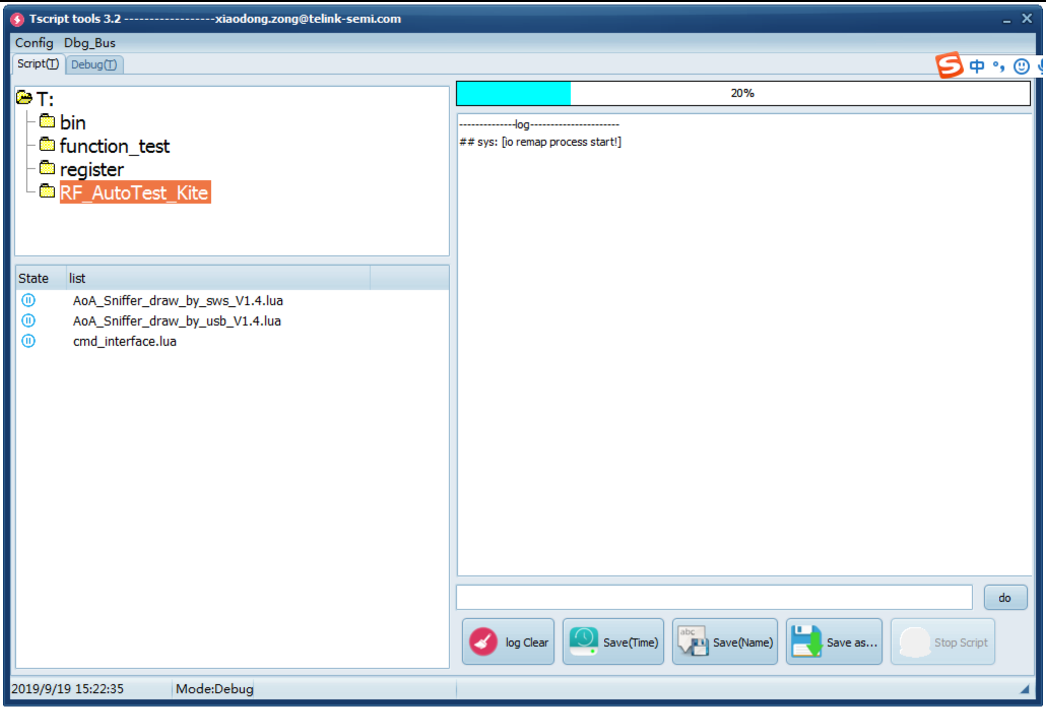

Figure 5-6 Tscript Interface

Step3: choose continue mode or save mode to start, these two modes will be introduced in Section 5.3.2 Continue Mode and 5.3.3 Save Mode.

5.3.2 Continue Mode

Continue mode is designed to show calculation angle result of inner API. The receive board will continually receive data and calculate angle once receiving AOA/AOD data. After average angle data of fixed window, the result will show in interface and the pointer in table will point to corresponding position. In addition, received packet number and Frequency/Access Code/RSSI will show in interface as follows.

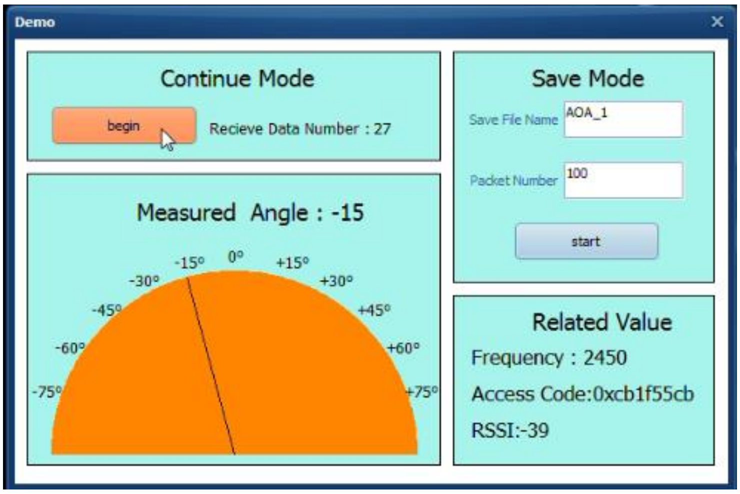

Figure 5-7 Continue Mode

5.3.3 Save Mode

Save mode is designed to collect AOA/AOD raw data. Click start button after inputting Save File Name and Packet Number. Then user can get Save_File_Name.txt that includes decimal sampled IQ value and Save_File_Name_backup.txt that includes hexadecimal source receive data. Users can use other algorithms to process these data or do other experiment.

Save_File_Name.txt will include decimal sampled IQ value of n packets, which n is the packet number set by user. Each packet contains 45 groups including 90 numbers corresponding to 45 sample point messages. Every group contains two numbers, the first number indicates the real part and the second number represents the virtual part of sample point. Figure 4-7 below indicates the slot chart of AoA receiver. In reference period, Chip will sample message every 1us, obtaining totally 8 groups of number. After that, Chip will sample message in each sample slot, totally 37 groups of number. So each packet includes 37 + 8 = 45 groups for total of 90 numbers.

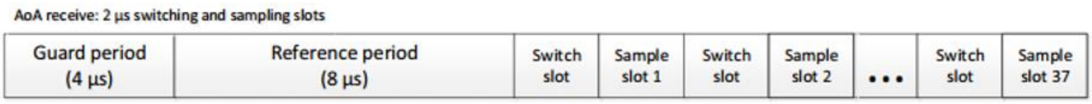

Figure 5-8 AoA Receiver Slot Chart

For example, Figure 4-8 indicates one packet of AOA testing containing totally 90 numbers mentioned before. The first line lists 16 numbers sampled in reference period and the sample results are:

-97 – 18i , 2 – 86i , 88 – 14i , 2 + 88i , -90 + 23i , -34 – 97i , 79 – 26i , 41 + 90i

User can also get other 37 sample slot data by this way.

```
-97 -18 2 -86 88 -14 2 88 -90 23 -34 -97 79 -26 41 90
64 63 74 78 95 47 94 27 92 -1 94 1 72 -38 83 -62
106 -119 47 -69 -6 -91 9 -102 -24 -74 -37 -68 -100 -127 -66 -58
-89 -38 -103 -12 -98 22 -74 17 -75 39 -46 75 -49 87 -17 68
19 100 20 82 42 81 116 87 70 38 75 27 95 -6 89 -1
88 -31 79 -64 93 -114 32 -89 32 -83
RSSI :-80
Input angle :1
```

Figure 5-9 Testing Data

File is located in .\kite_RF_AoA\project\RF_AutoTest_Kite\AutoTest_Report. The default transmission frequency is 2460 and antenna switch sequence is RF2-> RF4-> RF6-> RF8 for triangle board, RF2 as the primary antenna during reference period, and RF1-> RF2-> RF3-> RF4-> RF5-> RF6-> RF7-> RF8for polygon board, RF1 as the primary antenna during reference period.

5.3.4 Packet format

This part will introduce packet format and make an example . Packets formate are as bellows:

Packet Length (4 bytes) *1	Header 0 (1 byte)	Payload Length (1 byte)	AOA/AOD Specied data (1 byte) *2	Payload (n bytes)	Raw Data (90 bytes or 164 bytes) *3	Packet State Message (8 bytes)

*1 This 4 bytes are not included in length

*2 AOA : 0x14
AOD : 0x94

*3 Switch slot 1us : 164 bytes
Switch slot 2us : 90 bytes

Figure 5-10 Receive packet format

To make an example, here is a AOA packet of 2us switch slot received by triangle board(saved by Tscript).If multiple antenna board is triangle board, it can be analysed in following way according to packet format. In save mode of solution that we mentioned before, receiver will call function to calculate angle and rsquare once receiving a AOA/AOD packet , then put it behind rx_packet. Tscript will read total 130 bytes to get them all.

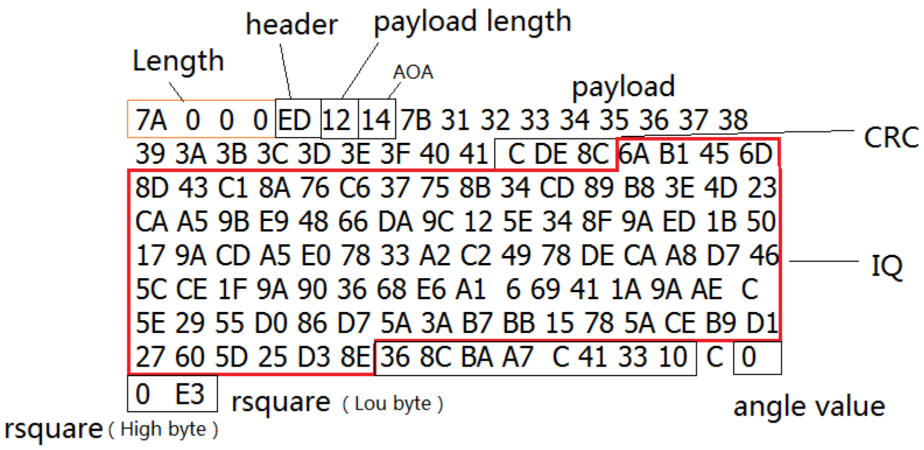

Figure 5-11 Example packet of triangle board

Raw data in rx_packet need to be treated as char variables . So the highest bit is sign bit and lower 7 bits are data bits. They can be transferred to decimal number in standard method. For the example, raw data in example can be converted as Figure 4-12. The antenna switch sequence is RF2-> RF4 -> RF6 -> RF8.

RF2		RF4		RF6		RF8	
Real Par	Imag Par	Real Par	Imag Par	Real Par	Imag Par	Real Par	Imag Part
6A	B1	45	6D	8D	43	C1	8A
76	C6	37	75	8B	34	CD	89
B8	3E	4D	23	CA	A5	9B	E9
48	66	DA	9C	12	5E	34	8F
9A	ED	1B	50	17	9A	CD	A5
E0	78	33	A2	C2	49	78	DE
CA	A8	D7	46	5C	CE	1F	9A
90	36	68	E6	A1	6	69	41
1A	9A	AE	C	5E	29	55	D0
86	D7	5A	3A	B7	BB	15	78
5A	CE	B9	D1	27	60	5D	25
D3	8E						

Convert to

RF2		RF4		RF6		RF8	
Real Par	Imag Par	Real Par	Imag Par	Real Par	Imag Par	Real Par	Imag Part
106	-79	69	109	-115	67	-63	-118
118	-58	55	117	-117	52	-51	-119
-72	62	77	35	-54	-91	-101	-23
72	102	-38	-100	18	94	52	-113
-102	-19	27	80	23	-102	-51	-91
-32	120	51	-94	-62	73	120	-34
-54	-88	-41	70	92	-50	31	-102
-112	54	104	-26	-95	6	105	65
26	-102	-82	12	94	41	85	-48
-122	-41	90	58	-73	-69	21	120
90	-50	-71	-47	39	96	93	37
-45	-114						

Figure 5-12 Example packet of pologon board

To make another example, here is a AOA packet of 2us switch slot received by pylogon board(saved by Tscript), it can be analysed in following way according to packet format. In save mode of solution that we mentioned before, receiver will call function to calculate angle once receiving a AOA/AOD packet , then put it behind rx_ packet. Tscript will read total 130 bytes to get them all.

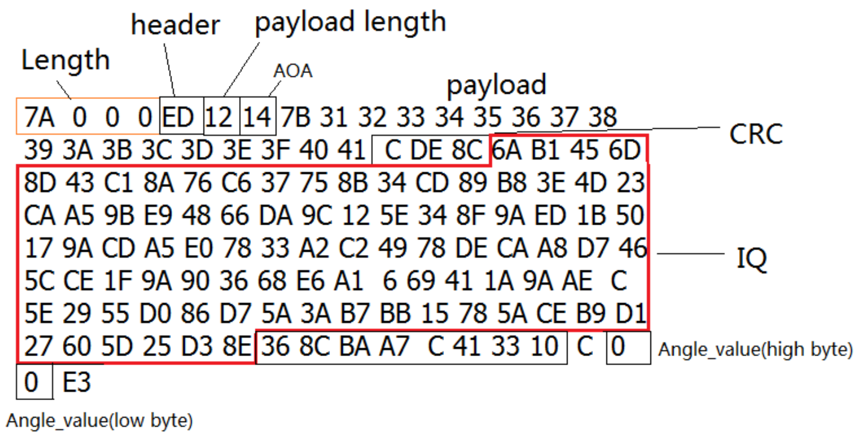

Figure 5-13 Example packet of polygon board

rawdata in examplecan be converted as Figure 4-14. Theantenna switch sequence is RF1-> RF2-> RF3-> RF4-> RF5-> RF6-> RF7-> RF8.

RF1		RF2		RF3		RF4		RF5		RF6		RF7		RF8	
Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part
6A	B1	45	6D	8D	43	C1	8A	76	C6	37	75	8B	34	CD	89
B8	3E	4D	23	CA	A5	9B	E9	48	66	DA	9C	12	5E	34	8F
9A	ED	1B	50	17	9A	CD	A5	E0	78	33	A2	C2	49	78	DE
CA	A8	D7	46	5C	CE	1F	9A	90	36	68	E6	A1	6	69	41
1A	9A	AE	C	5E	29	55	D0	86	D7	5A	3A	B7	BB	15	78
5A	CE	B9	D1	27	60	5D	25	D3	8E						

converted to

RF1		RF2		RF3		RF4		RF5		RF6		RF7		RF8	
Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part	Real Part	Imag Part
106	-79	69	109	-115	67	-63	-118	118	-58	55	117	-117	52	-51	-119
-72	62	77	35	-54	-91	-101	-23	72	102	-38	-100	18	94	52	-113
-102	-19	27	80	23	-102	-51	-91	-32	120	51	-94	-62	73	120	-34
-54	-88	-41	70	92	-50	31	-102	-112	54	104	-26	-95	6	105	65
26	-102	-82	12	94	41	85	-48	-122	-41	90	58	-73	-69	21	120
90	-50	-71	-47	39	96	93	37	-45	-114						

Figure 5-14 Example packet of polygon board

The value of RSSI represents the signal strength of the receive data. We can get the RSSI value from the packet. Use the data which get from packet minus110 (D) is RSSI. For example, the date is 0x33, 0x33 minus 110 is -59. So RSSI is -59.

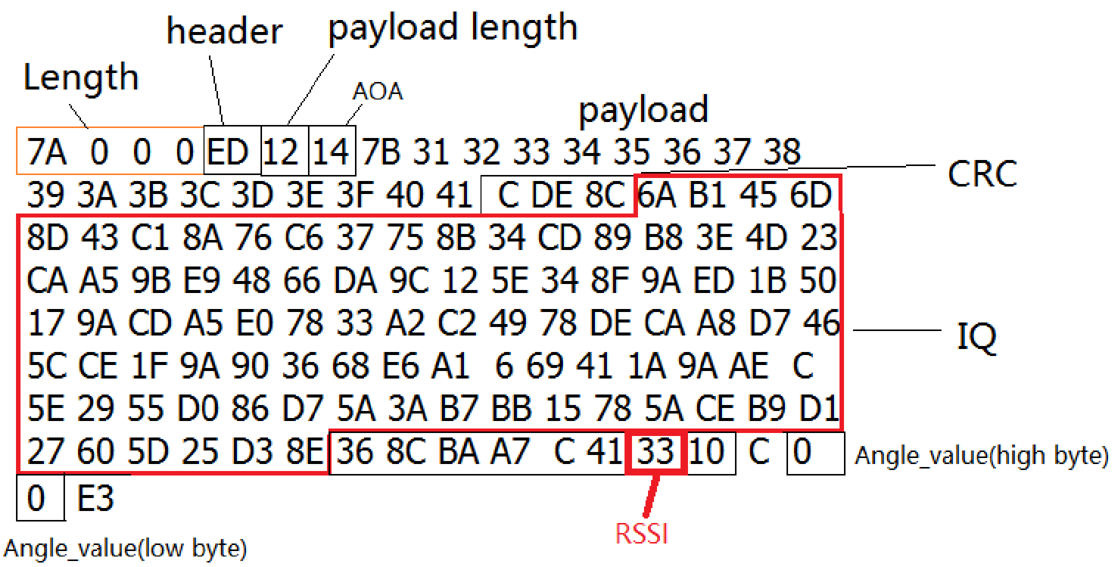

Figure 5-15 Example packet of triangle board(RSSI)

6 Field Test Result

6.1 Field Test Result of Reference Board 1

The indoor test environment is shown in. The multiple antenna side can switch antenna to transmit or receive constant single tone. It is placed 2 meters high from the ground attached to the wall. At the other side, a single antenna BLE modular is placed 5 meters away from the multiple antenna side. It is tested by 5 degrees step. The result is shown in Figure 5-1.

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Figure 6-1 Test Environment for Reference Board 1

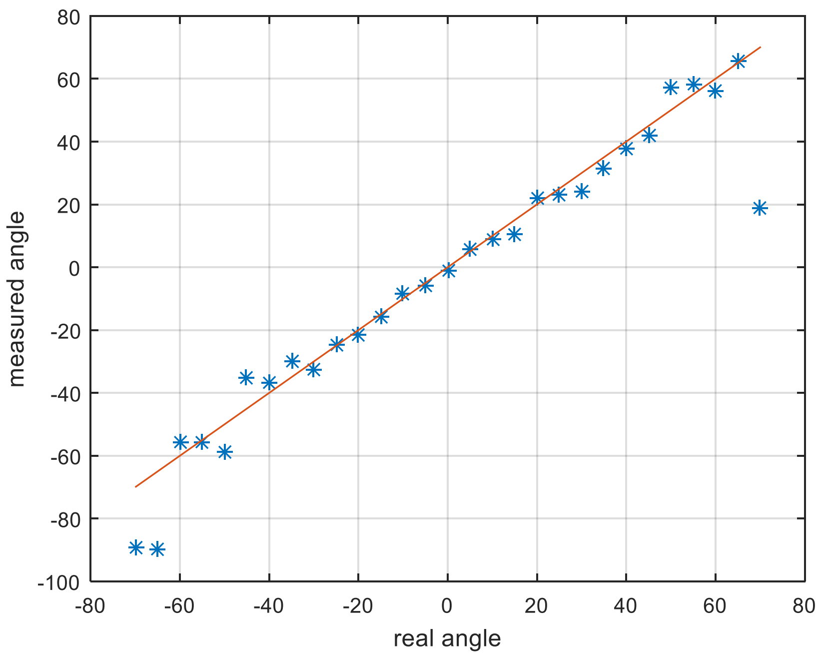

Figure 6-2 5 meters Indoor Test Result

Figure 5-3 is the test result for various scenarios which indicates the mean of absolute value of error versus real angle. The height of reference board 1 is 1 or 2 meters and the height of single antenna BLE module is 1 meter. The distance from wall to single antenna dongle is 0.5, 1, 2, 3 or 5 meters respectively following the below test.

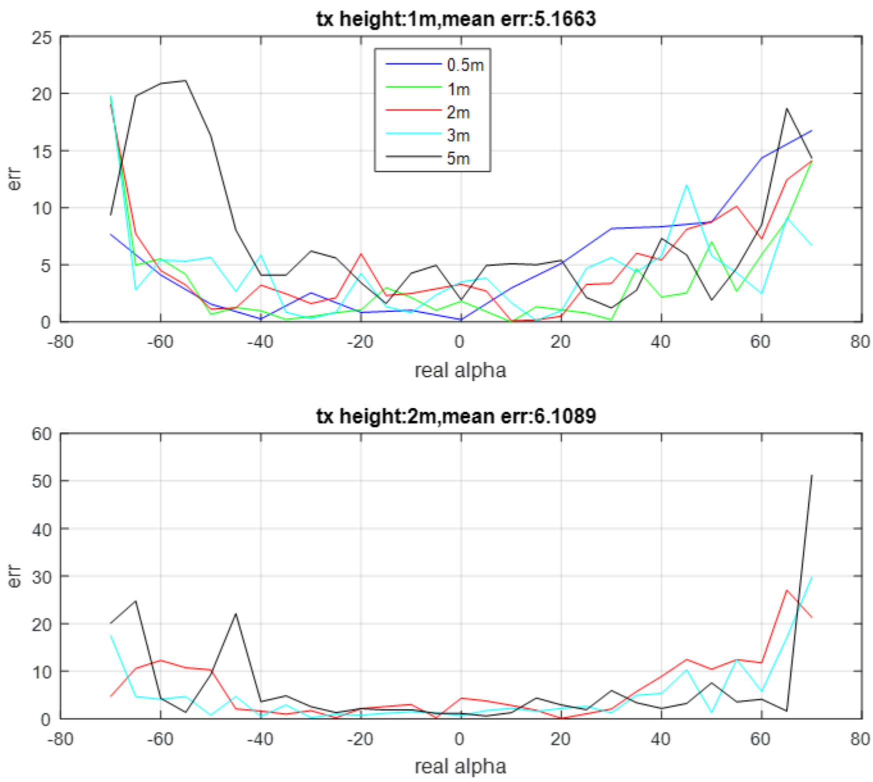

Figure 6-3 Mean of Absolute Value of Error Versus Real Angle

6.2 Field Test Result of Reference Board 2

The indoor test environment is shown in Figure 5-4. The multiple antenna side can switch antenna to transmit or receive constant tone extension. It is hanging on the bracket which is 1.8 meter high. The other side is a single antenna BLE modular, placed on the floor or 0.9 meter high marked as H, 1 or 2 meters far from the bracket marked as D. It is tested by 5 degrees step. The result is shown in Figure 6- and Figure 6-.

Scenario 1: D = 1, H = 0;

Scenario 2: D = 2, H = 0;

Scenario 3: D = 1, H = 0.9;

Scenario 4: D = 2, H = 0.9.

The angle of alpha and theta (Refer to Figure 3-4) is measured simultaneously.

Figure 6-4 Test Environment for Reference Board 2

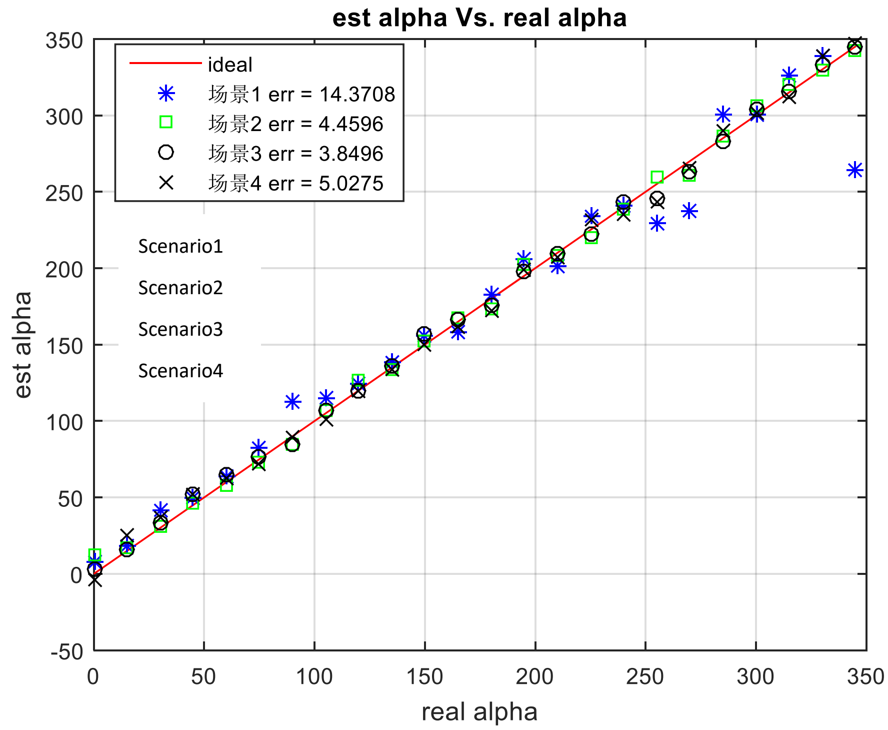

Figure 6-5 Estimation of alpha vs. real alpha

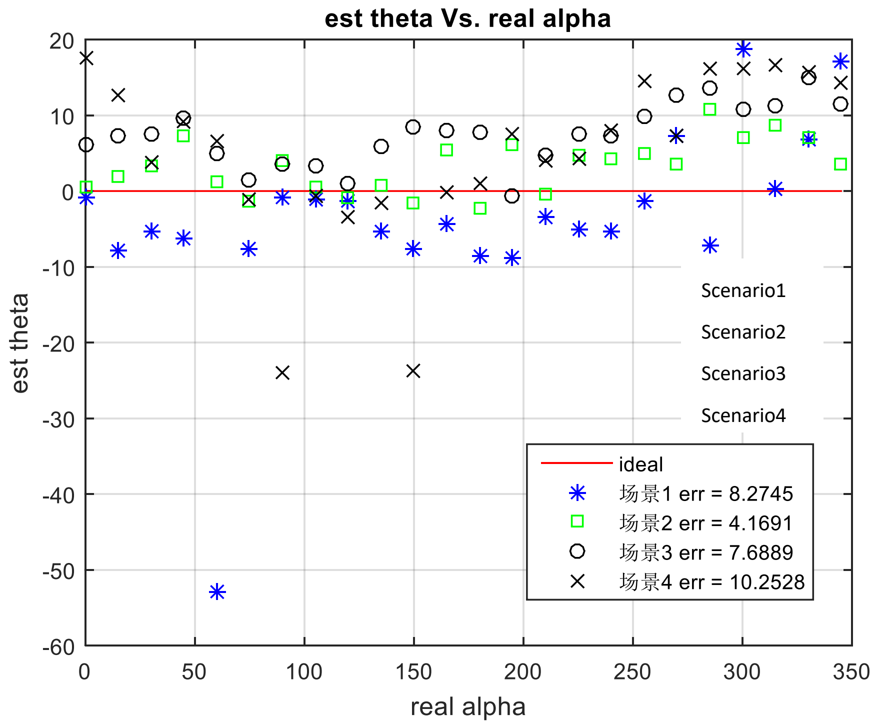

Figure 6-6 Estimation of theta vs. real alpha

6.3 Field Test Result of Reference Board 3

The indoor test environment is shown in Figure 6-7. The multiple antenna side can switch antenna to transmit or receive constant tone extension. It is hanging on the bracket which is 2.5 meter high. The other side is a single antenna BLE modular, placed on the floor or 1.0 meter high marked as H, 1 or 2 meters far from the bracket marked as D. It is tested by 5 degrees step. The result is shown in Figure 6-8 to Figure 6-11.

Scenario 1: D = 1, H = 0;

Scenario 2: D = 2, H = 0;

Scenario 3: D = 3, H = 0;

Scenario 4: D = 1, H = 1;

Scenario 5: D = 2, H = 1;

Scenario 6: D = 3, H = 1;

The angle of alpha and theta (Refer to Figure 3-4) is measured simultaneously.

Figure 6-7 Test Environment for Reference Board 3

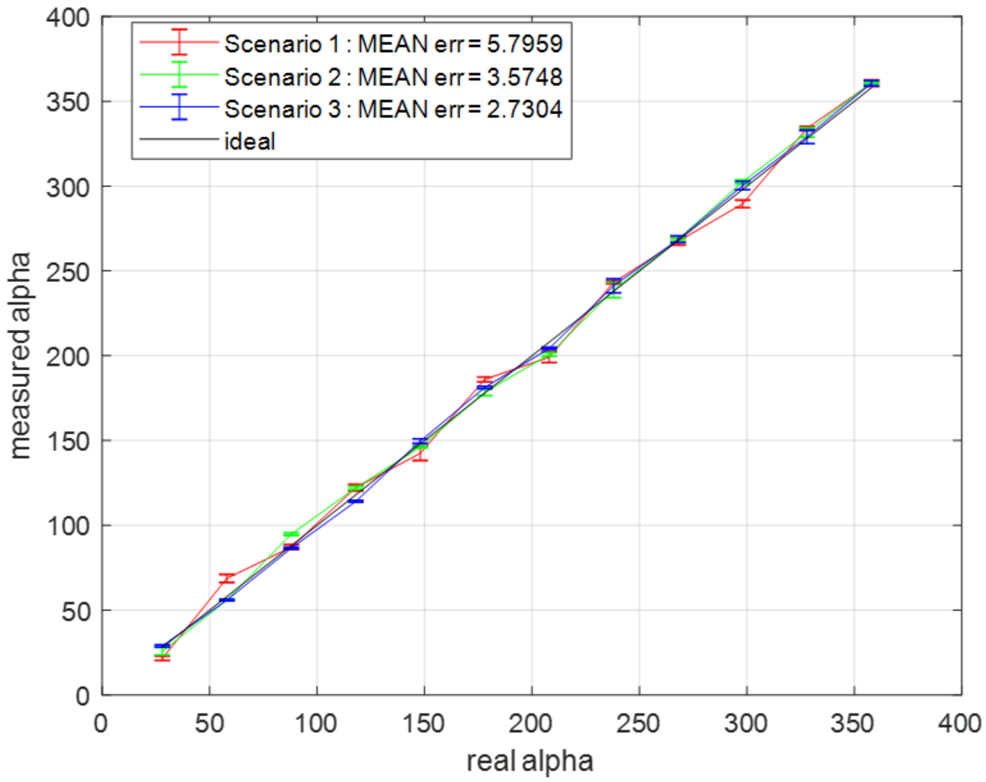

Figure 6-8 Estimation of alpha vs. real alpha

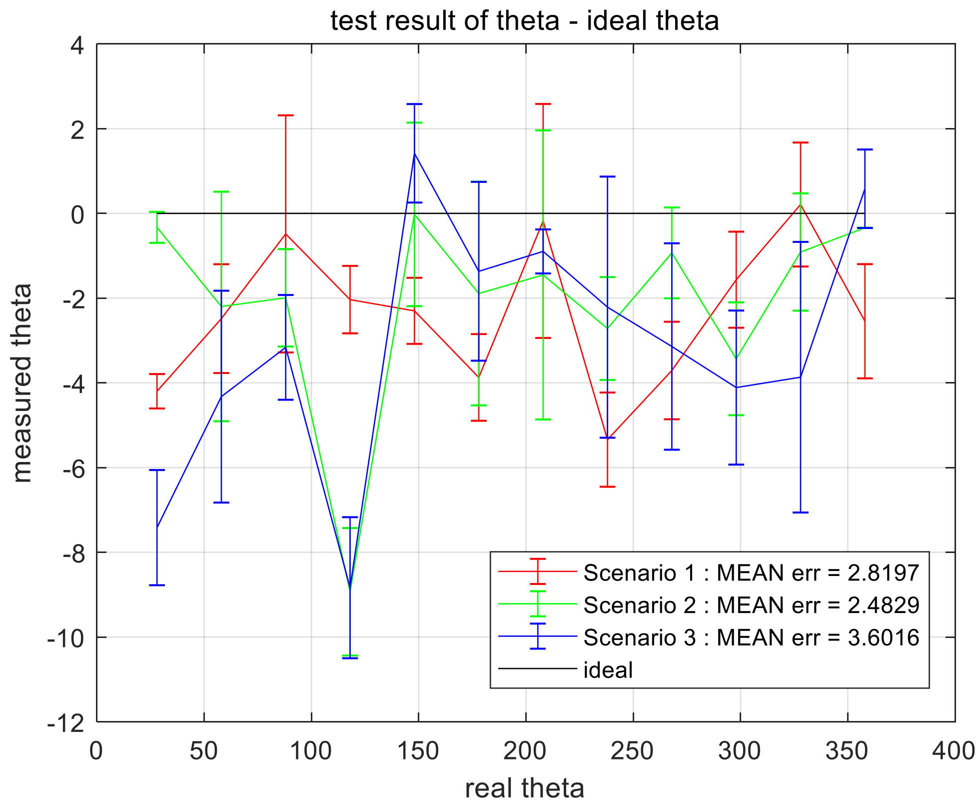

Figure 6-9 Estimation of theta vs. real alpha

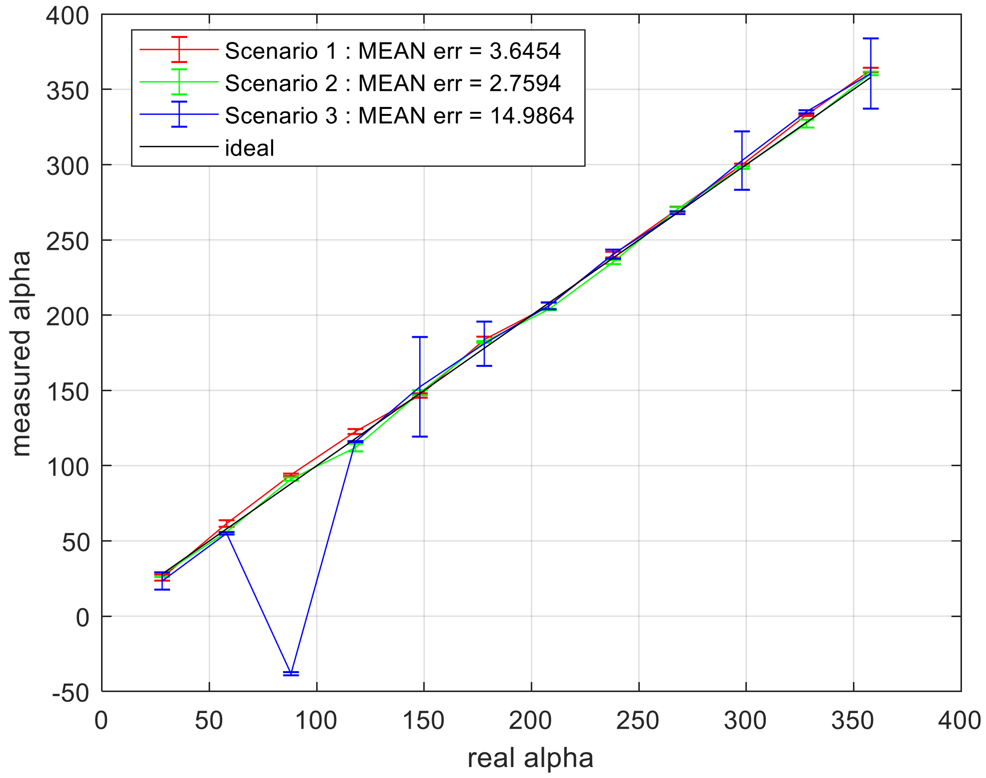

Figure 6-10 Estimation of alpha vs. real alpha

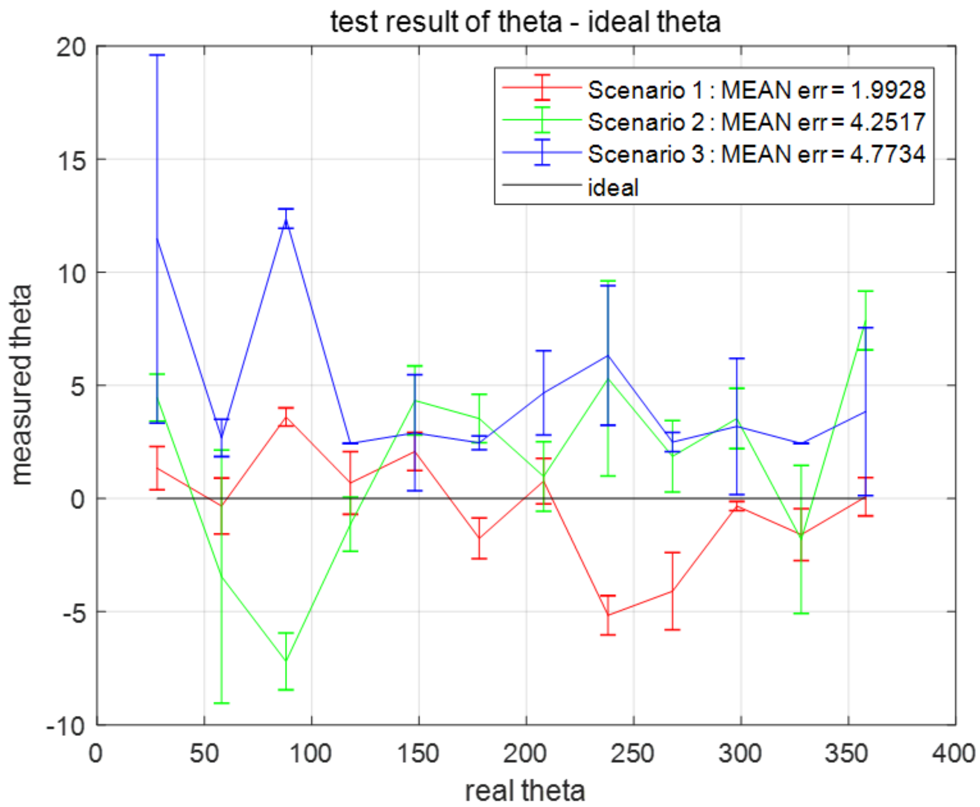

Figure 6-11 Estimation of theta vs. real alpha

7 Schematic for Reference Board

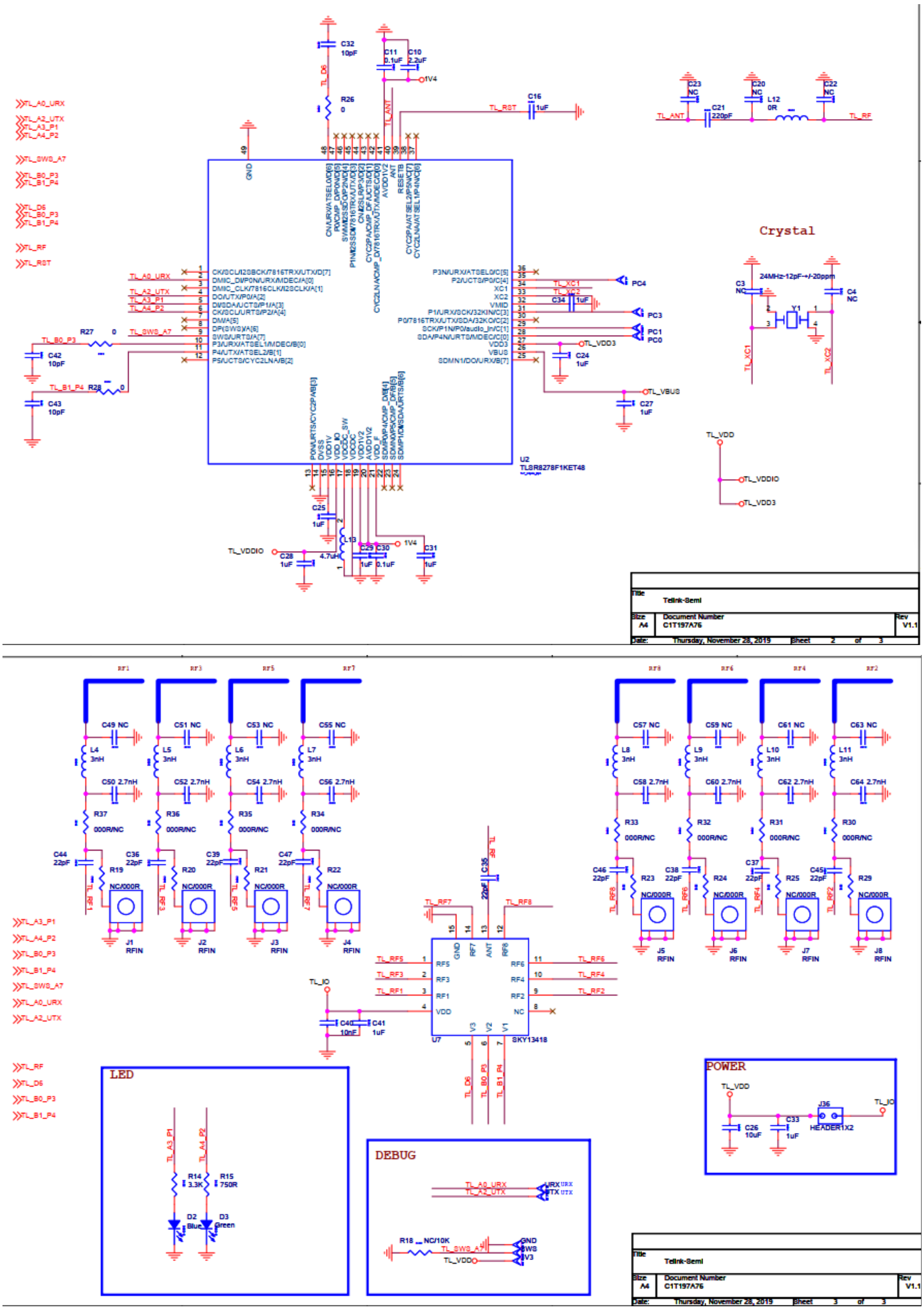

Figure 7-1 Schematic for Reference Board