Development of 3GPP 5G Physical Layer Evaluation Software

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[Summary] Development of 3GPP-compliant 5G products and services is accelerating with the start of the first rollouts in late 2019. Additionally, the 3GPP standards have defined the 28- and 39-GHz bands (mmWave band) as FR2, and the frequency band below 6 GHz (Sub-6 GHz band) as FR1.
To meet the physical-layer evaluation requirements of the 3GPP standards, we developed application software for the Signal Analyzer MS2850A supporting mmWave band Tx tests, as well as for the Signal Analyzer MS269xA, which is used on LTE tests previously, for Sub-6 GHz band Tx tests. We have also developed the IQproducer, which generates 5G NR waveform pattern, to support Rx sensitivity tests by outputting those waveforms from the Vector Signal Generator MG3710A and MS269xA with installed signal generator option.

1 Introduction

The 3rd Generation Partnership Project (3GPP) international organization for standardizing mobile communications systems is progressing with the new fifth generation (5G) standard. Consequently, makers of wireless communications equipment are starting full-scale development of devices supporting the so-called New Radio (NR) communications technology without backwards compatibility with the prior Long Term Evolution (LTE) technology. Development and manufacturing of commercial products requires TRx tests in compliance with the various test standards, including 3GPP TS38.211 and 3GPP TS38.141 regulating the physical layer.

3GPP has defined the 5G frequency bands as the mmWave band using the 28- and 39-GHz bands, and the band below 6 GHz (Sub-6 GHz). At Tx tests, the phase noise of the measuring instrument has a large impact on the Error Vector Magnitude (EVM) due to the high frequency of the mmWave band. Additionally, some specified interference waveforms are also required at Rx tests. Those are the Cyclic Prefix OFDM (CP-OFDM) waveforms and the Discrete Fourier Transform-Spread-OFDM (DFT-s-OFDM) waveforms. Moreover, at Sub-6 GHz, 5G NR has the Non Stand Alone (NSA) mode, supporting the operation of both LTE and 5G NR with shared equipments. For more effective use of customers' resources like as presenting equipments for LTE, it is needed to use these equipments to evaluate also 5G NR transceivers. To meet these requirements, we have developed measurement software meeting the 5G NR standards on Tx testing (5G NR measurement software) for the Signal Analyzer MS2850A and MS269xA. Furthermore, we have also developed waveform generation software meeting the 5G NR standards on Rx sensitivity tests for the Signal Generator MG3710A and MS269xA with installed signal generator option. This article describes the key design points in these software developments.

2 Design Concepts

Development was based on the following key concepts.

2.1 Base Station Tx Test Measurement Software

2.1.1 High-Speed Measurement

Since in the 5G NR standard, compared to the Verizon 5G standard for Pre-5G correspondence, there are parameters, such as Subcarrier Spacing and Channel Bandwidth, with more complex parameter combinations, applying a design similar to that of the already commercialized Pre-Standard CP-OFDM measurement software (Pre-5G measurement software) results in lower measurement speed.

Lower measurement speed increases customers' product-inspection times, which makes their costs increase. The aim in developing this measurement software was to improve measurement speed by comparison with the Pre-5G measurement software.

2.1.2 Improved Noise Tolerance (Mainly for mmWave Band)

Since the mmWave band uses a higher carrier frequency than the existing microwave band, frequency errors and phase noise have a serious impact on EVM.

At the development of the Pre-5G measurement software, these caused a degraded-EVM issue at customers' product inspection. Therefore, improving the frequency error lock-in range and phase tracking performance was a problem to be solved.

Consequently, we aimed to achieve the noise tolerance equal to or greater than the Pre-5G measurement software for 5G NR at 100 MHz channel bandwidth.

2.1.3 Improved User Operability

Since 5G NR has more physical layer parameters than either LTE or Pre-5G, manual setting of all these parameters is extremely difficult for users. It causes setting errors resulting in incorrect measurement results.

To improve user operability, we aimed to automate setting of the following parameters.

- Modulation Schemes (QPSK, 16QAM, 64QAM, 256QAM)
  Since the modulation method for PDSCH (Physical Downlink Shared Channel) and PUSCH (Physical Uplink Shared Channel) can be changed in every slot, there are so many setting items and procedures. As a result, modulation setting mistakes occur when changing the target signal for evaluation, causing degraded EVM. An aim of this software development was automation of modulation method identification to suppress setting errors.
- Level Settings (Input Level and Attenuator (ATT))
  Obtaining the best EVM measurement results requires adjusting the input level and ATT to maximize the signal-to-noise ratio (SNR). This adjustment procedure takes time and is difficult because it requires consideration of the input level to the mixer and Analog Digital Converter (ADC) in the measuring instrument. To reduce the burden of this procedure, we aimed to automate the input level and ATT adjustments for SNR optimization.

2.2 Base Station Rx Sensitivity Test Waveform Generation Software

The 3GPP base station test standards define not only Tx tests using the modulation analysis software and spectrum analyzer functions, but also Rx tests. To generate modulated signals required for base station Rx sensitivity tests, we developed waveform generation software (5GNR TDD Sub-6 GHz IQproducer) for outputting waveforms in combination with the Signal Generator MG3710A and MS269xA with installed signal generator option.

This waveform generation software is used to generate the waveform patterns required for base station Rx tests. The Rx test can be performed with outputting the generated waveform pattern from the signal generator. The Rx test standards specifies not only tests with a wanted waveform, but also tests using an interference waveform. As a consequence, the waveform generation software must have functions of generating the following waveforms.

- Waveform patterns for desired wave
  The Fixed Reference Channel (FRC*) waveform pattern, used as the desired waveform for the Rx sensitivity test, primarily requires PDSCH data generation with PDSCH and Channel Coding.
  *FRC: PUSCH data Channel Coding
- Waveform patterns for interference wave
  While the desired signal is a CP-OFDM signal, a DFT-s-OFDM signal is prescribed for the interference signal. Thus, DFT-s-OFDM signal generation would be necessary.

Aside from generating waveforms for base station Rx tests, the waveform generation software must be able to generate a downlink signal that could be utilized as a signal source forevaluation tests for parts, such as amplifiers and filters, used in base stations. Consequently, in addition to the aforementioned target usage, the software was developed to generate waveforms that could support mapping for the Primary Synchronization Signal, Secondary Synchronization Signal, SS-Block (Synchronization Signal Block) consisting of PBCH (Physical Broadcast Channel; including Demodulation RS), PDCCH (Physical Downlink Control Channel; including Demodulation RS), and PDSCH (including Demodulation RS).

2.3 Base Station Transmission Tests using only 1 Measurement Device Unit (Sub-6 GHz)

For Sub-6 GHz tests, a maximum carrier bandwidth of 100 MHz, and an operating band below 6 GHz, the hardware requirements can be covered using the conventional models MS269xA and MG3710A. Thus, the measurement software was developed not only for the mmWave band measurement-capable MS2850A, but also for the conventional models to make it available for use to a wider range of customers. Moreover, the base station transceiver test can be implemented with only one unit of a signal generator option-installed MS269xA, contributing to the reduction of the customer's capital investment.

3 Key Design Points

The key design points meeting the development concepts are as follows.

3.1 Base Station Tx Test Measurement Software

3.1.1 High-Speed Measurement

3.1.1.1 Frame Tracking

To get analysis results, the start timing of frame need to be detected. Since the start timing of frame are unknown without a trigger signal, it is necessary to do frame synchronization by searching the pilot signal (Synchronization signal (SS) or Reference signal (RS)) each time. However, for the case where the periodic signal is measured continuously, it can be assumed that the input signal is a frame period (10 ms) signal.

Since the MS2850A has a built-in Frame Trigger function for generating trigger signals at a constant period, the synchronization processing speed can be increased from the second measurement.

In concrete terms, as shown in Figure 1, the frame's start timing of the signal under test is acquired at the first frame synchronization processing (Frame Acquisition processing). The timing offset between the Frame Trigger at 10 ms period and frame's start timing can be calculated. Then the frame synchronization processing can be faster by shortens the search range (Frame Tracking processing).

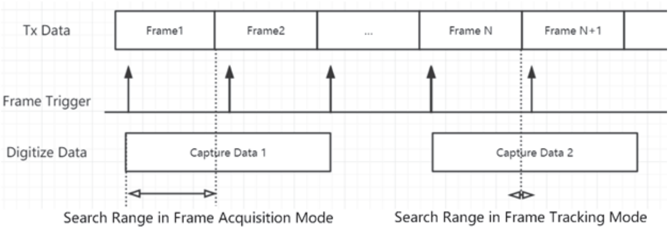

Figure 1 Frame Acquisition and Frame Tracking Processings

3.1.1.2 Multi-carrier Measurement

Similar to LTE, the 5G NR specifications also define the Carrier Aggregation (CA). To reduce the measurement procedures and measurement times by switching each carrier of multiple carriers, we implemented the same Carrier Aggregation measurement used by the Pre-5G measurement software[4] for the 5G NR measurement software. The Carrier Aggregation measurement can measure up to eight carriers at once.

3.1.2 Improved Noise Tolerance (Mainly for mmWave Band)

3.1.2.1 Frame Synchronization Joint Frequency Error Estimation Algorithm

Generally, in comparison to lower frequency bands, the higher frequency bands cause larger multipath fading error and larger phase noise. Consequently, the frame synchronization algorithm must be improved.

Since the frame start position can be detected from the correlation between an ideal signal and the received signal, we proposed a new correlation algorithm by multiplying the complex conjugate of the ideal signal and received signal, by the amplitude of the correlation without being affected by frequency error, the frequency lock-in range is improved.

By applying this algorithm, even with AWGN addition (SNR = 10 dB), the frequency error lock-in range can be extended up to about 8 times the subcarrier spacing, even though the frequency lock-in range of the OFDM signal is only up to 1/2 of the subcarrier spacing in the modulation's principle. This is illustrated by the New Method line in Figure 2. By up to 8 times extension of the frequency error lock-in range, measurements on large frequency error cases can be achieved even in the mmWave Band.

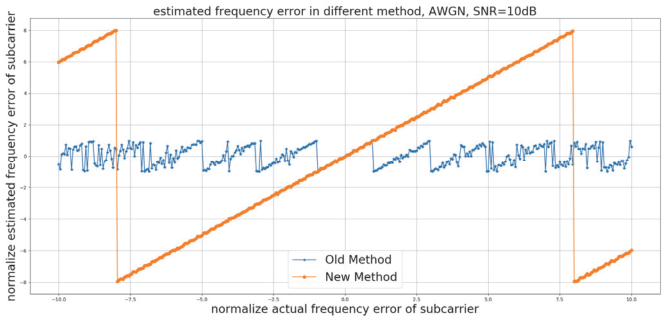

Figure 2 Simulated Frequency Drawing Range Results

3.1.2.2 Phase Tracking

Phase error in the mmWave band becomes large as phase noise becomes large, resulting in degraded measured EVM results. However, EVM measurement results can be improved by improving the phase error correction performance even when the phase error is large.

As shown in Figure 3, it is possible to improve the phase error correction performance by correcting using not only the pilot symbol (Demodulation reference signal (DM-RS) and Phase-tracking reference signal (PT-RS)), but also by using a data symbol replica, such as PDSCH.

The phase error of pilot symbol is easily calculated because the ideal pilot signal is known. On the other hand, the data signal requires temporary demodulation and estimation of the ideal signal (replica creation). Consequently, the phase error correction (phase tracking) processing first calculate and correct the phase error of the pilot signal, then correct the phase error of the data symbol calculated by pilot symbol, after that calculate and correct the phase error of the data symbol by replica creation.

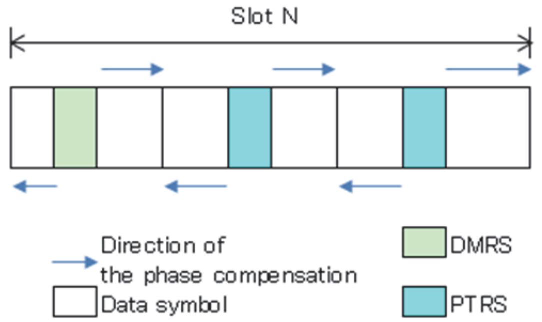

Figure 3 Phase Tracking Method Including Data Symbols

As a result, we proposed an algorithm for feeding-back the phase error calculated from the last time for each OFDM symbol as shown in Figure 4, and then tracking the phase of the data symbol separated from the pilot symbol.

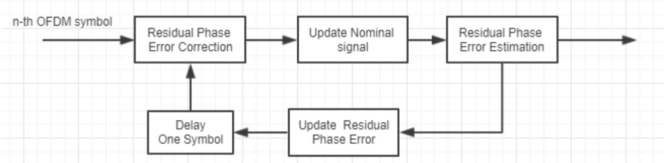

Figure 4 Phase Tracking Process Flowchart for Each Symbol

3.1.3 Improved User Operability

3.1.3.1 Modulation Scheme Automatic Recognition

5G NR also defined 256QAM which specified in LTE from release 8. In addition, the settings are complex because the modulation scheme can be set for each slot. To reduce the setting workload and reduce setting errors, we implemented a function for automatically recognize the modulation scheme. The modulation scheme recognition accuracy can be improved by estimating the SNR using DM-RS.

For example, to recognize QPSK from the other QAM modulation schemes (16QAM, 64QAM, 256QAM), although the MSE (Mean Square Value) between QPSK (red) 16QAM (green) is about 0.15 when the SNR is good enough as shown from Figure 5 (points from about 20 to 40 dB on the horizontal axis). If the recognition threshold is fixedly set to 0.15 the recognition may fail which recognize QPSK to “not QPSK” since the MSE rises when the SNR becomes worse.

Consequently, it is possible to recognize the modulation scheme more accurately by setting the recognition threshold softly according to the SNR vs MSE curve (Figure 5).

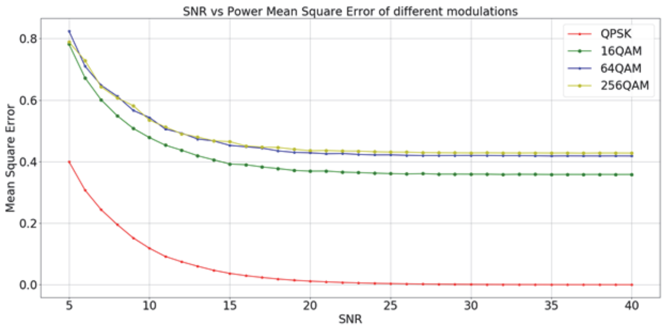

Figure 5 Modulation Scheme SNR vs MSE

For other high-order QAM modulation as 16QAM or higher, with mapping process from quadrants 2, 3, and 4 to quadrant 1 (Figure 6), which maps high-order QAM to QPSK, the recognition can be achieved using the same algorithm of QPSK. The example of mapping 16QAM to QPSK is shown in Figure 6, if the input is 64QAM, we can map 64QAM to 16QAM first, then do the processing again to map to QPSK.

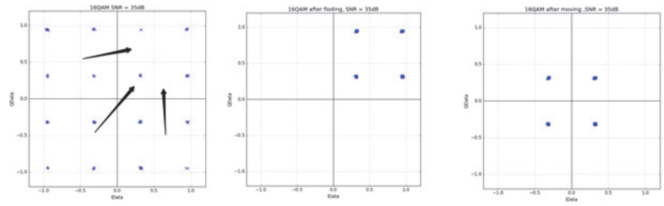

Figure 6 Constellation folding process (16QAM)

The SNR vs MSE shown in Figure 7 after the above mapping process, it is possible to recognize from 16QAM (green) and 64QAM and other (red and yellow lines) by setting the soft threshold. (The 64QAM and 256QAM recognition is similar, and only requires once more mapping processing more.)

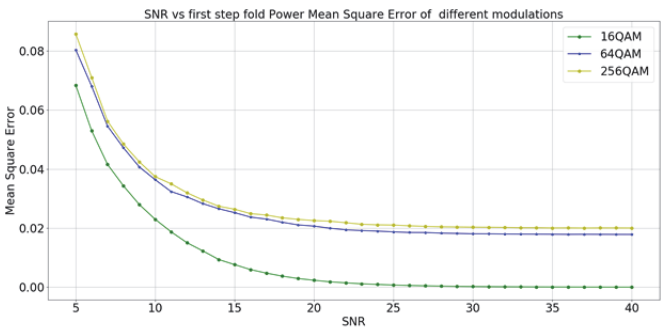

Figure 7 SNR vs MSE After 16QAM Mapping Processing

3.1.3.2 Auto Ranging

The EVM results can be more accurately, by adjusting measuring instrument internal settings[4].

The 5G NR measurement software has a built-in Auto Range function[5] like that in the Pre-5G measurement software. Additionally, to port the 5G NR measurement software to the MS269xA, different consideration was given to design of the MS269xA hardware.

Different with the MS2850A, when the MS269xA correct the RF-ATT for adjusting the input level to the front end mixer or the IF-ATT for adjusting the ADC input level, the MS269xA can't correct them by each frequency band. Consequently, the best RF-ATT and IF-ATT attenuation level is determined by considering the frequency characteristics to get the EVM optimum conditions as shown in Figure 8.

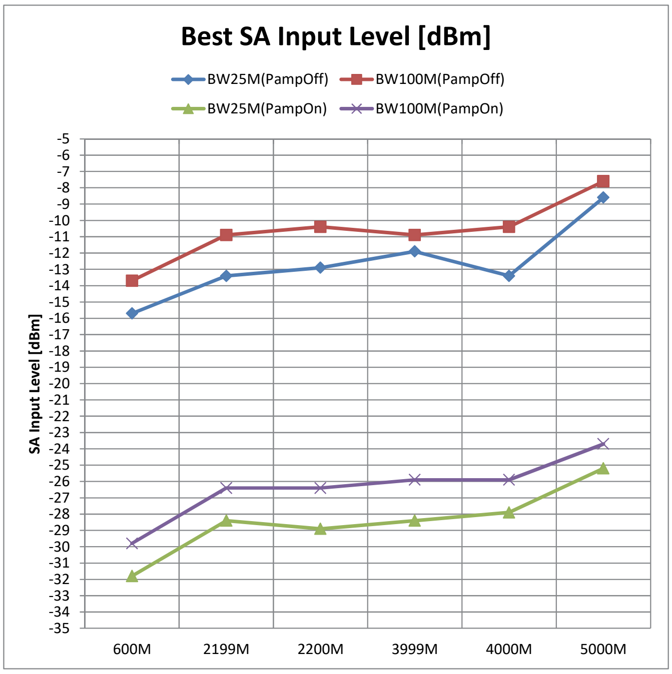

Figure 8 Best SA Level for EVM at Each Frequency (RF-ATT = 0 dB, IF-ATT = 0 dB)

3.2 Base Station Rx Sensitivity Test Waveform Generation Software

The design of the waveform generation software GUI was based on the LTE-TDD IQproducer waveform generation software, which generates waveforms based on the 3GPP standard. Since the 5G NR waveform generation software is also based on the same 3GPP standard, adopting the same user GUI operations helps shorten development time. Table 1 and 2 show Subcarrier Spacing (SCS) and bandwidth combinations required by the Sub-6 GHz band. The differences in the generated Downlink and Uplink bandwidth occur because the bandwidth with the number of resource blocks (RB) where the SS-Block cannot be allocated is not supported in Downlink.

Table 1 Bandwidth vs SCS (Downlink)

SCS* (kHz)	Bandwidth (MHz)												
	5	10	15	20	25	30	40	50	60	70	80	90	100
15	○	○	○	○	○	○	○	○	—	—	—	—	—
30	—	○	○	○	○	○	○	○	○	○	○	○	○
60	—	—	○	○	○	○	○	○	○	○	○	○	○

*: Subcarrier Spacing

Table 2 Bandwidth vs SCS (Uplink)

SCS* (kHz)	Bandwidth (MHz)												
	5	10	15	20	25	30	40	50	60	70	80	90	100
15	○	○	○	○	○	○	○	○	—	—	—	—	—
30	○	○	○	○	○	○	○	○	○	○	○	○	○
60	—	○	○	○	○	○	○	○	○	○	○	○	○

*: Subcarrier Spacing

For the physical channels and generated signals, refer to Table 3 for the Test Model signals used at the Rx sensitivity test and the Tx test.

In addition, both Low Density Parity Check (LPDC) and Polar encoding are specified as channel encodings by the 5G NR standard. To generate waveform patterns for the Rx tests, LDPC encoding of PUSCH data, required by Rx tests, is included in the design. Furthermore, support for switching Uplink modulation scheme between CP-OFDM and DFT-s-OFDM is provided to create both wanted and interference waveforms.

Table 3 Physical Channel vs Signal

Downlink	Primary Synchronization Signal
	Secondary Synchronization Signal
	PBCH
	Demodulation RS for PBCH
	PDCCH
	Demodulation RS for PDCCH
	PDSCH
	Demodulation RS for PDSCH
Uplink	PUSCH
	Demodulation RS for PUSCH

3.3 One Unit Covering Base Station TRx Tests (Sub-6 GHz)

With one MS269xA unit, the followings were implemented to perform TRx tests as well as to evaluate base station parts, such as amplifiers and filters.

- Measurement software for evaluating 3GPP Sub-6 GHz 5G NR using the MS269xA based on measurement software designed for MS2850A
- Output of waveform data generated by waveform generation software from MS269xA signal generator option

4 Functions and Performance

This section shows the functions and performance implemented on the basis of each development concept.

4.1 Base Station Tx Test Measurement Software

4.1.1 High-Speed Measurement

Figure 9 shows the data for 10 test measurements executed with and without the Frame Trigger under the same conditions (SCS = 120 kHz, channel bandwidth = 100 MHz).

Due to the randomness in the frame timing, randomness of between about 1.2 s and 2.4 s occurred at each measurement as shown in the top part of Figure 9. Using the Frame Trigger to perform frame synchronization in the minimum time for each measurement (orange parts in graph approximate lower limit) achieved the lower limit measurement time as shown in the bottom part of Figure 9.

For example, focusing on the measurement time for the third measurement, the measurement time without frame tracking was about 2.3 seconds, falling to 1.3 with frame tracking, which is an improvement over the time of about 2.0 s recorded for the Pre-5G measurement software.

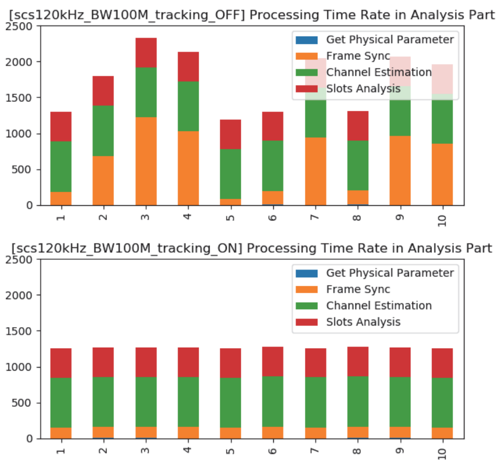

Figure 9 Measurement Time Before/After Using Frame Trigger (10 times)

4.1.2 Improved Noise Tolerance (Mainly for mmWave Band)

By applying the new correlation algorithm described in section 3, synchronization was achieved even when the frequency error was several times the subcarrier spacing. As a result, the lock-in range was improved to ±8 Subcarrier from the Pre-5G measurement software lock-in range of ±1 Subcarrier.

Moreover, applying phase tracking using the data-symbol replica improved the phase error tolerance compared to the Pre-5G measurement software, getting good EVM results even when adding phase modulation (Figure 10 and 11). Consequently, it is possible to measure signals with large phase noise even in high-frequency bands.

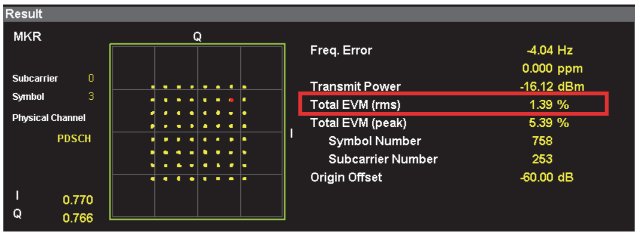

Figure 10 Measured Phase Modulation (0.5 rad) 5G NR Measurement Software Results

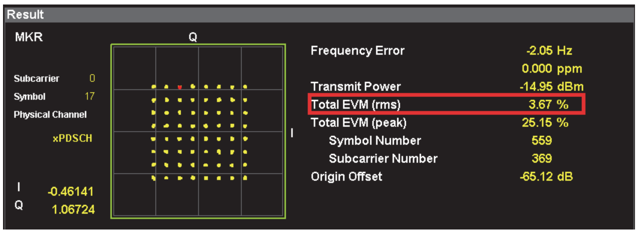

Figure 11 Measured Phase Modulation (0.5 rad) Pre-5G Measurement Software Results

4.1.3 Improved User Operability

By implementing the automatic recognition of modulation schemes including 256QAM, and the automatic setting of the optimum level in the 5G NR measurement software ported to the MS269xA, the user operability was improved.

Figure 12 shows the measurement results for waveforms with different modulation schemes at each slot using the automatic function for recognition the modulation scheme. From this figure, it is clear that the automatic recognition function is operating correctly at EVM measurement for each modulation scheme even with mixed modulation schemes.

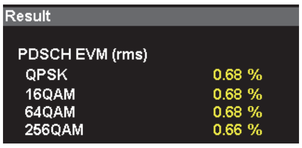

Figure 12 Measured EVM Analysis Results for Modulation Waveforms (Modulation Scheme Auto- Recognition)

Figure 13 shows the results of measuring a 256QAM, 100-MHz channel bandwidth, 5G NR Sub-6 GHz signal with a center frequency of 3.75 GHz using the MS2691A. An EVM of 0.30% was achieved using the automatic modulation recognition setting (Auto) and the Input Level and ATT settings performed automatically using the Auto Range function. The optimal EVM results was obtained without adjustment of the input level to the measuring instrument.

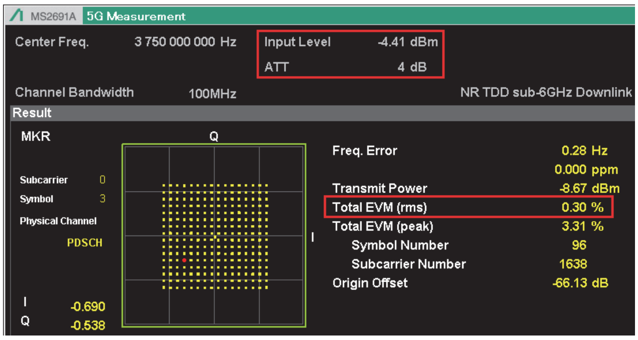

Figure 13 MS2691A EVM Analysis Results (After Auto Range)

4.2 Base Station Rx Sensitivity Test Waveform Generation Software

Figure 14 shows the 5G NR TDD Sub-6 GHz IQproducer main screen. As can be seen, the GUI uses the same operations as LTE TDD IQproducer, providing an easy-to-use IQproducer to the users who knows the 3GPP 5G NR standards.

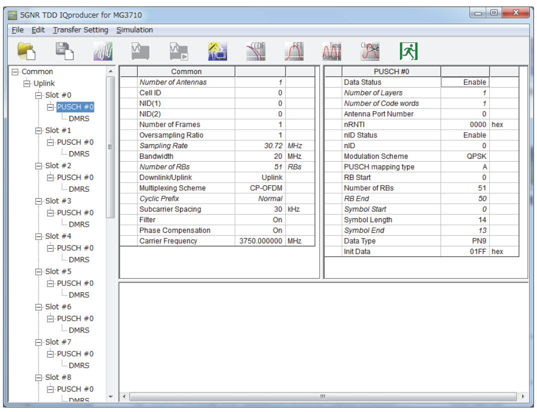

Figure 14 5G NR TDD Sub-6 GHz IQproducer Main Screen

The key design points for 5G NR TDD Sub-6 GHz IQproducer explained in section 3.2 were implemented to generate G-FR1-A1 and G-FR1-A2 Rx test signals specified in 3GPP TS 38.141-1. Figure 15 shows the UL-SCH settings required for generating Rx test signals.

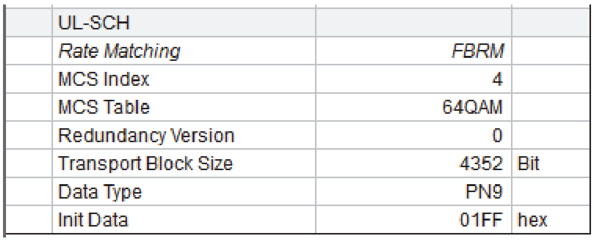

Figure 15 5G NR TDD Sub-6 GHz IQproducer UL-SCH setiing Screen

Generation of both wanted and interference waveforms is implemented. Consequently, as shown in Table 4, generation of waveforms required for Rx sensitivity test items specified by 3GPP TS 38.141-1 has been implemented. The 5G NR TDD Sub-6 GHz IQproducer application software generates the 5G NR signal waveforms outputing at the MG3710A and the MS269xA with vector signal generator option. Both the wanted and interference waveforms can be output using one MG3710A unit. Additionally, when the 5G NR measurement software is also installed simultaneously in the MS269xA, the modulation analysis function required by the Tx test is supported and the wanted waveform required by the RX sensitivity test is output.

Table 4 Test Items (Conducted Receiver Characteristics)

Measurement Item	Wanted Waveform	Interference Waveform
Reference sensitivity level	○	—
Dynamic range	○	—
Adjacent Channel Selectivity (ACS)	○	○
In-band blocking	○	○
Out-of-band blocking	○	—
Receiver spurious emissions	○	—
Receiver intermodulation	○	○*
In-channel selectivity	○	○

*: Excluding CW carrier in interference waveform

4.3 One Unit Covering Base Station TRx Tests (Sub-6 GHz)

Figure 16 and 17 show the 3GPP TS38.211 waveforms measured by the MS269xA. These waveforms are generated by 5G NR TDD Sub-6 GHz IQproducer and are outputted from the MS269xA signal generator option.

With these results, we can see that one MS269xA unit can output and analyze 5G NR waveforms to perform TRx tests and evaluate base station parts, such as amplifiers and filters. Additionally, users already owning the MS269xA can maximize the efficiency of their high-cost investment simply by installing this software to support 5G NR evaluations.

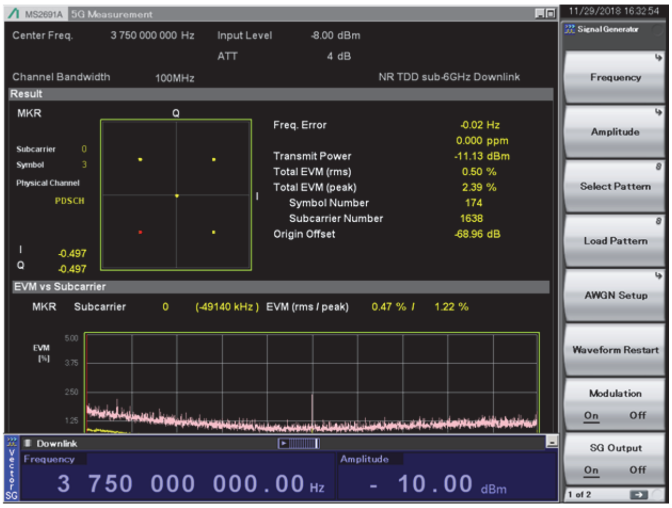

Figure 16 MS269xA EVM Measurement Results (Downlink)

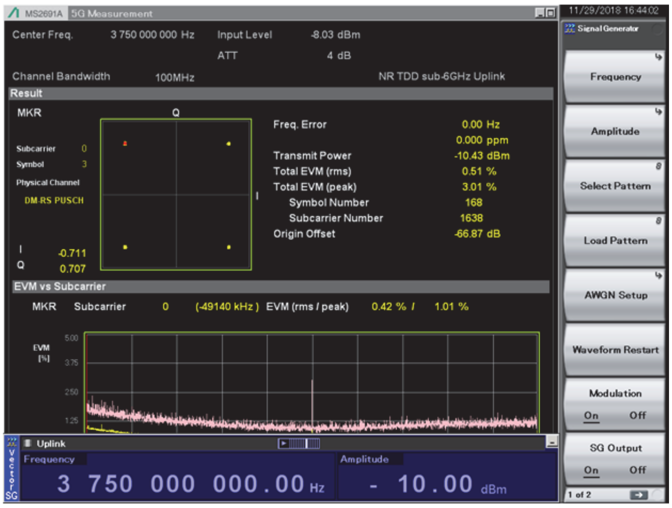

Figure 17 MS269xA EVM Measurement Results (Uplink)

5 Conclusion

We have successfully developed application software using either the high-performance Signal Analyzer MS2850A with a wide modulation analysis bandwidth of 1 GHz at carrier frequencies up to 40 GHz, or the MS269xA for supporting Sub-6 GHz 5G NR Tx tests. They are suited to evaluation of the 3GPP-defined 5G NR physical layer. In addition, we have also developed IQproducer software for generating waveform patterns used for Sub-6 GHz Rx sensitivity tests by outputting from either the Signal Generator MG3710A or MS269xA with signal generator option. Moreover, With maximizing the usefulness of the MS269xA key function (signal generator option), one MS269xA is able to support both 5G NR Tx and Rx tests.

As a result of these developments, Anritsu's customers can now choose the best measurement solution matching development and commercial manufacturing of their 5G NR products.

Anritsu is continuing our efforts to provide makers of wireless equipment with the best measurement solutions by promoting research into advanced wireless communications technologies.

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