Horizon 2020 Grant Agreement no: 814523

Tera**h**ertz end-to-end wireless systems supp**o**rting ultra-high data **R**ate applications

ThoR

Deliverable D3.5

Testing report of the 60 GHz TRX modules

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Start date of project: 01-Jul-2018

Date of issue: 22-Apr-2021
Due date: 31-Ju2-2020
ThoR Ref:
ThoR_HRCP_210308_C_WP3

Leader in charge of deliverable: Keitarou Kondou
HRCP Research and Development

Project co-funded by the European Commission within the Horizon 2020 programme and the National Institute of Information and Communications Technology in Japan (NICT)		
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PU	**Public**	**x**
PP	**Restricted to other program participants (including the Commission Services)**	
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Contents

Change register

Version	Date	Author	Organisation	Changes
A	8-Mar-2021	Keitarou Kondou	HRCP Research and Development	First full draft
B	30-Mar-2021	Keitarou Kondou	HRCP Research and Development	Revised after review process
C	1-April-2021	Tetsuya Kawanishi	Waseda University	Revised after review process

Reviewed by Akihiko Hirata Chiba Institute of Technology

1. Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the ThoR project. Any external source is properly referenced.

Confirmation by Authors: Keitarou Kondou HRCP Research and Development

2. Abbreviations

ADC	Analogue to Digital Converter
AWGN	Additive White Gaussian Noise
BB	Baseband
BW	Bandwidth
CW	Continuous Wave
CES	Channel Estimation Sequence
DAC	Digital to Analogue Converter
DC	Direct Current
EVM	Error Vector Magnitude
FCS	Frame-Check-Sequence
FDD	Frequency Division Duplex
FEC	Forward Error Correction
IF	Intermediate Frequency
I/F	Interface
IMRR	Image Rejection Ratio
IQ	In-phase and Quadrature-phase
ISI	Inter-Symbol-Interference
LDO	Low Dropout regulator
LDPC	Low-Density Parity-Check
LLR	Log-Likelihood-Ratio
LNA	Low Noise Amplifier
LO	Local Oscillator
LOFT	Local Feed Through
LOS	Line Of Sight

MAC	Media Access Control
MCS	Modulation and Coding Scheme
PA	Power Amplifier
PCIe	Peripheral Component Interconnect express
PLL	Phase Locked Loop
P2P	Point to Point
PSD	Power Spectrum Density
QAM	Quadrature Amplitude Modulation
RAM	Random Access Memory
RC	Resistor and Capacitor
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RX	Receive[r]
SerDes	Serializer/Deserialize
SNR	Signal to Noise power Ratio
SFD	Start Frame Delimiter
SFP	Small Form-factor Pluggable
SPI	Serial Peripheral Interface
SSB	Single Side-Band
TDD	Time Division Duplex
TPC	Transmit Power Control
TX	Transmit[ter]
TRX	Transmit[ter] and Receive[r]
UART	Universal Asynchronous Receiver/Transmitter
VCO	Voltage Controlled Oscillator
VGA	Variable Gain Amplifier
WG	Wave Guide

3. Executive summary

The system specification [1] defined in WP2 defines the requirements from a carrier class point-to-point (P2P) wireless link operating at the terahertz band around 300 GHz. The implementation of this P2P link is attempted in two variations, one operating in Time Division Duplex (TDD) manner and using an Intermediate Frequency (IF) frequency around 60 GHz and the other operating in Frequency Division Duplex (FDD) manner and using an IF frequency around 70/80 GHz.

This document includes measurement results obtained with the 60 GHz module [2] [3], which is to be employed in the TDD system. The measurement results include basic transmitter characteristics of the module, such as transmit power, spectral mask, phase noise and EVN, receiver characteristics, such as receiver sensitivity, and transmitter and receiver characteristics, such as frame-error rate and TDD operation. Interoperability with a reference 60 GHz system is also reported.

The unit-level test has been performed at HRCP and system-level validation has been performed at Waseda University.

4. Introduction

Figure 1 shows the system block diagram of the terahertz wireless link, which employs E-band (70/80 GHz) or V-band (60 GHz) system. One of the objectives on terahertz wireless link with 60 GHz module is demonstrating a terahertz wireless system compliant with a terahertz wireless standard, IEEE 802.15.3d-2017.

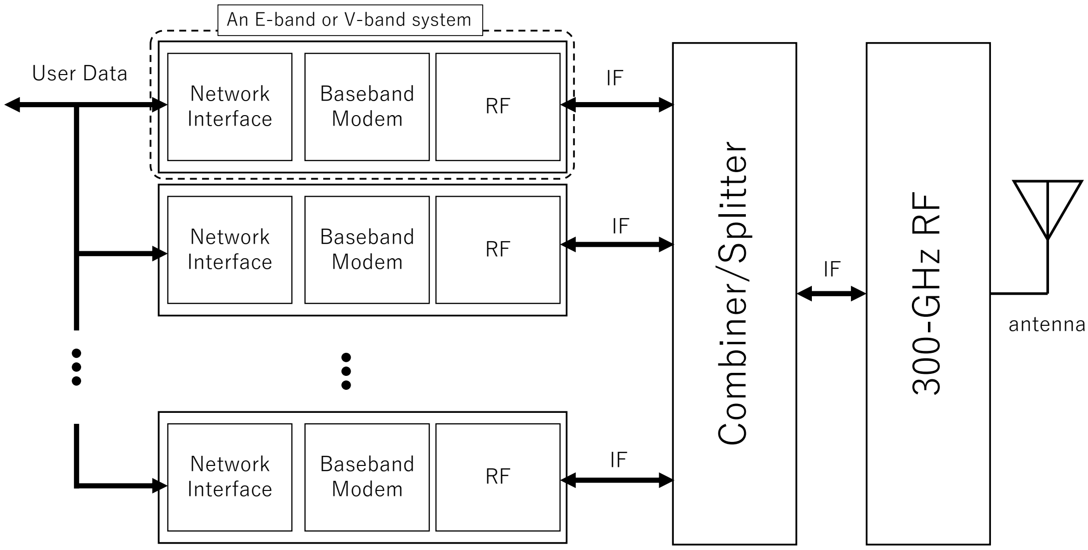

Figure 1 System block diagram of terahertz wireless link

The specification of the 60 GHz transceiver [3] employed in the terahertz wireless link is compliant with the IEEE standard, IEEE 802.15.3e-2017 [4], whose P2P Media Access Control (MAC) architecture is as same as that of a terahertz standard, IEEE 802.15.3d-2017 [5]. Both IEEE 802.15.3e and IEEE 802.15.3d define channels with a 2 GHz bandwidth and the same spectral mask employed in both. Thus, combined with appropriate up conversion and down conversion, terahertz wireless link, which is compliant with the standard, will be realized by employing such 60 GHz modules with appropriate up or down conversion scheme.

Currently, 60 GHz RF chips can be designed with CMOS bulk processes because of improvement on f_T and some of chips are already integrated with a digital circuit, which enables baseband (BB)-signal processing, MAC and high-speed user data interface. We already employed one of such 60 GHz chips for the 60 GHz module and add the RF waveguide port for connecting with up or down convertor [2].

The first section on this document provides the brief description on the 60 GHz transceiver module from both functional and mechanical aspect. In the next section, component test setup of 60 GHz module is described, followed by basic characteristics obtained from measurement. Further analysis of characteristics compared with a reference 60 GHz system are shown in the last section.

5. Overview of 60 GHz TRX module

5.1. 60 GHz TRX module diagram

The ThoR system with 60 GHz module demonstrates wireless link that is compliant with terahertz standard, IEEE 802.15.3d, by employing an existing 60 GHz wireless system that is compliant with IEEE 802.15.3e, which shares same MAC architecture with IEEE 802.15.3d.

Figure 2 shows general architecture of 60 GHz Transmitter-Receiver (TRX) module.

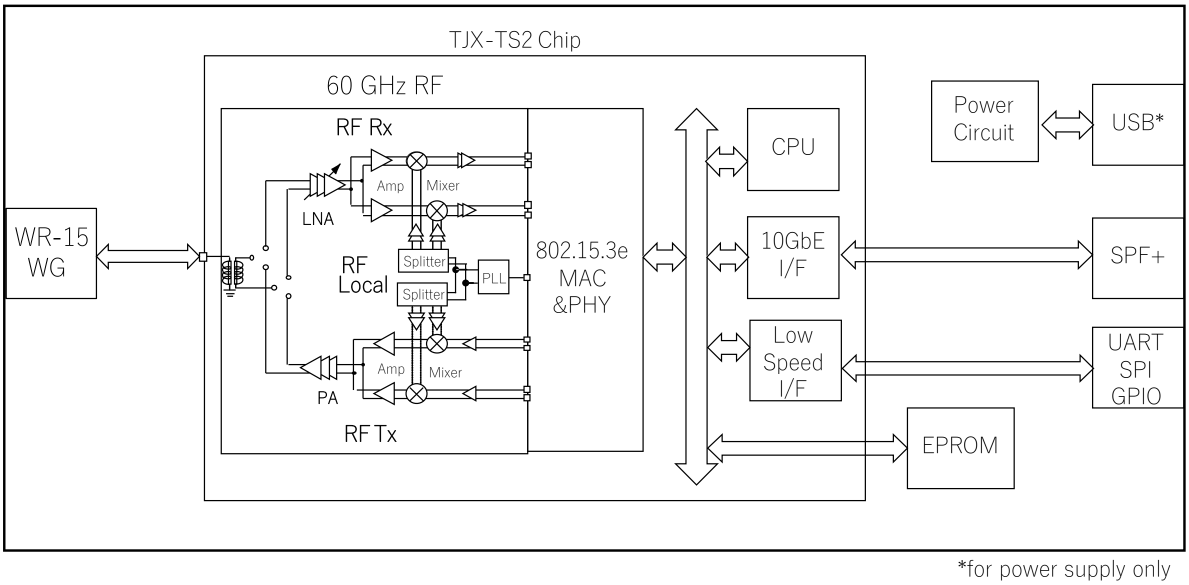

Figure 2: 60 GHz TRX Module block diagram

The 60 GHz TRX Module integrates a 60 GHz chip called TransferJet X(TJX) TS2 chip, which is the 2nd test chip of the next generation of TransferJet technology. This chip integrates 60 GHz RF which supports two channels of 2 GHz bandwidth over 60 GHz, IEEE 802.15.3e compliant MAC and Physical Layer (PHY), Central Processing Unit (CPU) and high speed 10 GbE Interface for transferring user data. A waveguide port on the module is used for connecting 60 GHz RF signal to up or down converters.

TDD operation is employed in IEEE 802.15.3e MAC, so that both TX and RX shares same frequency channel. IEEE 802.15.3e MAC supports only P2P network topology. Two types of devices, parinet coordinator (PRC) and pairnet device (PRDEV), send data alternatively.

Data packet received from 10GbE interface (I/F) is send to IEEE 802.15.3e MAC, then encapsulated to a MAC data frame. The data frame is encoded as a PHY data packet according to one of the modulations and coding scheme specified. Then Digital to Analogue Converter (DAC) converts this digitized data packet to analog BB signal. 60 GHz RF upconverts the BB signal to 60 GHz RF signal by a direct conversion Mixer combined with 60 GHz phase locked loop (PLL), then the RF signal is amplified by a power amplifier (PA) and transmitted through waveguide port. At receiver (Rx) side, RF signals are converted to 10GbE Data packet along with Rx side of data path.

The module also has a capability of testing, such as sending test packet and monitoring errors. These features are enabled by a set of command through Universal Asynchronous Receiver/Transmitter (UART) or Serial Peripheral Interface (SPI).

5.2. Transceiver integration in the overall block diagram

Figure 3 shows overall block diagram of terahertz P2P link transceiver employing two 60 GHz TRX modules. Each 60 GHz TRX modem operates in TDD mode, where both transmitter and Rx share the same frequency channel. Each TDD modem converts user data from Ethernet to the 60 GHz RF signals with a different channel, which is treated as an IF signal in this system. Then 60 GHz RF signals from TRX modules are combined with combiner, which is shown in 2:1 combiner in Figure 3. The combined IF signal is upconverted to around 300 GHz of frequency with a terahertz mixer.

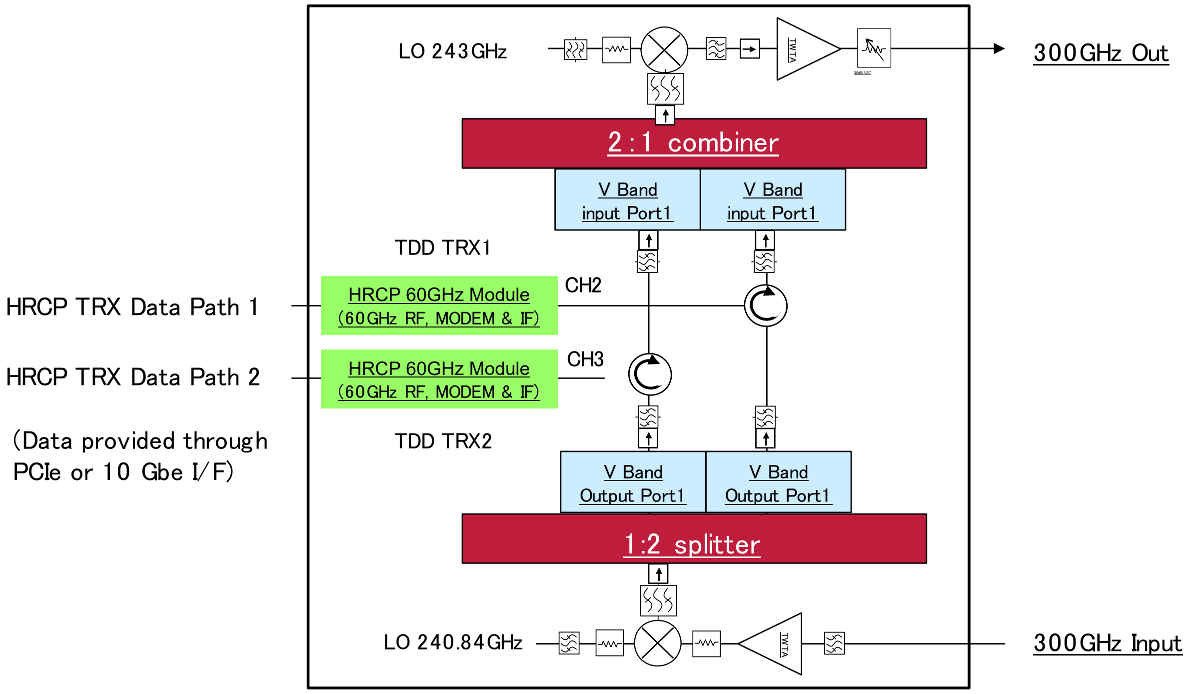

Figure 3: Example of terahertz wireless system with 60 GHz TRX modules

Figure 4 shows channel assignment for each of V-band and terahertz region, when 243 GHz of local frequency is employed. In this case, two 60 GHz channels, which are corresponding to CHNL_ID 2 and CHNL_ID 3 specified within IEEE 802.15.3e, are upconverted to two 300 GHz channel, which are corresponding to CHNL_ID 24 and CHNL_ID 25 specified within IEEE 802.15.3d.

Both of specification, IEEE 802.15.3e and 802.15.3d, have same requirement for clock accuracy, which is 30 ppm in frequency, so the accuracy of clock shall be maintained in terahertz region when IEEE 802.15.3e compliant modems are employed in this wireless system.

Once two-channel integration is confirmed to work with this scheme, total throughput of a terahertz wireless system can be increased by combining more channels or using higher bandwidth channels. However, this is out of current scope.

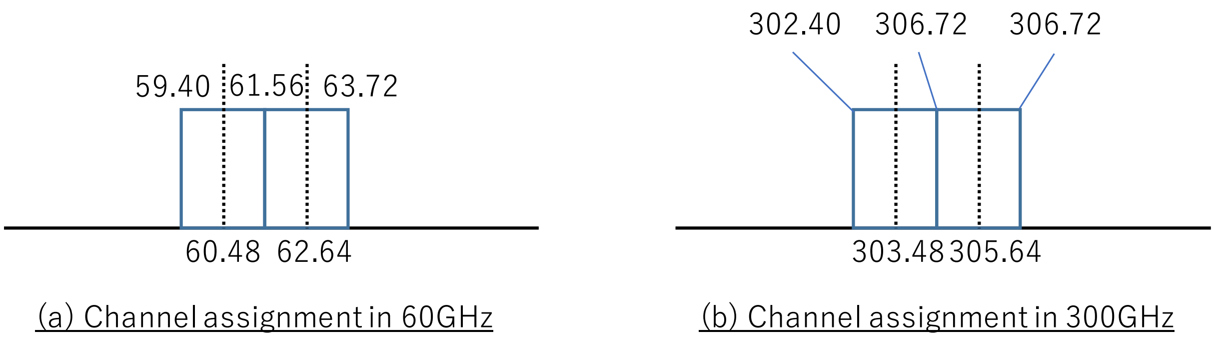

Figure 4: Channel assignment employed in V-band and 300GHz band

5.3. Mechanical construction

Figure 5 shows the picture of 60 GHz TRX module currently considered. On the base plate, there exist a PCIe I/F board combined with a 60 GHz Wave Guide (WG) module board.

TJX TS2 Chip is mounted on the 60 GHz WG module under the metal parts shown in the figure. PCIe I/F board is used for providing a Peripheral Component Interconnect express (PCIe) card edge connecter for connecting host devices such as PC or mobile platform, which are capable of a PCIe connection capability. Another small board is also connected on the PCIe I/F board for serial debugging.

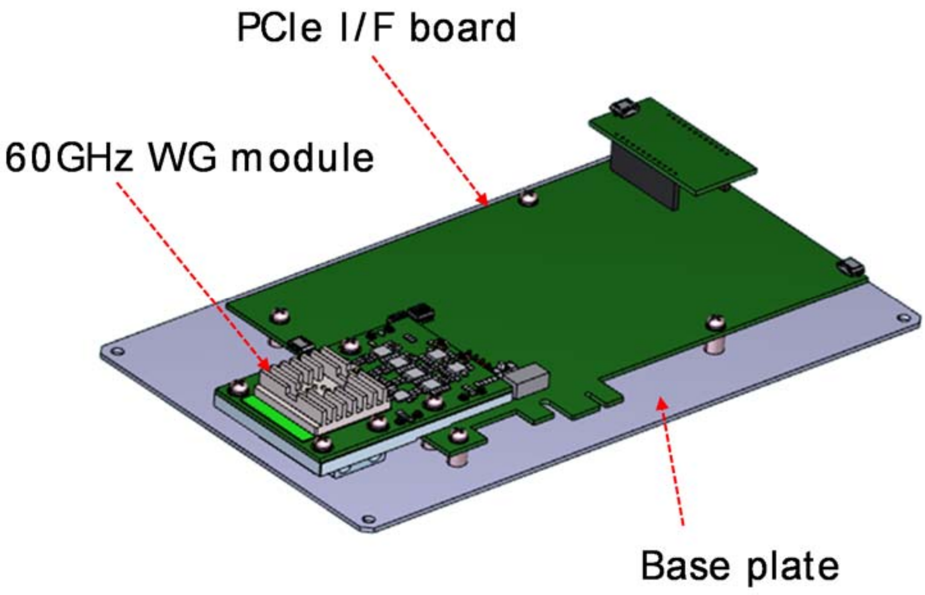

Figure 5: Mechanical construction of 60 GHz TRX module

Figure 6 shows top and bottom view of the 60 GHz TRX module. At the bottom view, there is a WG port with the size of WR-15, which is capable of connecting high frequency RF devices via waveguide. For terahertz wireless system, circulator device, which is shown in Figure 3, shall be connected to the WG port.

A 60 GHz TRX module with built-in antenna is also prepared for some performance evaluation.

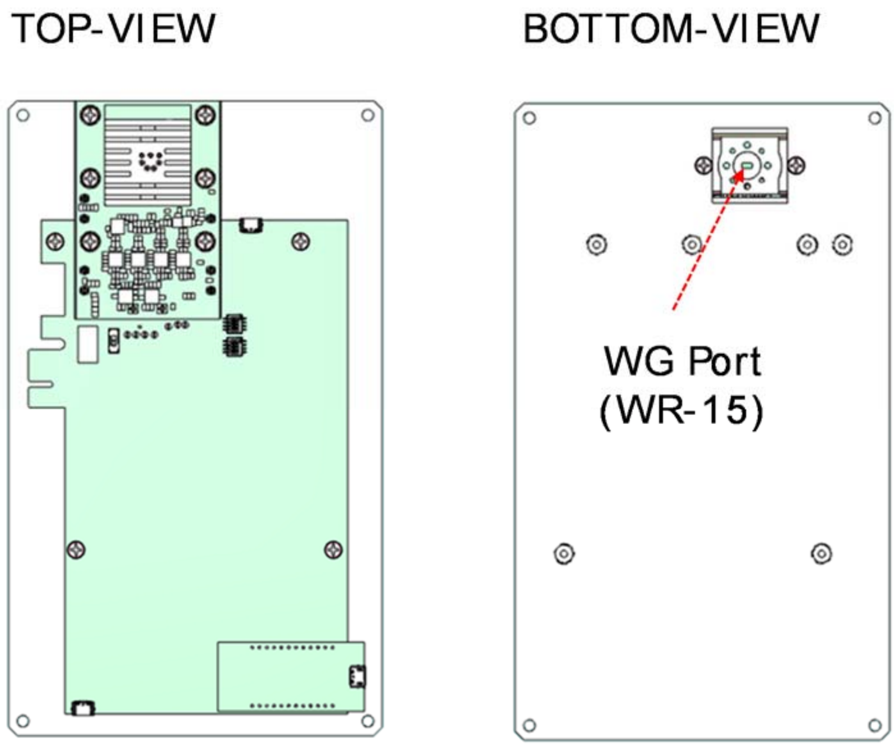

Figure 6 Top and bottom-view of 60 GHz TRX module

6. Test setup

Figure 7 describes functional block diagram of the 60 GHz chip (TS2).

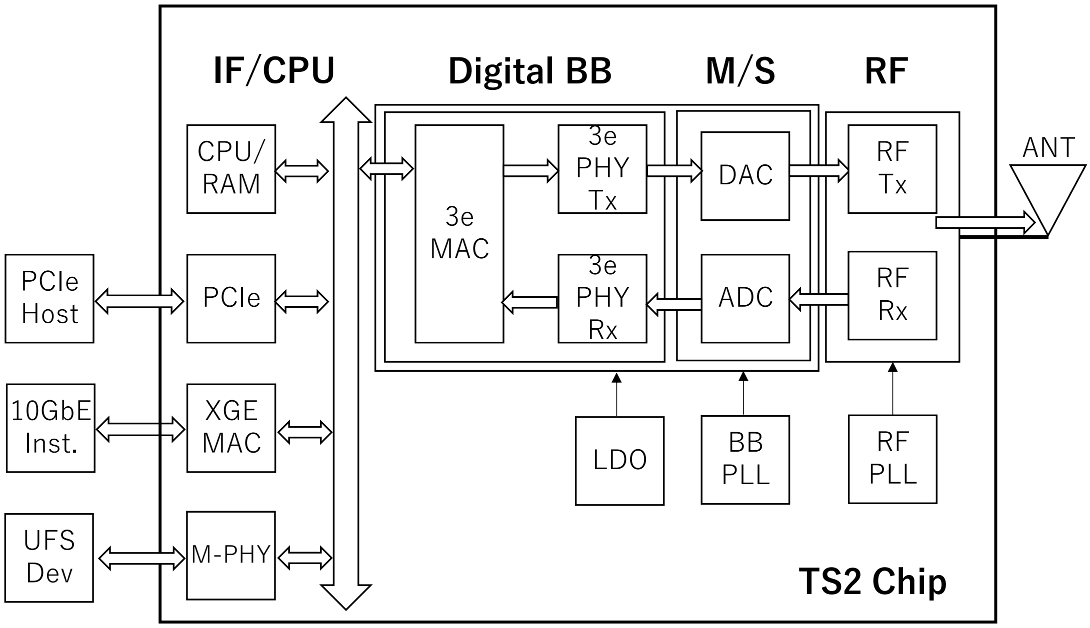

Figure 7 Functional block diagram of the 60 GHz chip

The TS2 chip consists of RF, Mixed signal, Digital Baseband and IF blocks.

The RF block employs direct-conversion architecture, which convert the base-band signal to or from 60 GHz radio wave directly with a 2 GHz-bandwidth. Mixed signal part employs high-speed DAC and Analogue to Digital Converter (ADC), which are operated with 3.520 GHz and 2.347 GHz.

PLLs for both RF and BB PLL are also integrated and internal Low Dropout regulator (LDO) generates various type of power voltage required each block and suppress the power noise from external power source.

Digital BB part consists of PHY and MAC for supporting modulation, frame detection, error correction and frame composition and decomposition scheme compliant with IEEE 802.15.3e [4]. IF/CPU part includes embed CPU for controlling various function in the 60 GHz chip and industrial standard interfaces, such as PCIe, 10Gb Ethernet and M-PHY so that the ThoR system can interact with an actual user system.

For testing purpose, Random Access Memory (RAM) can be used for storing samples from ADC or IQ symbols directly. PHY and MAC also support some test functions used TRx testing, which are described in following section.

6.1. Tx test setup

Figure 8 Shows the blocks used in Tx test along with the TX data path.

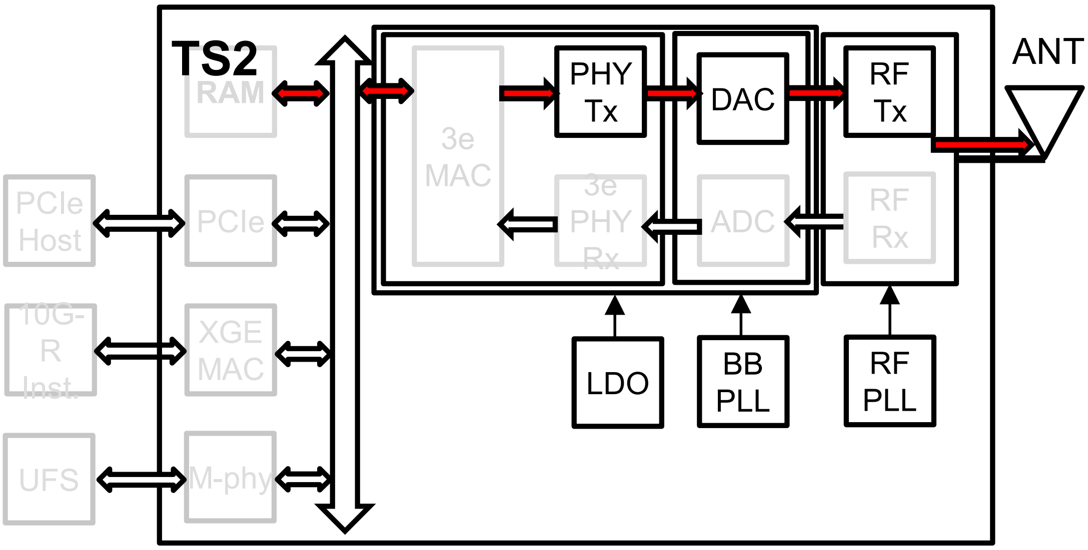

Figure 8 Tx test set-up

The PHY Tx supports generating test signals such as sine wave and modulated signals for each Modulation and Coding Scheme (MCS). For example, a continuous sine wave is provided for DAC and later RF for measuring output power and modulated signals are employed for spectral mask verification and EVM measurement.

RF Tx can be calibrated through register settings for mitigating degradation due to device mismatch, such as Local feed through (LOFT) suppression. Upon measuring each characteristic, such type of calibration is employed.

6.2. Rx test

Figure 9 shows the blocks used in Rx test along with the RX data path.

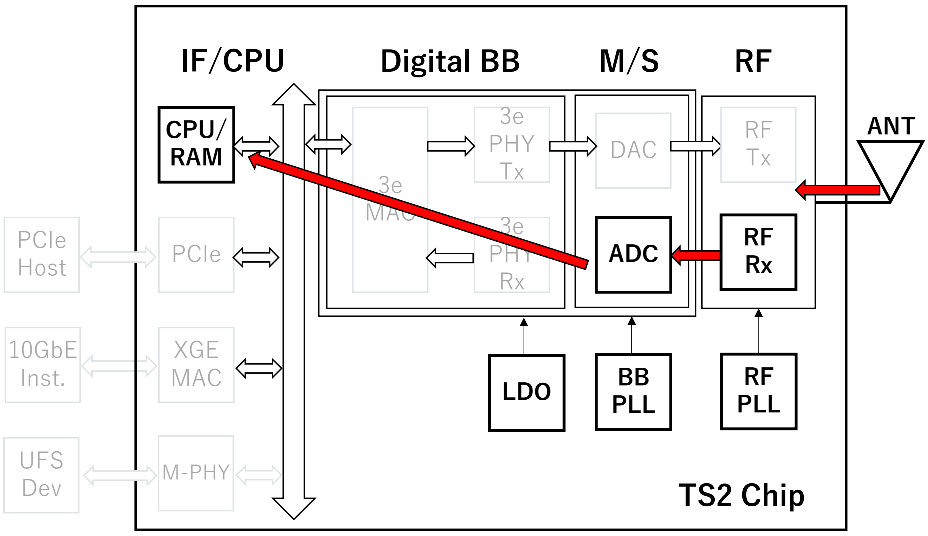

Figure 9 Rx test Setup

In the RX module testing, only receiver sensitivity is measured, then only RF and ADC are enabled during RF test.

6.3. TRx test

Figure 10 Shows TRx test setup using a pair of Transmitter and Receiver.

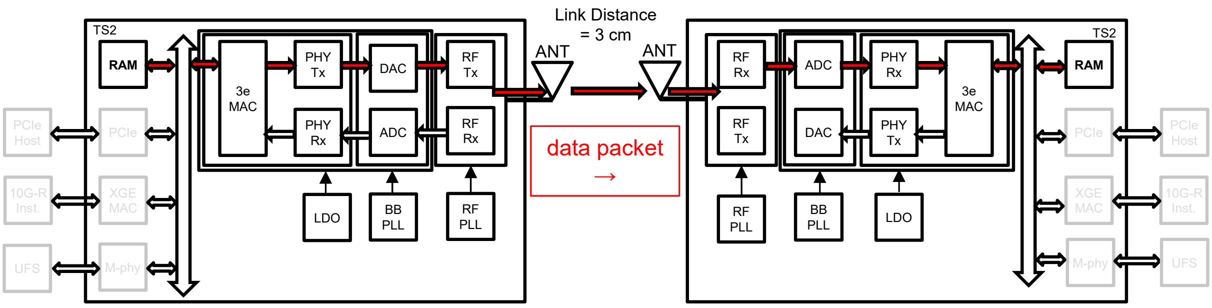

Figure 10 TRx test set-up

In the TRx test, Transmitter generates test frames, which is compliant with IEEE 802.15.3e format, with a built-in test function in MAC block, then at the Receiver side, number of erroneous frames are counted by using an error counter within MAC.

Parameters such as MCS and frame-length can be set through serial interface and measurement results such as frame-error rate or current Variable Gain Amplifier (VGA) gain can be observed through serial interface also.

In the following section, frame-error rate of each MCS are observed using this setup and phase-noise measurement of RF PLL is also included.

7. Measurement Results

7.1. Tx test

7.1.1. Transmit power

By using built-in signal generator in digital baseband block, sine waves with 90-degree phase difference are fed into Tx RF through DAC when measuring transmit power.

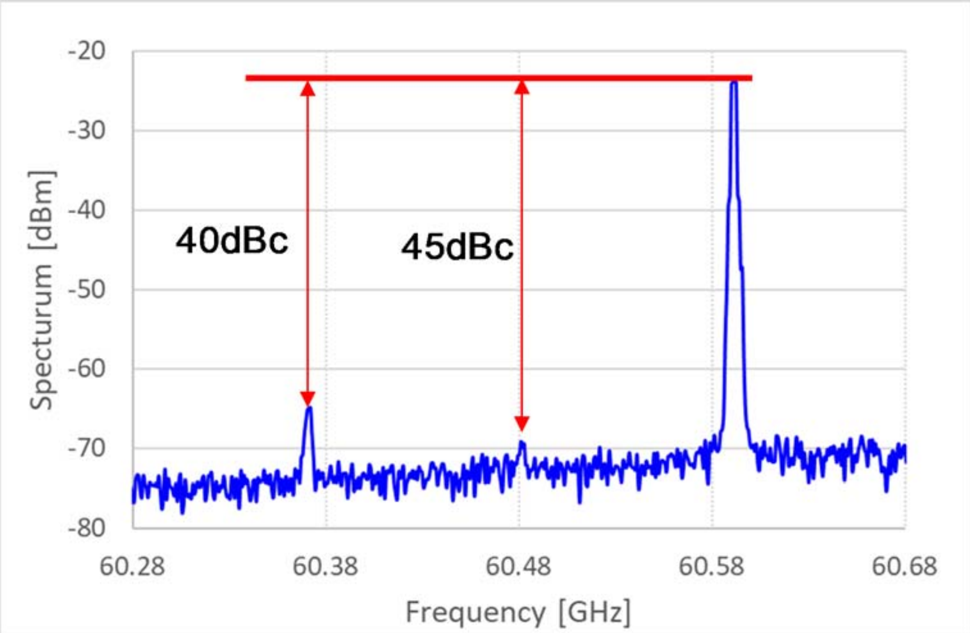

Figure 11 Tx output spectrum with Continuous Wave (CW)

The 60 GHz module transmits CW from the built-in antenna and its power is measured using a power meter with a horn antenna. The estimated power is −5.3 dBm at chip port, considering built-in antenna gain of 4dB and total insertion loss of 1 dB.

Figure 11 shows measured spectrum with this setting. 40 dBc of sideband suppression is achieved after calibration.

7.1.2. Spectral mask

Figure 12 shows Tx output spectrum with modulated signal. In this measurement, modulated signals are provided from digital baseband block. The center channel frequency is set to 60.48 GHz, which is a center frequency of channel number 2.

Compared with a spectrum mask, which is shown in black solid line in Figure 12, the output signal of the 60 GHz module matches with the requirements specified in IEEE 802.15.3e.

In IEEE 802.15.3d, the shape of the spectrum mask is same as defined in IEEE 802.15.3e with a difference of center frequency. So, we can expect that the output signal from the ThoR system will compliant with IEEE 802.15.3d specification with an appropriate up conversion.

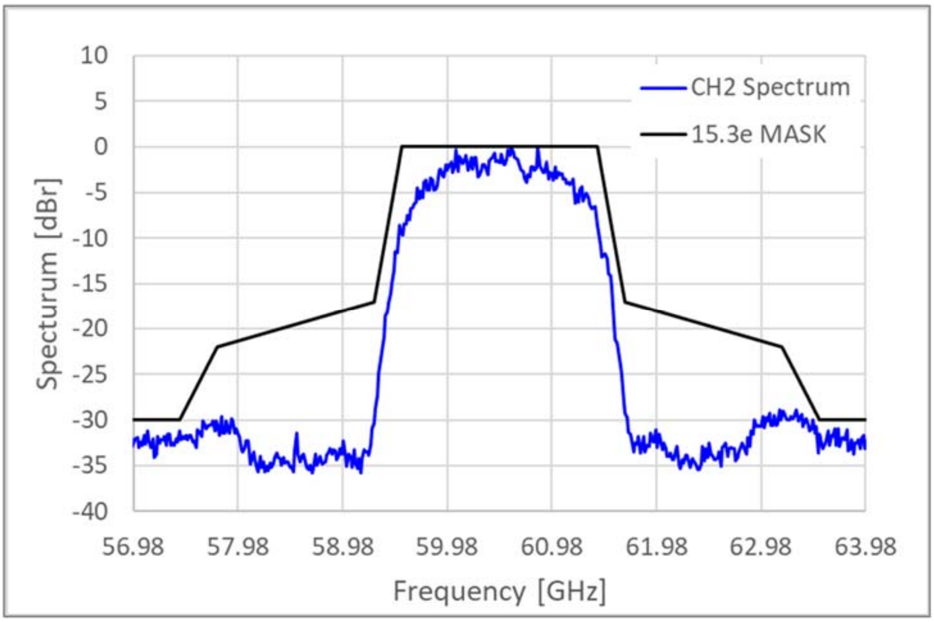

Figure 12 Tx output spectrum with modulated signal

7.1.3. Phase noise

Figure 13 shows the measurement and simulated results of phase noise of RF PLL.

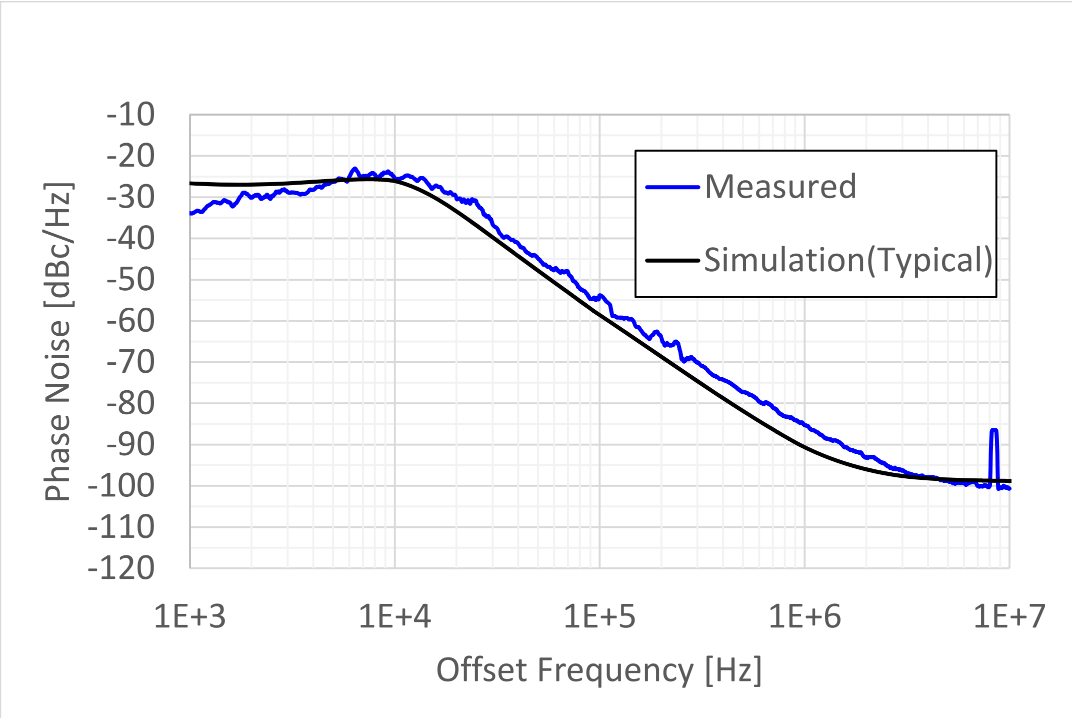

Figure 13 Phase noise of RF PLL

Measured phase noise at the 1 MHz offset from carrier frequency is −86.4 dBc/Hz and a few dB degradation is observed compared with the simulation results.

The degradation is from a fault in compensation circuit connected with Voltage Controlled Oscillator (VCO). This issue will be fixed with a newer version of the chip (TS3), which is available on May 2021.

7.1.4. EVM

Theoretically, Error Vector Magnitude (EVM) is calculated with an ideal receiver, which can track signal rotation within IQ plane caused by phase noise introduced by a PLL. However, with an actual system, loop bandwidth of the carrier locking algorithm employed in the receiver shall be considered.

In this test, EVM of the output signal is measured by a vector signal analyzer with a various loop bandwidth setting for estimating actual performance of the system.

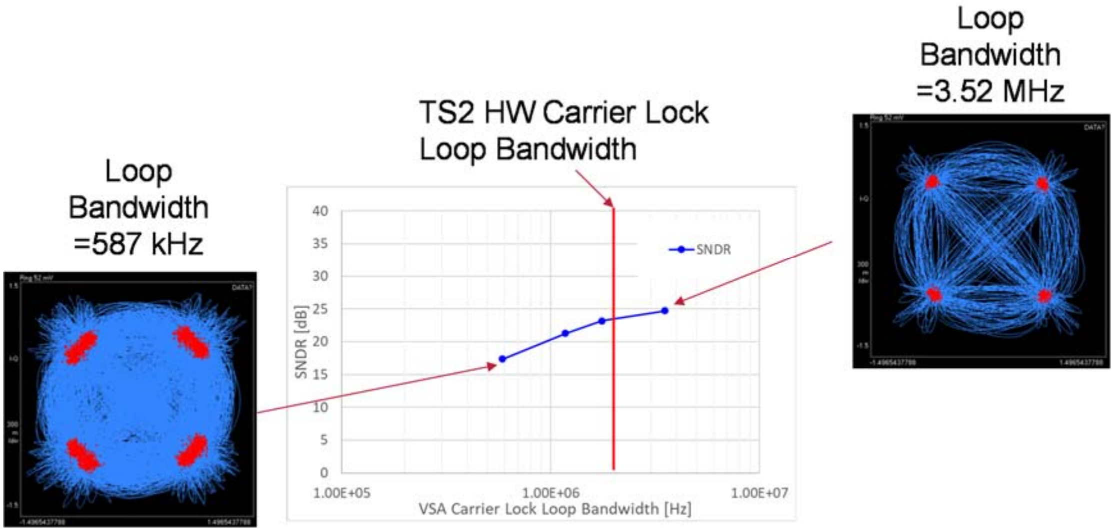

Figure 14 Measured EVM

Figure 14 shows measured EVM as a function of loop bandwidth. As shown in Figure 14, higher bandwidth gets the better EVM results but lacks stability with an actual system.

Typically, the loop bandwidth is set to around 2MHz in the 60 GHz module considering both performance and stability. With this setting, we can expect around −24 dB of EVM at receiver side.

7.2. Rx test

7.2.1. Receiver Sensitivity

Receiver sensitivity is defined as the RF power at the antenna output in the receiver. For each modulation and coding scheme, receiver is expected to process the signal properly when the incoming signal power is greater than the threshold.

Table 1 shows the receiver sensitivity for each modulation and coding scheme. Higher modulation requires higher receiver sensitivity, because higher modulation requires a better SNR.

Table 1 Receiver Sensitivity defined in IEEE 802.15.3e

	Modulation	FEC rate	PHY SAP rate (Gb/s)	Receiver Sensitivity (dBm)
0	π/2 QPSK	11/15	2.5813	− 61
1	π/2 QPSK	14/15	3.2853	− 58
2	16QAM	11/15	5.1627	− 55
3	16QAM	14/15	6.5707	− 51

Figure 15 shows a measured signal-to-noise and distortion ratio (SNDR) of received signal with various received power. The gray line describes the required SNDR for each MCSs. For example, at −61 dB, which is receiver sensitivity of MCS 0, required SNDR for stable transfer is about 5.7 dB.

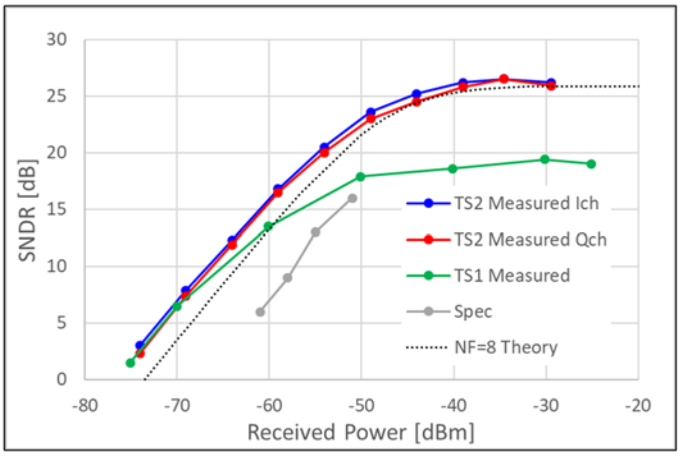

Figure 15 Measured SNDR as a function of Received power

As seen in Figure 15, current TS2 chip achieves better SNDR compared with the requirements and also see some improvements from previous version of chip, TS1.

In this test, the SNDR is obtained by measuring single tone RF signal. So actual SNR of modulated signal will be degraded due to phase noise or RF impairments.

7.3. TRX test

7.3.1. Frame-error rate

Frame error rates and received SNR of MCS1 MCS2 and MCS3 are evaluated with TRx test.

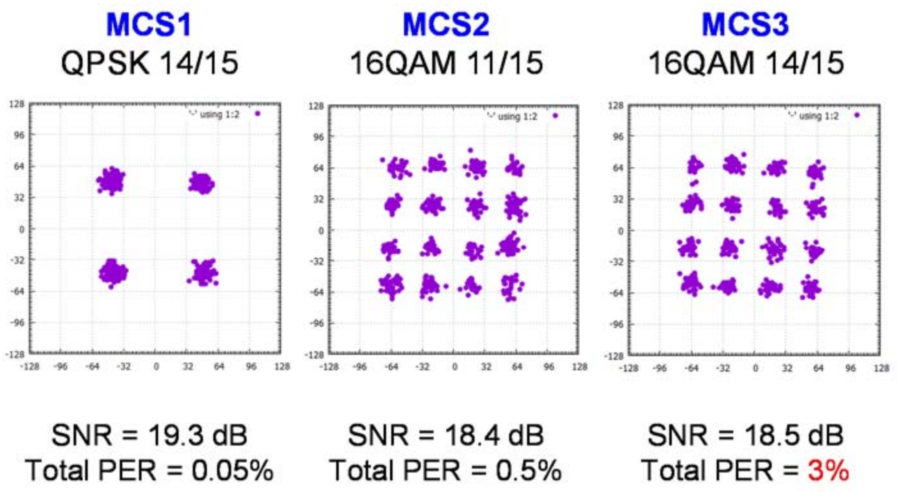

Figure 16 Frame-error rate and SNR

Figure 16 shows the results of the frame-error rate test. For MCS1 and MCS2, frame-error rate below 1% is achieved.

Some degradation in frame-error rate is observed with MCS3. As we see some phase noise degradation in Tx test, the frame-error rate will be improved with a new version of the 60 GHz chip.

7.3.2. T/RX TDD operation

For the 60 GHz module employed in the ThoR system, TDD operation is required because it shares same center frequency channel for both Tx and Rx.

We evaluated the switching capability of the 60 GHz as shown in Figure 17. As shown in Figure 17, Tx and Rx functions are switched over micro-second order, which is sufficient for stable TDD operation required in IEEE 802.15.3e specification.

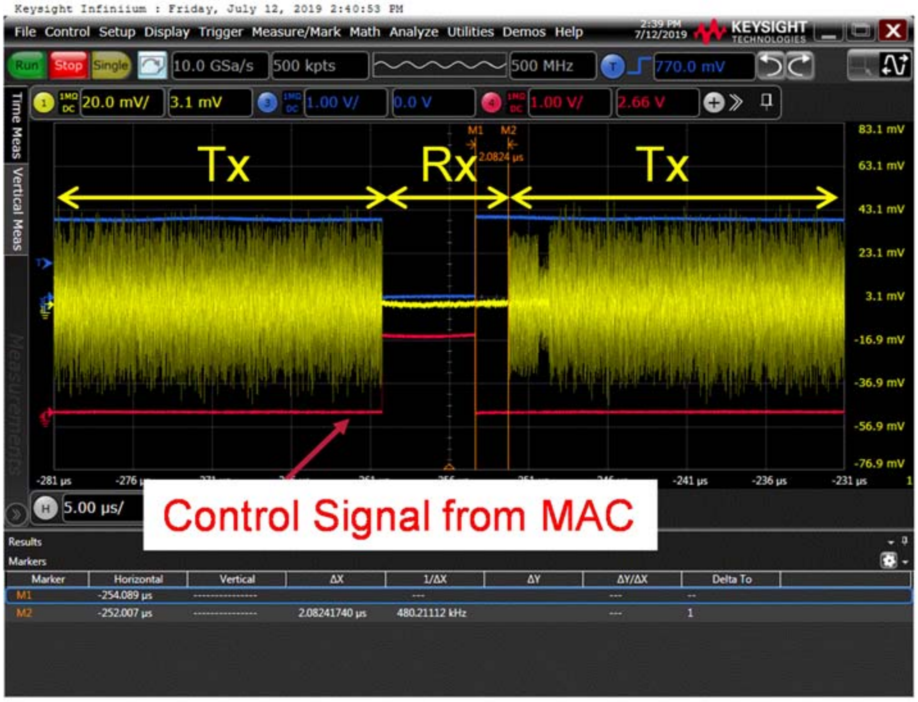

Figure 17 TRx switching

8. V-band PHY/RF characterization system for IEEE802.15.3e devices

8.1. Introduction

Terahertz radio with ultra-wideband signal modulation have been garnering sufficient attention, to provide massive wireless data transmission dedicated to beyond 5G. As one of prototypes of terahertz radio systems with high spectral efficiency, the Thor project employs multi IF stage with V-band (57-70 GHz) and E-band (71-86 GHz) to accommodate the current technology.

To pursue massive bit rate in terahertz communication, the proposed scheme is established by bunch of terahertz channels with existing V-band high speed PHY/RF and MAC layers. Currently, IEEE802.11 and 802.15 extend V-band channels from previous 4ch to 6ch, which avoids the channel-confliction in actual cases. Therefore, the regulation of adjacent channel leakage power will become stricter, and the same thing will happen in terahertz band in the future. On the other hand, under this modulation scheme, the accuracy of signal path fidelity (magnitude and phase flatness) and power measurement will become more important even though the bandwidths of the testing signals are over 2 GHz. This report focuses on precise characterization of V-band transmitters and receivers based on IEEE802.15.3e.

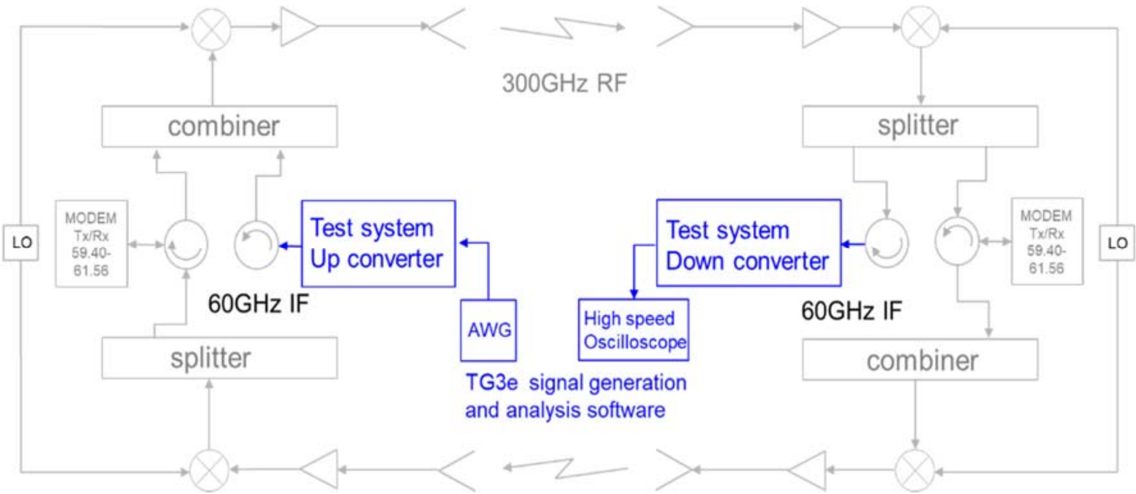

Figure 18 The apparatus to evaluate terahertz channels through IF (V-band) stage

Precise calibration over more than a few GHz signal bandwidth is required to offer transmission performance characterization of 60-GHz V-band broadband radio systems, where distortion sensing and collection functions for providing accurate reference signal and analysing capability. Figure 18 illustrates the apparatus for evaluating the characteristics of the transmitted terahertz RF signal with each signal-path channel as the loop through IF (V-band) stage. Magnitude and phase reference planes at input and output points so as to evaluate terahertz signal-path channel appropriately. As one of the terahertz-system examples, an IEEE802.15.3e V-band device is characterized and set to accommodate the actual data transceiver functions on terahertz channels through IF stage. Moreover, a conformance test facility is required for the proof and quality management on IEEE802.15.3e (modulation bandwidth: 2.16 GHz/ch). V-band transmitters and receivers can be evaluated by using the setup shown in Figure 19.

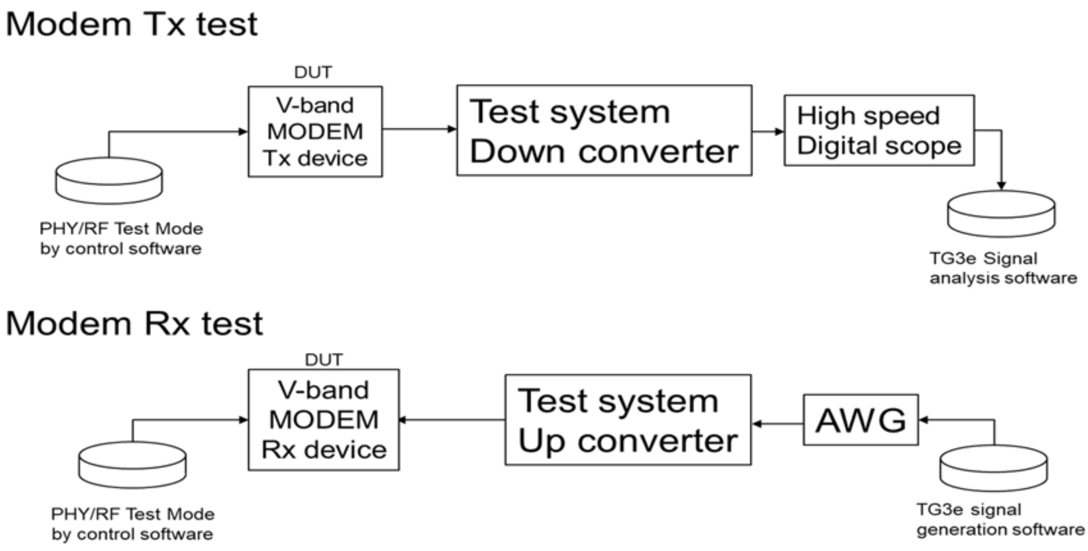

Figure 19 PHY/RF test and evaluation function dedicated to V-band devices

8.2. Configuration of broadband V-band radio characterization system

Generation and diagnosis of broadband V-band RF signals with complex multilevel modulation formats require accurate magnitude and phase calibration over a few GHz, while conventional measurement systems are dedicated to narrowband applications. To offer broadband and accurate performance evaluation, we have developed broadband millimetre-wave radio performance test systems, which guarantees precise measurement of the modulation bandwidth from several GHz to several tens of GHz. In such broadband test systems, the power density distribution (PSD) of the signal is significantly reduced (inverse proportion to the increase of modulation bandwidth), which degrades the signal-to-noise ratio (SNR). On the other hand, the total thermal noise in the receiving system increases, which also results in SNR degradation. Take a 2.16-GHz modulation bandwidth case for example, the total in-band noise level rises to about −80 dBm.

The output signal power should be less than 0 dBm to suppress undesired nonlinearity inside the oscilloscope. The PSD of the signal is -30dBm/Hz. The noise floor of the oscilloscope with 10-bit ADC is -70 dBm/Hz. Thus, we have only 40-dB power difference. In addition, the signal will be further attenuated due to the magnitude and phase correction and excess loss in cables and devices in our measurement system. To perform precise measurement, it is necessary to accommodate the signal within narrow dynamic range. In addition, the SNR would be degraded in frequency converters, so that it would be difficult to maintain the required SNR (error correction limit) of the multi-rate modulated signal. Therefore, to keep the dynamic range large enough, it is necessary to optimize the link budget and gain distribution. The frequency converter has variable gain function which ranges up to 50 dB with 1-dB steps for both up and down conversion. Figure 20 shows the configuration of the RF measurement system.

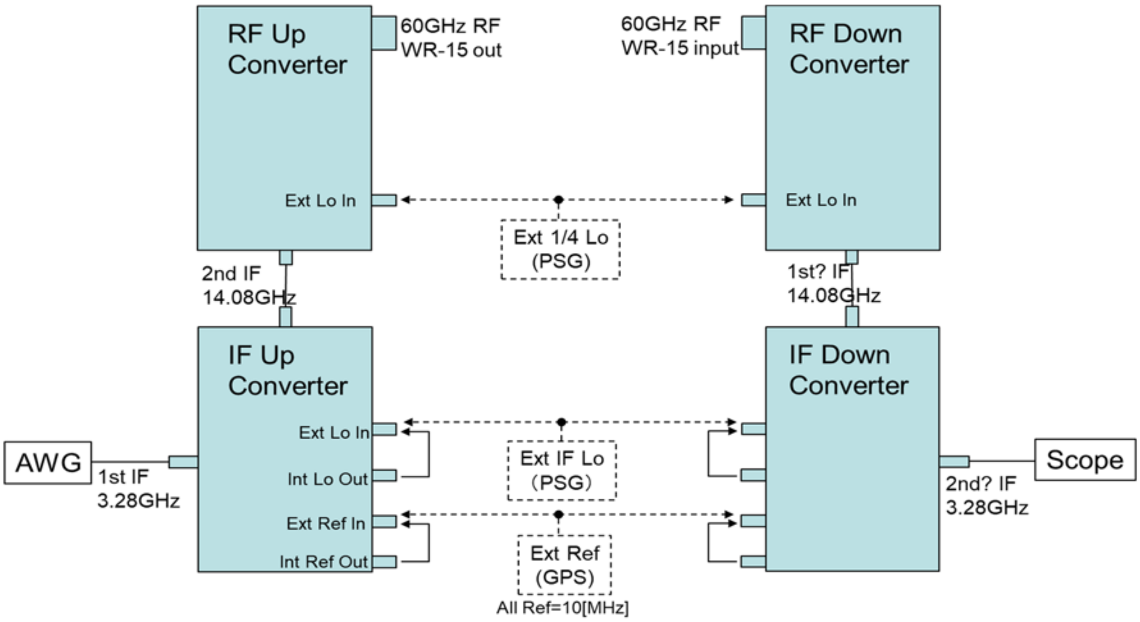

Figure 20 Measurement equipment for V-band system

The first IF signal, whose frequency was set to 3.28 GHz for utilizing the general-purpose low sampling rate AWG, was converted into the second IF signal whose frequency was set to 14.08 GHz. The transfer characteristics of the IF up converter can be calibrated at the output port of the converter by the use of a caliblated digital oscilloscope. Normally, the digital oscilloscope has a self-calibration scheme to put magnitude/phase reference planes by means of internal impulse response calibration. If magnitude/phase reference planes can be defined at the output port of the IF up converter and at the input port of the IF down converter, millimeter-wave or terahertz-wave measurement setup can be configured by using additional frequency converters which connected to the IF converters. Figure 21 illustrates the frequency characteristics of magnitude and phase of IF stage after calibration by the digital oscilloscope.

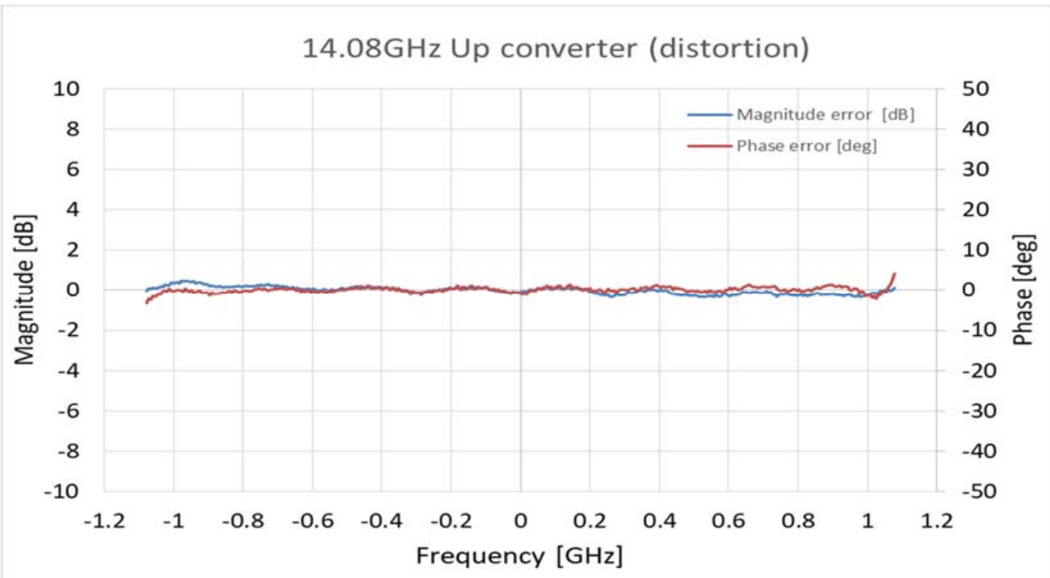

Figure 21 The reference signal of IF stage used as base signal for upper stage

Accurate signal generation and receiver analysis with low crest factor OFDM calibration scheme with channel estimation and digital pre-distortion (DPD) technology are useful for the PHY/RF test function in IEEE802.15.3e / 15.3d conformance test cases. Regarding the test signal environment, the following two types of test signals were prepared. In each case, the signal quality that was confirmed to be error-free at 10^{-6}.

Distortion detection and confirming the correction

Center frequency: One of the IEEE802.15.3e channel, CH1 to CH4

Modulation bandwidth: 2.16 GHz/ch

Modulation scheme: LC-OFDM

Number of sub-carriers: 368

Sub-carrier spacing: 5.859375 MHz

Modulated reference signal

Center frequency: One of the IEEE802.15.3e channel, CH1 to CH4

Modulation bandwidth: 2.16 GHz/ch

Modulation scheme: pi/2BPSK, pi/2QPSK, 16QAM, 64QAM

Symbol rate: 1.76 G symbol/s

Roll-off rate: 0.25

8.3. Calibration of V-band frequency converters

Conventional method of characterization for frequency converter are mentioned below:

a). Magnitude calibration by a spectrum analyzer

Although the spectrum analyser has its amplitude characteristics precisely calibrated, it cannot obtain the phase characteristics. This method can be applicable to frequency conversion devices where the input and output signal frequencies have difference.

b). Magnitude and phase calibration by a vector network analyzer (RF loopback measurement)

This method can measure magnitude and phase responses simultaneously. A VNA has functions of signal generation and reception, while an AWG and digital oscilloscope can configure the loopback measurement setup as well. However, it can only measure the overall response of the system including the up-converter and down-converter, as shown in Figure 22.

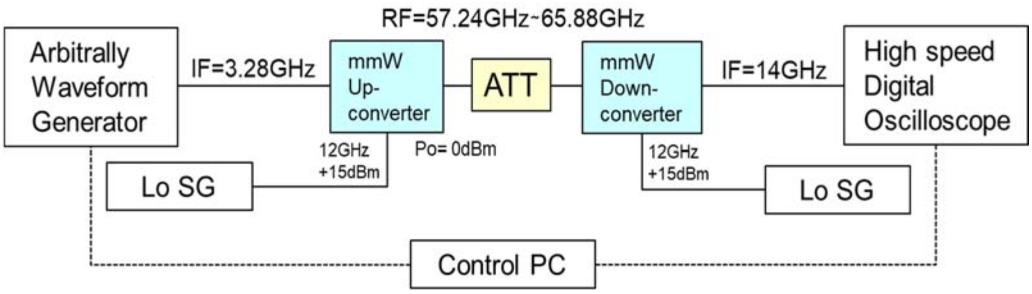

Figure 22 General RF loopback characteristic measurement

In addition to the two calibration methods mentioned above, we also used a new calibration method to measure the responses of the up-converter and down-converter separately, as shown in Figure 23.

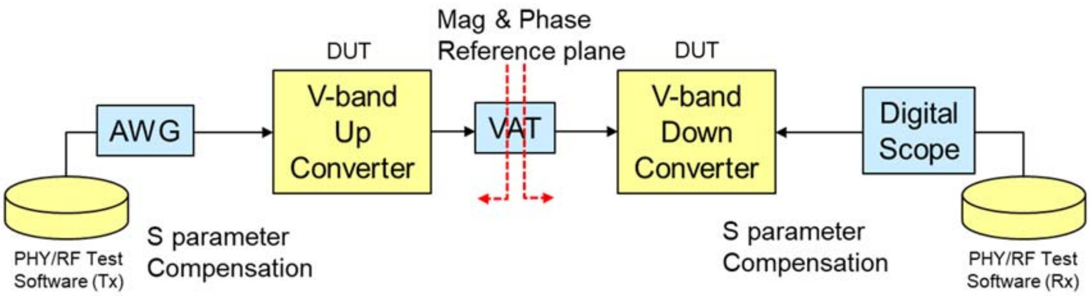

Figure 23 Individual evaluation of a frequency converter

The following two methods can be used for calibration of frequency converters.

1) 2 tone phase shift method: Measuring the phase difference of two single-tones with frequency shifting

2) Acquiring phase information by a comb-generator with usual scalar-amplitude-measurement (SMC)

We used the second option, SMC+Phase technology, which offers more accurate measurement than in the first option.

As of now, because of the lack of precise control of terahertz-wave generation and detection, evaluation of the terahertz signal-path should rely on the RF lookback method, while we can evaluate signals in IF blocks precisely by using the calibration methods mentioned above.

8.4. Evaluation result of the measurement system

The V-band converter's CH2 and CH3 frequency response with magnitude/phase characteristics are shown in Figure 24. The data were acquired through VNA calibrated by SMC + Phase technology. These parameters can be used to transmitter pre-distortion and receiver equalization for the vector modulated signals. Afterwards, these data are compared with RF loopback measurement ones, which is a simple conventional method of RF characterization. As Figure 25 shows, left side are the characteristics projected by overlapping up and down converter through RF loopback; right side are the characteristics synthesized by the VNA up and down individual data. The shapes are almost the same except for small details. In other words, we were able to accurately grasp the characteristics of up and down converter respectively.

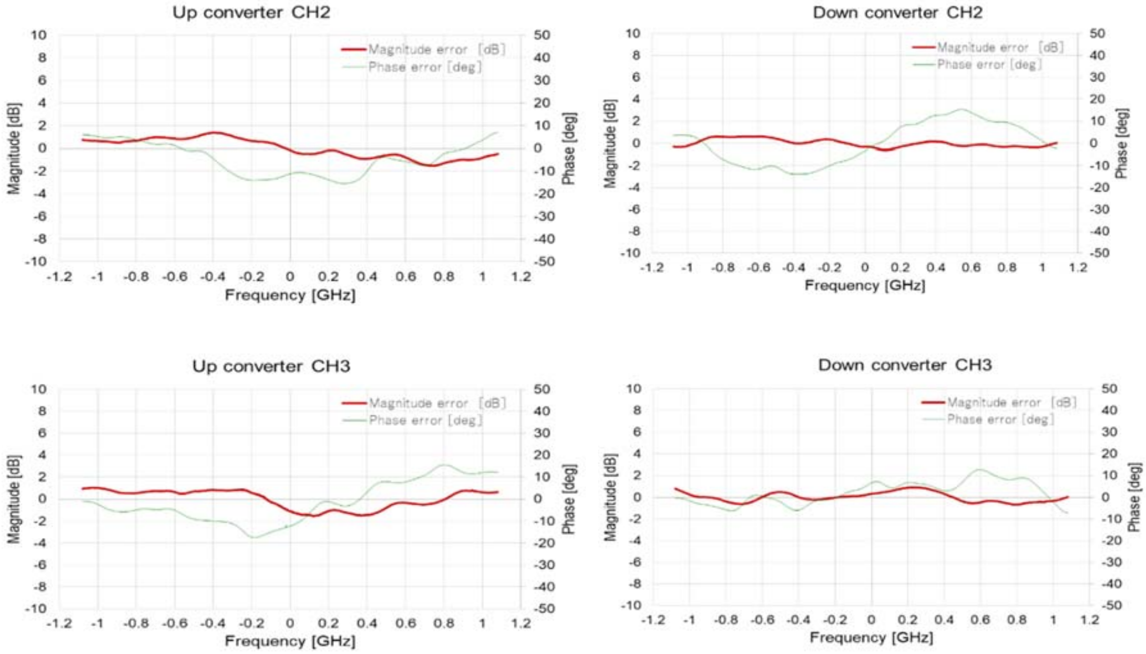

Figure 24 Acquired characteristics of the up and down converters

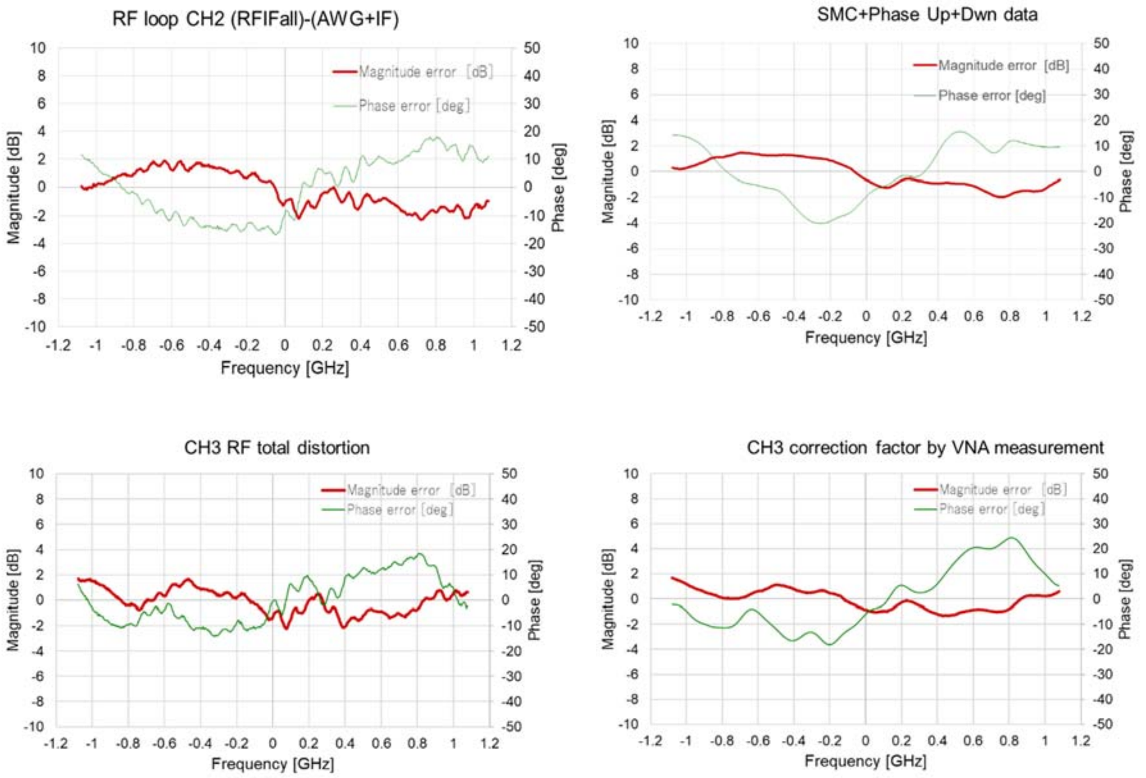

Figure 25 S21 parameter respectively obtained by RF loopback (left) and the synthesized data from Network Analyzer (right)

In this test, a calibrated π/2 QPSK signal was fed to the loopback of the V-band converter. Besides, the on/off of S-parameter correction was compared in this case.

No compensation: EVM = 19.0%

With individual S parameter compensation for up and down converter: EVM = 6.6%

The final residual modulation accuracy is projected by overlapping up side and down side of the frequency converter. Each modulation accuracy is estimated to be 4.7% by the root mean square as first look estimation. In other words, it is possible to perform accurate measurement for evaluating the terahertz signal-path by the reference signal with 4.7% modulation accuracy.

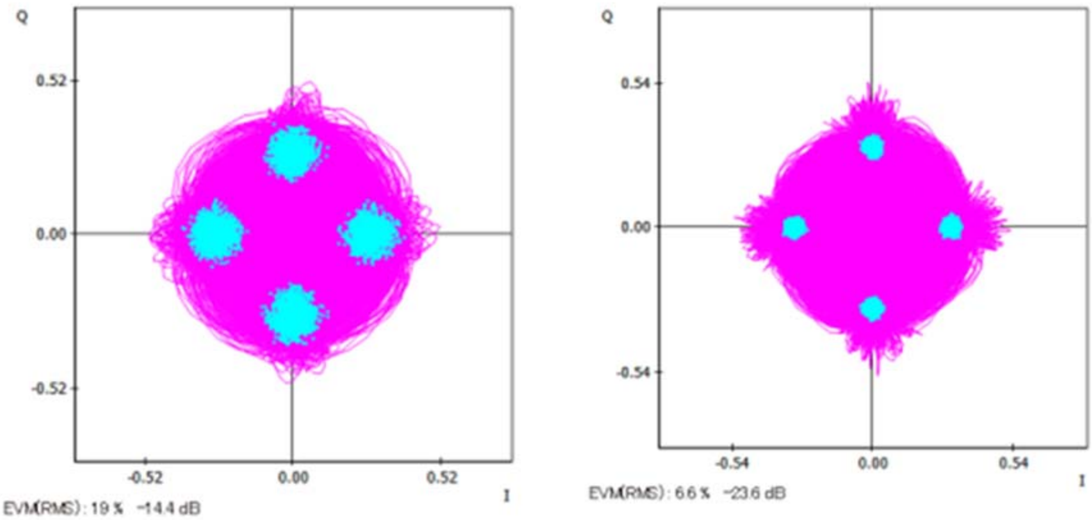

Figure 26 Modulation accuracy without S21 compensation (left) and with S21 parameter compensation from VNA data (right)

8.5. Result of head-to-head test with HRCP devices

The V-band vector signal evaluation system can be directly applied to the V-band communication devices. Therefore, the PHY/RF test support function for the HRCP device was adopted, which was accommodated in the terahertz system to proof actual bi-directional communication. Specifically, the PHY/RF test software was used for the HRCP device, which was originally implemented on the measuring equipment based on the IEEE802.15.3e specification. Besides, its Tx/Rx function were verified. Both the HRCP device side and our measuring equipment side are independently implemented based on the IEEE802.15.3e specifications. Consequently, it will be valuable as a conformance test by identifying differences in the interpretation of the description or ambiguity of the specification.

Tx functional check by HRCP modem device

The output test signal from the device's test mode was received by the measuring equipment, and the signal accuracy and/or packet signal standard conformity were confirmed.The apparatus of measurement configuration is shown in Figure 27.

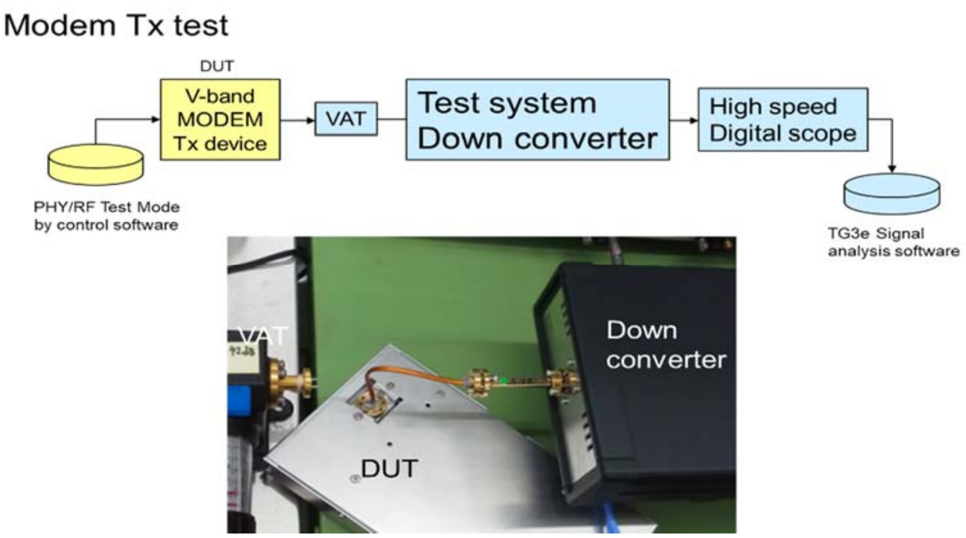

Figure 27 Apparatus configuration for testing the HRCP modem Tx function

The following packet format has been confirmed as the first step

1). At the beginning, the MCS and payload length seems match.

The bit sequence from the scramble seed of the measurement side seems reverse.

Bit mapping of a payload seems not matching.

Scramble code seems not matching. (under investigation)

2). The result of test report was shown as in Figure 28, which was obtained by test equipment.

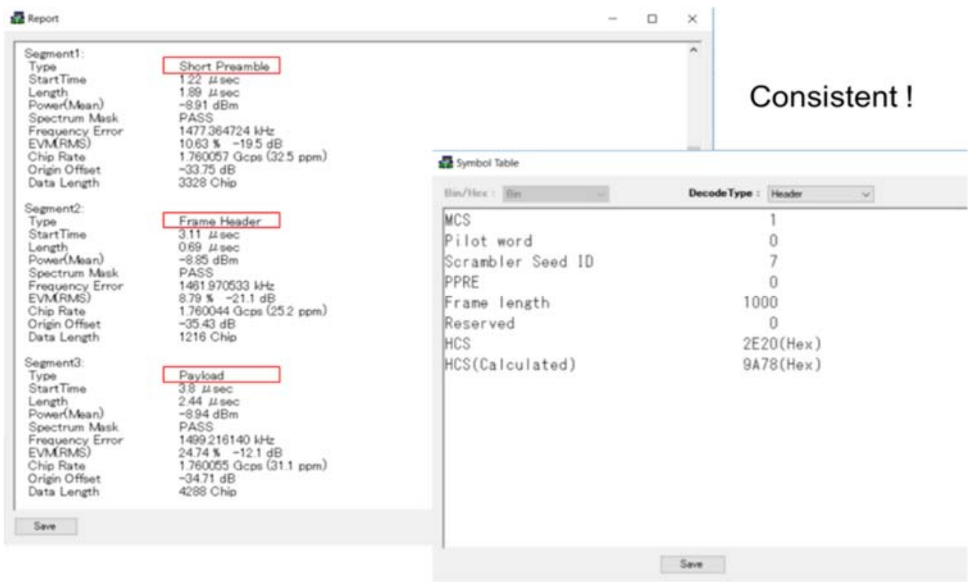

Figure 288 Consistency test report

3). Modulation accuracy and the phase transition were measured as shown in Figure 29. While the signal has some phase and frequency excursion, the frequency tracking embedded in HRCP Rx would compensate them properly to offer stable data transmission.

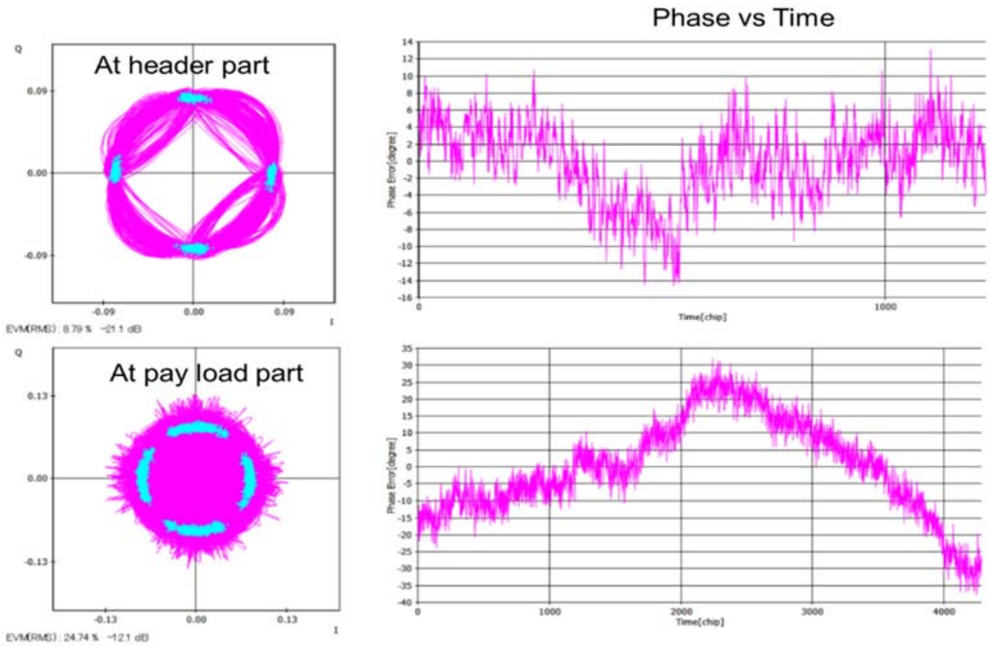

Figure 299 Measured constellation diagram and phase transition

Rx functional check of the HRCP modem

A repeated signal of a specific packet was sent out from the test equipment, received by the HRCP modem, and analyzed by the testing software. The apparatus configuration is shown in Figure 30. The testing signal waveform after transmission is shown in Figure 31. IQ signal waveforms obtained from HRCP modem software is shown in Figure 32, where AGC behaviour was observed. At this moment, the transmitting modulation accuracy of the test equipment is not managed. However, the amplitude fluctuation is largely suppressed in HRCP Rx as shown in Figure 32. Thus, we can deduce that the equalization scheme inside the HRCP device worked well.

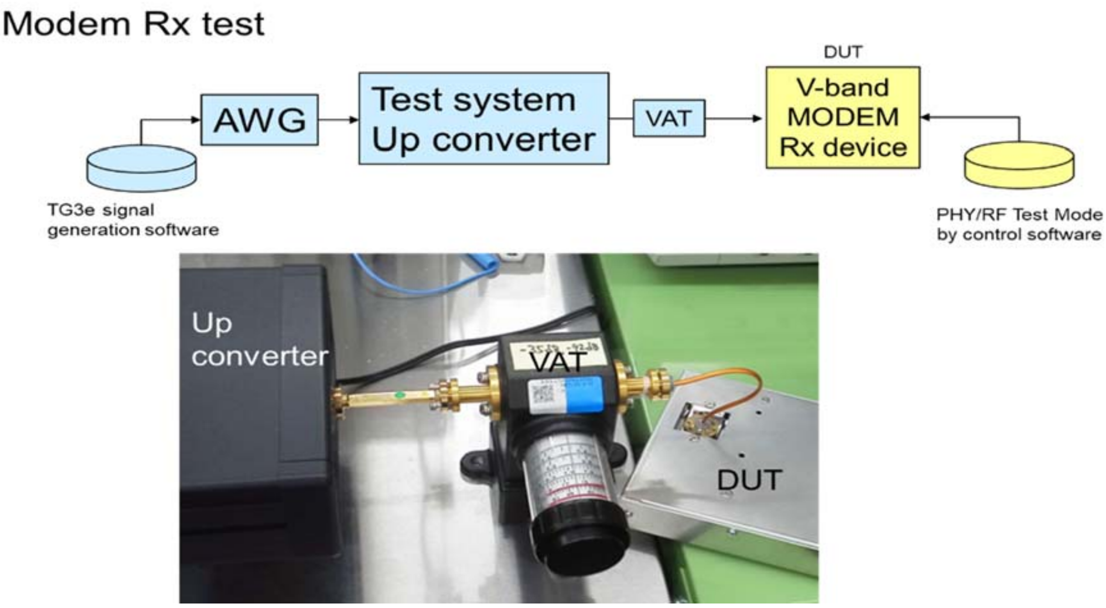

Figure 30 Configuration for testing the HRCP modem Rx function

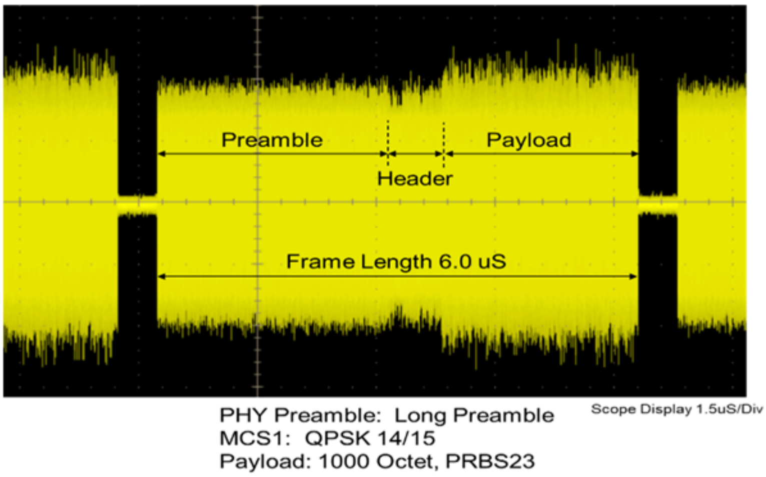

Figure 31 Testing signal waveform after transmission

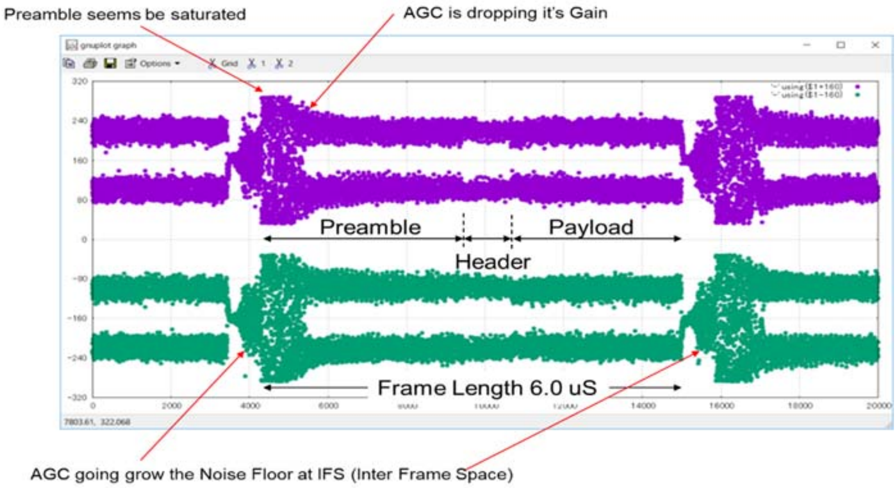

Figure 32 IQ signal waveforms obtained from HRCP modem software

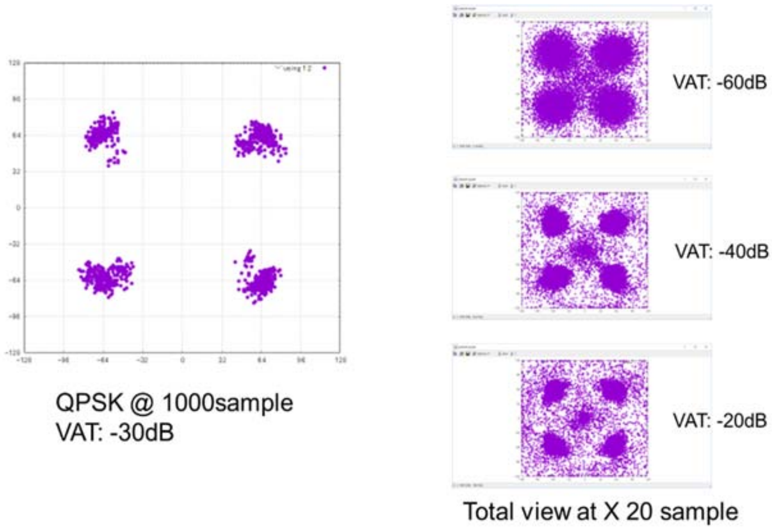

Figure 33 Constellation plots obtained from HRCP modem software

9. Conclusion

The measurement results of the 60 GHz TRX module have been reported.

Basic functionalities and characteristics of both Tx and Rx transceiver has been confirmed with the module testing including some of MAC functions, such as TDD operation.In the system level testing, interoperability with a reference 60-GHz has been also validated and detailed characteristics has been evaluated compared with the reference system.

For Tx side, Tx power of -5.3 dBm is confirmed with the spectral mask maintained. For Rx side, above SDNR margin of 6 dB is confirmed. TRx test shows frame error rate below 1 % for both QPSK and 16QAM modulation.By these results, we can estimate the target characteristics of IF part of the terahertz link for the future integration.

10. References

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