Wideband mm-Wave Signal Generation and Analysis
Application Note

Products:
- R&S®SMW200A
- R&S®FSW
- R&S®SMB100A
- R&S®RTO
- R&S®SMF100A
- R&S®FSW-B2000
  - R&S®FSW-B21
  - R&S®FSW-K70
  - R&S®FS-Zxx

Generation of wideband digital modulated signals in V-band and above is a challenging task and typically requires a set of multiple instruments. This application note aims at simplifying the task and looks into the analysis part as well. Latest signal and spectrum analyzers like the R&S®FSW67 are first to allow use in V-band up to 67 GHz without external frequency conversion. Up to 2 GHz of modulation bandwidth can be covered using the option R&S®FSW-B2000.

Former application note 1MA217 describes V-band signal generation and analysis up to 500 MHz modulation bandwidth. This application note expands modulation bandwidth to 2 GHz but also an alternative setup is used to cover the necessary bandwidth and to obtain enhanced purity in signal generation.

Note:
Please find the most up-to-date document on our homepage:
http:\\www.rohde-schwarz.com/appnote/1MA257
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This application note uses the following abbreviations for Rohde & Schwarz products:

- The R&S®SMW200A Vector Signal Generator is referred to as SMW
- The R&S®SMB100A RF and Microwave Signal Generator is referred to as SMB
- The R&S®SMF100A Microwave Signal Generator referred to as SMF
- The R&S®FSW Signal and Spectrum Analyzer is referred to as FSW
- The R&S®RTO Digital Oscilloscope is referred to as RTO
- The R&S®FSW-B2000 2 GHz Analysis Bandwidth is referred to as FSW-B2000
- The R&S®FSW-B21 LO/IF Connections for External Mixers is referred to as FSW-B21
- The R&S®FSW-K70 Vector Signal Analysis is referred to as FSW-K70
- The R&S®FS-Zxx Harmonic Mixers are referred to as FS-Zxx

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1 Motivation

High modulation bandwidth with up to 2 GHz is proposed e.g. for automotive radar and "5G" mobile communication applications. Beside bands below 6 GHz and around 11 GHz, 28 GHz and 38 GHz, a large chunk of potential "5G" bandwidth is available in the mm-wave bands within the either unlicensed or "license-light" 1) bands. Wireless LAN according to 802.11ad standard uses already the frequency range in V-band with a modulation bandwidth of 1.76 GHz (single carrier mode). Below a table of bands in the mm-wave range which are already used by communication and automotive radar applications or which are considered as interesting for "5G" as unlicensed of "license-light" bands.

<table>
<thead>
<tr>
<th>Frequency bands in the mm-wave range (license light or unlicensed)</th>
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<tbody>
<tr>
<td>V-band (57 GHz to 64 GHz)</td>
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<tr>
<td>Lower E-Band (71 GHz to 76 GHz)</td>
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<tr>
<td>Middle-E-band (77 to 81 GHz)</td>
</tr>
<tr>
<td>Upper E-band (81 GHz to 86 GHz)</td>
</tr>
<tr>
<td>W-band (92 to 95 GHz)</td>
</tr>
</tbody>
</table>

Table 1-1: Bands in the mm-wave range which are already used by communication and automotive radar applications or which are considered as interesting for "5G" as unlicensed of "license-light" bands.

Fig. 1-1 illustrates available license-light or unlicensed frequency ranges in V-, E- and W-band in the frequency domain.

```
7 GHz
60 GHz
V-Band
unlicensed

5 GHz
4 GHz
5 GHz
2 GHz + 0.9 GHz
E-Band
license-light

4 GHz
reserved for automotive radar
lower

W-Band
indoor: unlicensed

outdoor: license-light

Fig. 1-1: Unlicensed or license-light frequency ranges in V-, E-Band and W-Band
```

1) Wireless communication regulators in the USA, UK and many other countries have introduced “light licensing” schemes for managing these bands due to their characteristics. The short range and highly directional transmissions allow for excellent frequency reuse since systems can be engineered to operate in close proximity to one another without causing interference. These innovative licenses retain the benefits of full interference protection that wireless license guarantees, but can be applied for significant less cost.
Generation of wideband digital modulated signals in V-band and above is a challenging task and typically requires a set of multiple instruments. Latest signal and spectrum analyzers like the FSW67 are first to allow use in V-band 67 GHz without external frequency conversion. With option FSW-B2000 the FSW frequency family cover a demodulation bandwidth of up to 2 GHz.

This application note describes a setup for wideband digital modulated signal generation for V-band and shows the use of FSW67 for wide-band V-Band applications.
2 Setup

Fig. 2-1: Setup for Wide band mm-wave Signal Generation and Analysis

- **Generation of modulated IF signal 4 to 16 GHz:**
  
  A SMW200A (20 GHz model) with up to 2 GHz modulation bandwidth is externally modulated by a suitable wideband arbitrary waveform generator e.g. a Tabor WX2182C and its signal fed to the IF input of a V-band waveguide mixer.

- **Generation of LO signal for up-conversion**

  The second channel of the SMW200A (or alternatively a suitable SMB100A or SMF100A) produces a CW signal e.g. 13.25 GHz which is fed to the input of an active quadrupler. The forth harmonic output of the quadrupler e.g. 53 GHz is filtered further by a band pass filter and used as a local signal for a V-band up-converter-mixer.

- **Up-conversion**

  The mixer linearly up-converts the IF input signal to RF (mm-wave frequency range) following the formula: \( f_{RF} = f_{LO} \pm f_{IF} \).

  The RF output of the up-converter mixer is terminated by an isolator and followed by a high pass filter which suppresses the lower sideband: \( f_{LO} - f_{IF} \) and the LO.
feedthrough. The isolator serves to get low ripple in the pass band. The used upper sideband $f_{LO} + f_{IF}$ is amplified and is available at the “mm-Wave reference plane” for testing e.g. a V-band receiver or V-band transceiver components like an amplifier.

### Signal Analysis:

Wide Band Signal Analysis is provided either by:

- an FSW67 with VSA option FSW-K70 and option FSW-B2000 (up to 67 GHz) or by
- a suitable FS-Zxx harmonic mixer and an FSW43 or FSW50 with VSA option FSW-K70 and options "Connections for external mixers" FS-Z21 and FS-B2000

To analyze a signal with up to 2 GHz bandwidth the FSW down-converts it to an intermediate frequency of 2 GHz, which is then digitized by an RTO oscilloscope at sample rate of 10 GHz. The FSW equalizes this digital signal and adjusts the sampling rate. The entire signal path including the oscilloscope is calibrated. For ease of operation the FSW controls the RTO remotely.
Considerations when using the setup for mm-Wave Band signal generation

Using the recommended setup for mm-Wave signal generation and - analysis is fairly straightforward. However, depending on the frequency settings, some crucial points and how to overcome them are highlighted in the following.

3.1 Spurious due to harmonics of multiplier

The quadrupler nominally multiplies its input signal by a factor of 4. Due to imperfections of the quadrupler also other harmonics of the input signal occur. Typical suppression of these other harmonics is -30 dB relative to the wanted 4th harmonic. For a LO frequency of 53 GHz the quadrupler input signal is 13.25 GHz. The 5th harmonic is 66.25 GHz and is the closest one to the wanted frequency band 57 to 64 GHz, but it is still 2.25 GHz outside of this band (this is an advantage of the quadrupler instead of the 6x multiplier proposed in [1]).

The band pass filter after the quadrupler (Fig. 2-1) suppresses these harmonics to a negligible extent.

3.2 Spurious due to mixing

Possible spurious at the mm-reference plane caused by the formerly described up-conversion follow the rule:

\[ f_{SP} = n^*f_{IF} \pm m^*f_{LO}, \text{ where } n = \pm 0, 1, 2, 3... \text{ and } m = \pm 0, 1, 2, 3... \]

Beside multiples of the \( f_{LO} \) component, spurious appear in the shape of the digitally modulated IF signal. The bandwidth of these signals is \( n^* \) (bandwidth at \( f_{IF} \))

Typically, the lower order spurious like \( 2^*f_{LO} - 3^*f_{IF}, 2^*f_{LO} - 4^*f_{IF}, 3^*f_{LO} - 4^*f_{IF},... \) have the higher power levels compared to the higher order ones.

Low order spurious signals may become critical if they fall into the band of interest and/or get close to the wanted output signal. Modulation parameters such as EVM of the wanted signal may degrade significantly in this case.

The perhaps tempting choice of LO and IF frequencies being close to each other results in a situation where lower order (and hence stronger) spurious will fall into the vicinity of the wanted signal.

Example:

If we aim to generate a 63 GHz digitally modulated signal in license-exempt ISM V-band frequency range 57 to 64 GHz, then using e.g. an IF frequency of 10 GHz and a LO frequency of 53 GHz we get:

\[ 2^*53 \text{ GHz} - 3^*10 \text{ GHz} = 76 \text{ GHz: significant level (3rd IF harm.) but far out of band,} \]
Considerations when using the setup for mm-Wave Band signal generation

\[ 2\times 53 \text{ GHz} - 4\times 10 \text{ GHz} = 66 \text{ GHz}: \text{still 2 GHz out of band, but reasonably low level} \]

\[(4\text{th harm.}), \text{certainly must be monitored.}\]

\[ 3\times 53 \text{ GHz} - 4\times 10 \text{ GHz} = 119 \text{ GHz}: \text{far out of band} \]

Rules of thumb:

The higher IF frequencies used in composition of a band to be covered tend to be the more critical ones.

The lower order harmonics of any given IF are the more critical ones.

Mixing products with \(3\times f_{\text{LO}}, 4\times f_{\text{LO}}\) and higher which fall into the band of interest are higher order IF harmonics and therefore generally have low power.

3.3 Spurious due to harmonic mixer

The R&S®FSW67 covers measurements up to 67GHz. Using the FSW to carry out spectrum measurements beyond the nominal 67 GHz limit, e.g. further up in the E-Band is possible with external harmonic mixers of the FS-Z family. For frequencies below 67 GHz, use of harmonic mixers instead of the FSW67 model may also be attractive with regard to budget.

When the FS-Z family harmonic mixers are employed, additional considerations apply.

FS-Z mixers multiply the spectrum analyzer’s local oscillator output signal and use a suitable harmonic to down convert the DUT’s millimeter-wave signal to the analyzer’s intermediate frequency. However, the number of harmonics created in the mixer and the input signal and it’s own harmonics produce a multitude of signal components in the spectrum. In addition, the image frequency range is not suppressed as there is no pre-selector for this purpose.

The FSW signal and spectrum analyzer family with the FSW-B21 option (LO/IF connectors for external mixers) have a major advantage compared to conventional instruments. With an intermediate frequency of 1.3 GHz (in spectrum analyzer mode, in VSA mode an intermediate frequency of 2 GHz is used), the FSW analyzers have an image-free frequency range of 2.6 GHz. This makes it easy to measure wideband-modulated signals, even if their bandwidth reaches into the GHz range. Together with the latest generation of Rohde & Schwarz harmonic mixers, e.g. the FS-Z90 (60 GHz to 90 GHz), the achievable dynamic range is truly unique. The mixer has a typical conversion loss of 23 dB at 80 GHz, resulting in a displayed average noise level (DANL) of approximately \(-150 \text{ dBm/Hz}\) for the test setup, i.e. including the mixer’s and analyzer’s contributions.
Considerations when using the setup for mm-Wave Band signal generation

Fig. 3-1: Measurement of a 500 MHz bandwidth E band input signal with an FSW signal and spectrum analyzer with the FS-Z90 Harmonic Mixer. The input and image-frequency signal are 2.6 GHz apart. Measuring the spectrum mask or analyzing the modulation quality of significantly wider signals is possible without any difficulty.
4 Test Results

This section serves to verify and demonstrate the typical performance of both R&S signal generation and signal analysis capabilities in the mm-wave ranges covered by this paper. Note that for all of the following modulation measurements the FSW equalizer is active in VSA mode and eliminates the frequency slope influence within the modulation bandwidth. Without using the equalizer function in VSA mode, the measured EVM values increase by a factor of 4 to 5. However, for typical wideband digital modulation systems such as OFDM (also with IEEE 802.11ad single carrier mode) the EVM is defined with equalized frequency slope, so that the EVM measurement results shown are representative for real world values.

4.1 Typical performance of the proposed test setup

Fig. 4-1 shows the typical EVM performance of the proposed setup shown in Fig. 2-1 using an FSW67 with option "2 GHz Analysis Bandwidth" FSW-B2000. The SMW channel A generates an IF frequency of 5 GHz which is externally QPSK modulated by an arbitrary waveform generator with a symbol rate of 1.6Gsymb/s. This IF frequency is up-converted to 58 GHz using an LO signal of 53 GHz (13.25 GHz delivered e.g. from channel B of the SMW, multiplied by a factor of 4). The FSW analyses the 58 GHz signal and measures an EVM of 3.3%.

Fig. 4-1: Constellation diagram and EVM measurement on a 58 GHz up-converted wideband QPSK signal from an SMW200A signal generator externally modulated by an suitable arbitrary waveform generator

Fig. 4-2 shows another example: The performance of the test setup when generating and analyzing an IEEE 802.11ad (WiGig) signal at channel 2 (60.48 GHz) with π/2-QPSK single carrier modulation at 1.76 Gsymb/s. At this higher modulation rate still an EVM of < 5% can be achieved. The FSW displays the constellation diagram, result summary, capture buffer and the frequency response of the equalizer. (The configuration of the displayed results is conveniently possible using the FSW touchscreen.)
Fig. 4-2: Modulation Measurement of an FSW on an IEEE 802.11ad (WiGig) signal generated by the setup shown in Fig. 2-1
4.2 Typical applications and test results

This chapter demonstrates test results and setups with two different test devices:
- a commercial 802.11ad transmitter and
- a commercial V-band transceiver for backhaul applications

4.2.1 Tests on an commercial 802.11ad transmitter

Fig. 4-3: shows a spectrum emission mask measurement result of an FSW 67 of an IEEE 802.11ad device transmitting at channel 2. The left slope of the spectrum induces a FAIL of the spectrum mask, prompting a re-alignment of the device.

Fig. 4-4 shows a modulation measurement on an IEEE 802.11ad device transmitting at channel 2 by an FSW67. The constellation diagram, Result Summary, Magnitude of the capture buffer and the phase error are displayed.
Fig. 4-4: Modulation Measurement on an 801.11ad device transmitting at channel 2 by an FSW67 (showing Constellation diagram, Result Summery, Magnitude of Capture Buffer and Phase Error).
4.2.2 Tests on an V-band Transceiver 57 to 64 GHz for Backhaul Applications (Supplier: "Infineon Technologies AG")

In the following, test setups are described for tests on the receiver and transmitter part of a V-band transceiver. Measurement results from a commercial V-band transceiver for backhaul applications are presented.

4.2.2.1 Transmitter Part

Fig. 4-5 shows two possible test setups for testing the transmitter part of a V-band transceiver with wideband modulation. The wideband baseband I-Q signal is generated by a suitable arbitrary waveform generator e.g. a Tabor WX2182C and fed to the I-Q inputs of the transceiver.

The RF output of the transmitter is connected directly to the RF input of an FSW67 with VSA option and FSW-B2000.

Alternatively it can be connected via a suitable attenuator to an FS-Zxx series harmonic mixer. An FSW43 with VSA option, FSW-B2000 and external mixer option (FSW-B21) is used for analyzing the RF signal in this case.

If a harmonic mixer is used for measuring the output signal of a transmitter, care has to be taken not to overload it. The FS-Zxx harmonic mixers have a 1-dB compression point of typical -6 dBm. For not to degrade the performance of the measured signal in terms of adjacent channel power or EVM, the peak level of the signal should be well below the 1-dB compression point (rule of thumb: 15 to 20 dB lower) at the mixer input. Recommended is a wave-guide level setting attenuator in front of the harmonic mixer and its according adjustment for getting optimum dynamic range.

In both cases an RTO1044 Digital Oscilloscope is used to sample the IF output signal of the FSW which provides the signal analysis based on the sampled data. The use of RTO as a digitizer does not affect signal analyzer operation in any way; the FSW/RTO combination is operated just like a stand-alone FSW instrument.
Fig. 4-5: Possible test setups for testing the transmitter part of a V-band transceiver with wideband modulation.

Fig. 4-6 shows a spectrum and channel power measurement of an FSW67 on a commercial V-band transmitter 57 to 64 GHz for backhaul applications. The transmitter is modulated by a 16 QAM baseband signal with a symbol rate of 1.8 Gsymb/s which leads to a 2 GHz wide modulation spectrum. The shoulders left and right outside the channel bandwidth are aliasing products of the used arbitrary waveform generator.

Fig. 4-6: Spectrum and Channel Power Measurement of an FSW67 on a commercial V-band transceiver for backhaul applications.

Fig. 4-7 shows an FSW67 modulation measurement on a V-band transceiver modulated by a 16 QAM signal with a symbol rate of 1.8 Gsymb/s. The constellation...
diagram, the error summary, the magnitude of the capture buffer and the error vector magnitude over time are displayed. Again, the equalizer of the FSW Vector Signal Analysis measurement option was active with this measurement.

Fig. 4-7: Modulation measurement of an FSW67 on a commercial V-band transceiver for backhaul applications.

### 4.2.2.2 Receiver Part

The test signal for the V-Band receiver is generated as described in chapter 2 and shown in Fig. 4-8. The amplifier after the high pass filter may be omitted from the setup, because receivers normally are tested at low input power levels. The input level of the receiver is varied by changing the SMW’s output level; this change is transferred to the up-converting biased mixer’s RF output port with high linearity.

I and Q outputs of the receiver under test are connected to the RTO channel 1 and 2. Data is captured by the RTO in I-Q mode, setting its sample rate to 4 times the symbol rate of the modulation signal. The captured data are exported to the FSW with VSA option (e.g. via USB stick) which provides thus modulation analysis of the captured data.
Fig. 4-8: Schematic diagram for a setup to test the receiver part of a V-band transceiver

Fig. 4-9 shows a photo taken of a setup for testing the receiver part of a mm-Wave transceiver. The V-Band test signal is fed from the converter output waveguide to the receiver input of the receiver under test. I and Q outputs are connected to channel 1 and 2 of the RTO. The unit labelled "Converter" hosts the components inside the dotted lines in Fig. 4-8 above.
Fig. 4-8: Photo of a practical test-setup for testing the RX part of a V-band transceiver
(Supplier: "Infineon Technologies AG")

Fig. 4-10 shows the EVM performance of the receiver under test at an input power level of -50 dBm using a QPSK signal with 1.6 Gsym/s captured via Channel 1 & 2 of an RTO with a sampling rate of 6.4 Gs/s. The sampled signal is exported e.g. via USB stick to the FSW which analyzes it. The measured EVM is about 14 % rms. As can be seen in the I/Q constellation diagram, the different states can still be detected with low error probability at this extent of EVM.

Fig. 4-10: EVM measurement at the IQ outputs of a V-band receiver at -50 dBm input power level.
Modulation parameters: QPSK with 1.6 Gsym/s
5 Literature

[1] Roland Minihold, Application Note 1MA217 "mm-Wave Signal Generation and Analysis"


[3] Dr. St. Heuel, Dr. S. Michael, M. Kottkamp, Application Note 1EF92 "Wideband Signal Analysis"
## 6 Ordering Information

<table>
<thead>
<tr>
<th>Type of Instrument</th>
<th>Designation and range</th>
<th>Order No.</th>
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<tr>
<td><strong>Signal Generators</strong></td>
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<td>R&amp;S®SMW200A</td>
<td>Vector Signal Generator</td>
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<td>R&amp;S®SMW-B120</td>
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<td>1413.0404.02</td>
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<tr>
<td>R&amp;S®SMW-B220</td>
<td>Frequency Options, RF path B, 100 kHz to 20 GHz</td>
<td>1413.1100.02</td>
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<td>R&amp;S®SMW-B13</td>
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<td>RF and Microwave Signal Generator</td>
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<td>R&amp;S®SMW-B120</td>
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<td>RF Preamplifier, 100 kHz to 67 GHz</td>
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<td>OCXO 10 MHz</td>
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<td>R&amp;S®RTO-K11</td>
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* Other Signal and Spectrum Analyzers configurations and Harmonic Mixer Models are suitable as well. More options are available. The table shows the instrument's minimum configuration for this application, but for the analyzer, models FSW43/50 in conjunction with FS-Z series harmonic mixers allow significant savings at the expense of slightly reduced convenience and performance. Please ask your local representative for a suitable configuration according to all your needs.
Appendix

A Recommended parts for V-band up-converter

A.1 Mixer

Sage Millimeter Balanced Up-Converter, V-Band SFU-15-N1A

A.2 Band Pass Filter

BSC Filters Waveguide Band Pass Filter 51.5 – 54.4 GHz WB 8253 (Specification WB8253/01)

A.3 Quadrupler

Radiometer Physics GmbH AFM4 36 - 56 +15

A.4 Isolator

Radiometer Physics WFI-75

A.5 High Pass Filter

Sage Millimeter SWF-57353340-15H1A (pass band 57 GHz and higher)

A.6 V-Band Amplifier

Sage Millimeter Power Amplifier V-Band: SBP-5736433016-1515-E1A (BG-SV2)
Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

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Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

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