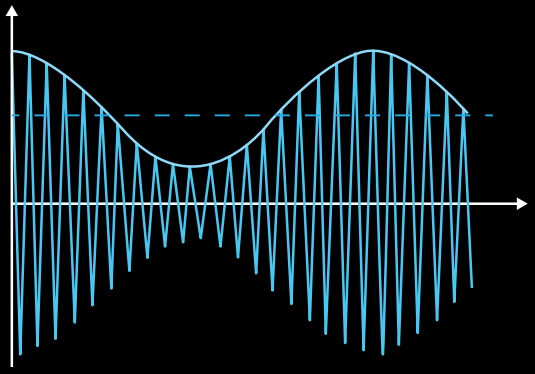
Key Characteristics of Signal Generators and Modulation Methods: Pocket Guide



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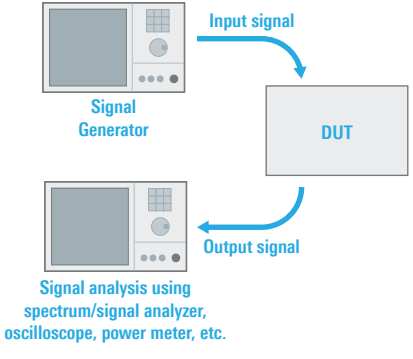
What are signal generators?

Signal generators play a vital role in electrical test and measurement. They generate the test signals that are applied to components such as filters and amplifiers, or even to entire modules, in order to ascertain and test the component's behavior and characteristics. Beyond the output of spectrally pure signals, a key function of signal generators is the generation of analog and digitally modulated signals.



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What are signal generators?

A signal generator generates electrical signals with a specific time characteristic. Depending on the type of signal generator, the generated signal waveforms can range from simple sine-wave, sawtooth and square-wave to analog-modulated signals such as AM, FM and PM and even complex digitally modulated signals such as those used in mobile radio. The frequency domain can extend from several kHz up to several hundred GHz.

Signal generators used in automated test setups for production can be remotely controlled via a LAN connection, a USB port or a GPIB port, depending on the available equipment.

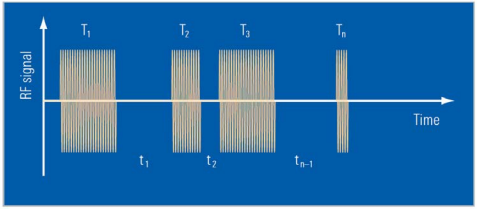
Signal generators are classified into three main types:

- Analog signal generators
- Vector signal generators
- Arbitrary waveform generators

Analog Signal Generators

With analog signal generators, the focus is on producing a high-quality signal. They provide support for the analog modulation modes AM / FM and φM. Many instruments can also produce precise pulsed signals with varying characteristics.

- Very high spectral purity (nonharmonics), e.g. –100 dBc
- Very low inherent broadband noise, e.g. –160 dBc
- Very low SSB phase noise of typ. –150 dBc/Hz (at 10 kHz carrier spacing, f = 1 GHz, 1 Hz measurement bandwidth)



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Analog Signal Generator
Applications

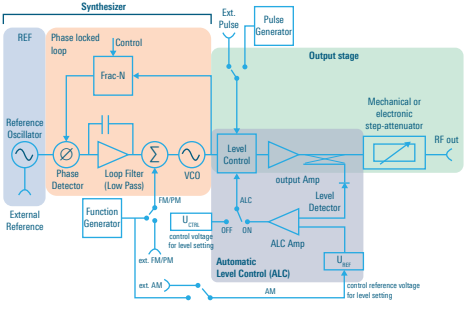
Signal generators can be used:

- As a stable reference signal for use as a local oscillator, i.e. as a source for phase noise measurements or as a calibration reference.
- As a universal instrument for measuring gain, linearity, bandwidth, etc.
- For receiver tests (two-tone tests, generation of interferer and blocking signals)
- For electromagnetic compatibility (EMC) testing
- As automatic test equipment (ATE) during production
- For avionics applications (such as VOR, ILS)
- For radar tests
- For military applications
- In the development and testing of RF and microwave chips and other semiconductor chips, such as those used for A/D converters

Analog Signal Generator
Applications

Analog signal generators include:

- A synthesizer for producing the oscillation
- An automatic level control for maintaining a constant output level
- An output stage with amplifiers and step attenuators for controlling the output power



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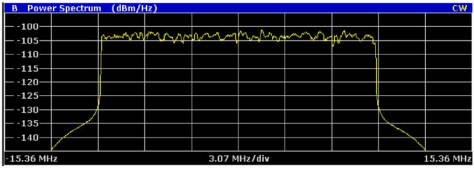
What are Vector Signal Generators?

Vector signal generators up-convert modulation signals (external or internal, analog or digital) and then output the signals. The modulation signal is digitally generated and processed as a complex I/Q data stream in the baseband. Using I/Q technology makes it possible to implement any modulation types – whether simple or complex, digital or analog – as well as single-carrier and multicarrier signals.



Vector Signal Generators
Applications

The requirements that the vector signal generators must meet are derived primarily from the requirements established by wireless communications standards, but also from digital broadband cable transmission, satellite communications, and from A&D applications (generation of modulated pulses).

The main areas of application for vector signal generators are:

- Generating standard-compliant signals for wireless communications, digital radio TV, GPS, modulated radar, etc.
- Testing digital receivers or modules in development and manufacturing
- Simulating signal impairments (noise, fading, clipping, insertion of bit errors)
- Generating signals for multi-antenna systems (multiple in / multiple out, or MIMO), with and without phase coherence for beamforming
- Generating modulated sources of interference for blocking tests and for measuring suppression of adjacent channels

Vector Signal Generators

Features

- Make it possible to generate signals for almost any conceivable scenario that might be required for specialized testing in development and production due to the fact that nearly all parameters of a digital standard are modified
- Convenient triggering capabilities, e.g., fit generator bursts precisely into a prescribed time grid
- Marker signals at the device's jacks that can be programmed for activation at any position in the data stream in order to control a DUT or measuring instrument
- Very high crest factors, which create considerable differences in the quality of individual generators

State-of-the-art generators far exceed the requirements of the current mobile radio standards, making them ready for the future. They also support a large number of international standards.

Vector Signal Generators

Characteristics

Important characteristics for vector signal generators are:

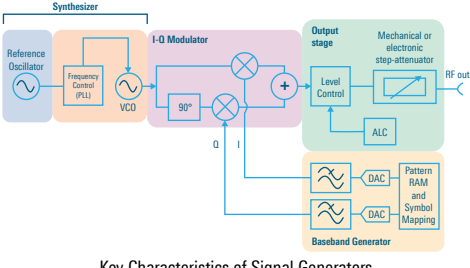
- Modulation bandwidth
- Achievable symbol rate
- Modulation quality (error vector magnitude, EVM)
- Adjacent channel power (ACP)
- Adjacent channel leakage ratio (ACLR)
- Output power
- Settling time
- Accuracy for frequency and level
- Low reflection coefficient or VSWR
- Low EVM values
- High dynamic range for ACP measurements
- Number of supported standards

Vector Signal Generators

Design

The essential components of a vector signal generator are identical to that of an analog generator. The synthesizer and output stage with ALC and step attenuator are found here as well. A baseband generator and an I-Q modulator are used to generate the modulation (analog and digital) or to generate standard-compliant mobile radio signals.

The baseband generation of the IQ signals can either be calculated in real-time or played from an internal ARB. Basebands that are capable of generating signals in real-time can usually also play signals from an ARB as well.



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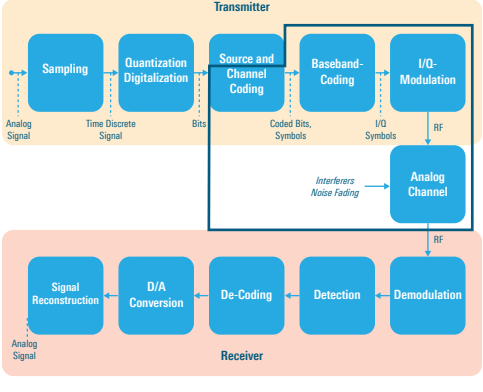
Vector Signal Generators
Example Application

In addition to baseband signal generation, modern instruments can insert additive white Gaussian noise (AWGN) on the signal and simulate multipath propagation (fading). With this feature, it is possible to generate signals as they would appear upon reception following transmission via a realistic radio channel, complete with interference.



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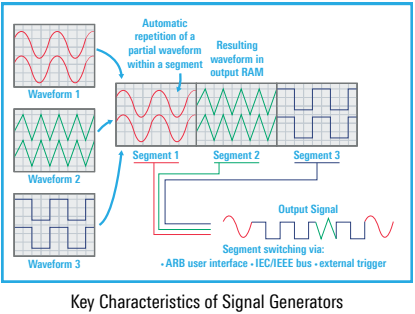
What are Arbitrary Waveform Generators?

Arbitrary waveform generators (ARBs) are specialized vector signal generators for the baseband. The modulation data for ARBs is calculated in advance (rather than in real time) and stored in the instrument's RAM. The memory content is then output at the real time symbol rate. Many vector signal generators have an ARB option.

Users can combine a variety of waveforms of varying durations into a single sequence for production. For example, the output sequence can consist of data streams with varying bit rates that must be verified during production.



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Arbitrary Waveform Generators (ARBs)

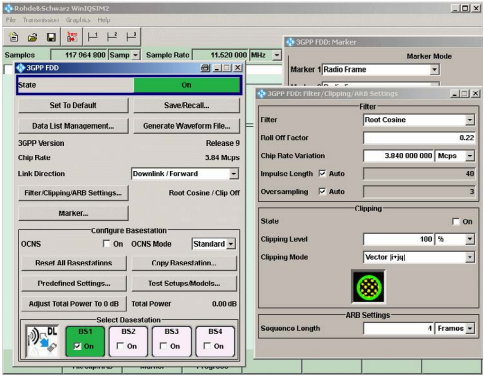
As with real time generators, ARBs offer different triggering options as well as the ability to output marker signals for controlling connected hardware and measurement instruments in parallel to the waveform playback.

ARBs differ from real time vector generators in use and application as listed here:

- ARBs have zero restrictions for configuring the content of an I/Q data stream (hence the name "arbitrary")
- Only time-limited or cyclic signals are allowed (the memory depth is finite)
- ARBs do not offer the same level of RF performance as vector signal generators

Arbitrary Waveform Generators (ARBs)

Many ARB generators can calculate additive Gaussian noise as a baseband source; some are also able to simulate multipath propagation (fading) or multi-antenna systems (MIMO) of the subsequent signal. In many cases, vendors that offer ARB generators also offer software for creating standard modulation sequences (I/Q data sets).



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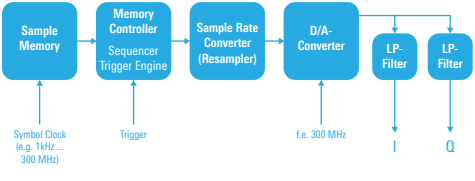
Basic Functioning of an ARB

The sequencer takes the waveforms saved in memory and combines them into a predefined sequence, then forwards them to the sample rate converter (resampler).

The resampler is used to adjust a variable memory symbol clock to a fixed clock rate from the D/A converter. This has two major advantages. First, the D/A converter always uses the optimal clock rate for the best possible resolution, and second, the variable memory clock ensures that the memory is optimally utilized. In other words, changing the clock ensures that the longest possible sequence can be generated.



Basic Functioning of an ARB

The memory depth and word width for the I/Q data sets are additional characteristics for ARBs. Some ARB generators allow sequential playback of different memory segments containing multiple pre-calculated waveforms, without any further preliminary calculation. This is illustrated in the following example:

An ARB with a memory depth of 1 Gsample can generate a GSM signal with 270 ksamples/s and triple oversampling with a duration of 1234 s.

$t = 1\ Gsample\ /\ (3 \cdot 270\ ksample)$

If the memory clock rate is equal to that of the D/A converter, for example 300 MHz, the possible duration for the signal output would be reduced to 3.3 s

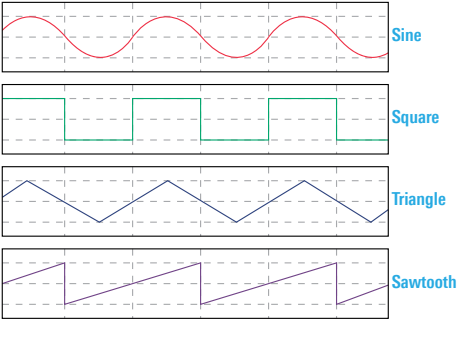
$t = 1\ Gsample\ /\ 300\ Msample/s$

Because the clock rate of the D/A converter is always within the optimal range, the output signal has a high, spurious-free dynamic range (SFDR) that is independent of the memory clock rate.

Additional Types of Signal Generators

Tone Generator - produce a sine-wave, square-wave, or sawtooth electrical signal in the human-audible frequency range, i.e. 20 Hz to 20,000 Hz. Most often used for acoustical test and measurement.

Function Generators - produce only simple, periodic signals. Example function generators applications include the assessment of electronic circuits such as amplifiers and filters.



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Key Signal Generator Characteristics

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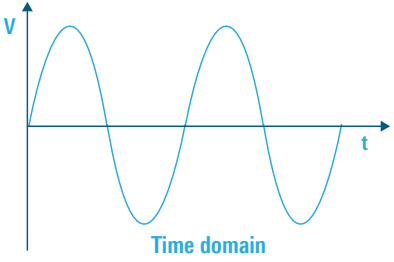
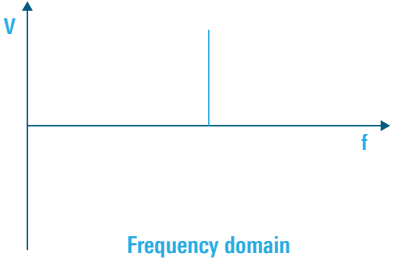
Ideal Signal Generation

An ideal assumed signal generator delivers an undistorted sine-wave signal that exactly matches the defined frequency and the defined level at its output.



Time domain



Frequency domain

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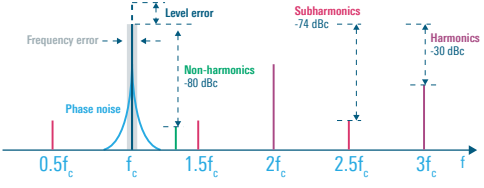
Signal Generation Reality

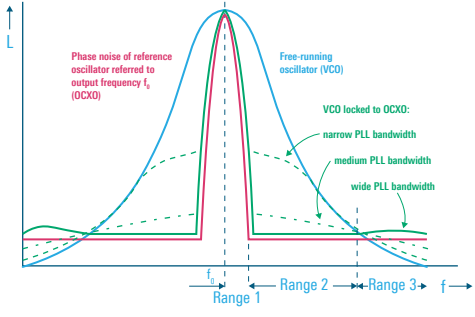
Because a signal generator is constructed from real components with non-ideal characteristics, the wanted carrier signal with frequency fc (c: carrier) arrives at the output along with other, unwanted signals. In reality, even the carrier signal will include a level error and a frequency error. In fact, as a result of the phase noise, the real carrier signal is not consistently displayed in the spectrum as a thin line, or Dirac pulse.



Phase Noise

Phase noise is a measure of the short-term stability of oscillators as used in a signal generator for producing signals of varying frequency and shape. Phase noise is caused by fluctuations in phase, frequency and amplitudes of an oscillator output signal, although the latter are usually not a consideration. These fluctuations have a modulating effect. Phase noise typically occurs symmetrically around the carrier, which is why it is sufficient to consider only the phase noise on one side of the carrier. Its amplitude is therefore specified as single sideband phase noise (SSB) at a defined carrier offset referenced to the carrier amplitude. The specified values are usually relative, i.e. they are defined as a noise power level within a bandwidth of 1 Hz. Accordingly, the unit is noted as dBc (1 Hz) or as dBc/Hz, where "c" references the carrier. Because the phase noise power is lower than the carrier power, negative values are to be expected in the specifications for a signal generator.

Phase Noise



Please see next page for further explanation on the three ranges.

Causes of Signal Generator Phase Noise

Range 1 - Close to the carrier (offsets up to about 1 kHz)

- In this range, the phase noise caused by the multiplication in the locked loop is higher than that from the reference oscillator.

Range 2 - Extending to the upper PLL boundary

- Within the PLL bandwidth, the phase noise corresponds to the total noise from multiple components in the locked loop, including the attenuator, the phase detector and the multiplexed reference signal. The upper boundary of this range is dependent on the signal generator, or more accurately, on the type of oscillator used.

Range 3 - Outside of the control bandwidth

- The phase noise is determined almost entirely by the phase noise of the oscillator during unsynchronized operation. In this range, it falls 20 dB per decade.

Effects of PLL Bandwidth

Large PLL Bandwidth - The loop gain in the locked loop is so high that the noise from the oscillator connected to the reference is reduced to the level of the noise from the reference. Far away from the carrier, however, the phase noise increases as a result of the phase shift caused by the filtering.

Medium PLL Bandwidth - The loop gain is not sufficient to reach the reference noise close to the carrier. However, the increase in phase noise far away from the carrier is less than with a large control bandwidth.

Narrow PLL Bandwidth - The phase noise far away from the carrier is not any worse than that from the unsynchronized oscillator. Close to the carrier however, it is significantly greater compared to the medium and large control bandwidths.

Mathematical Description of Phase Noise

$v(t) = V_0 + \varepsilon(t)) \sin (2\pi f_0 + \Delta\varphi(t))$

Where:

V_0	=	Signal amplitude
F_0	=	Signal frequency
$2\pi f_0 t$	=	Signal phase
$\varepsilon(t)$	=	The signal's amplitude variation
$\Delta\varphi(t)$	=	The signal's (phase variation or) phase noise

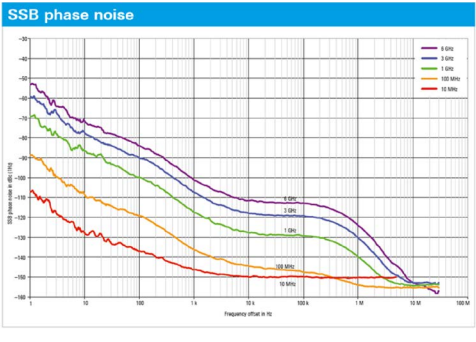
Noise Power Density $S_{\Delta\phi}(f) = \frac{\Delta\phi^2_{\text{rms}}}{1\,\text{Hz}} \frac{\text{rad}^2}{\text{Hz}}$

Single Sideband (SSB) Phase Noise $(f_{offset}) = \frac{P_{\text{SSB}}(1\,\text{Hz})}{P_{\text{Carrier}}}$

SSB Phase Noise in dBc $L_c(f_{offset}) = 10\lg(L(f_{offset}))\,\text{dBc}$

Measured SSB Phase Noise

Low phase noise values are particularly significant when a signal generator will be used as a stable reference signal, for example for phase noise measurements, or as a calibration reference during servicing. Low-jitter microwave signals, i.e. signals with low SSB phase noise – in particular close to the carrier – are essential for characterizing ever-faster A/D converters.



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Output Power

Demands on the output power of the signal generator are wide ranging because they are used in many applications, ranging from supplying a low level interfering signal, to delivering a high power stable reference signal. To accommodate this, generators can have output power range of -145 dB to +30 dB, with a resolution capability of 0.01 dB.

In many test set ups, there are cables, attenuators/ amplifiers, splitters, etc between the generator and Device Under Test (DUT). In these cases, the power level coming out of the generator is quite different from the power level actually being applied to the DUT. To simplify this, some generators can compensate for these external components and display the power level which is actually being applied to the DUT. This simplifies the use of the generator and allows the operator to enter the desired power level at the DUT, directly into the generator.

Higher Output Levels

It is important to note that the actual maximum output level from the generator may be higher than its specified output power level. Most signal generators will allow users to enter values above the maximum specified power level as there is always additional performance beyond the specifications. As you move further and further beyond the specified limit, the output amplifier stage of the generator is likely to go into compression and the actual output power may not increase at the same rate as the displayed output power which is entered by the user. Power sensors maybe used in these cases to ensure accuracy beyond the specified maximum output power level.

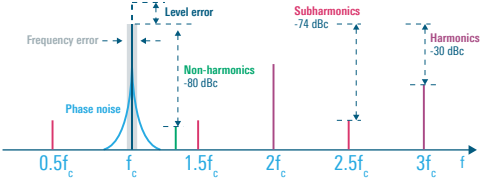
Some DUTs require very high input power or drive levels. In some cases an external amplifier is required to meet this need. A high power option on the signal generator may also meet this need in many cases. The external amplifier adds complexity, hassle and may need to be calibrated with the signal generator. Using a signal generator with high enough output power removes complexity and provides a calibrated, specified solution that will deliver repeatable results.

Lower Output Levels

For high sensitivity measurements on receivers, very low power levels are needed. Signal generators include, either standard or as an option, step attenuators to allow the lower level limit to be shifted from –20 dBm without the attenuator down to around –130 dBm with attenuator.

Spurious Emissions

Spurious emissions, such as harmonics and subharmonics, are the result of non-linearities in the components (amplifiers, mixers, etc.) in the signal path of the signal generator.



$$v_{out}(t) = \sum_{n=1}^{\infty} a_n \cdot v_{in}^n(t) = a_1 \cdot v_{in}(t) + a_2 \cdot v_{in}^2(t) + a_3 \cdot v_{in}^3(t) + \ldots$$

where	$v_{out}(t)$:	Voltage at the output of the two-port device
	$v_{in}(t)$:	Voltage at the input of the two-port device
	a_n:	Coefficient of the respective non-linear element for the voltage gain

In most cases, it is sufficient to consider the square and cubic members, so that the power series need only be developed up to n = 3. Signal generators should deliver the most distortion-free signals possible. Linearity is therefore a key criterion for assessing a signal generator.

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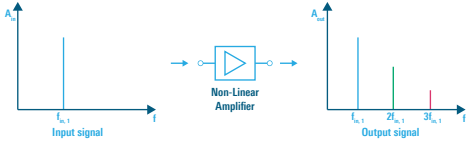
Single-Tone Modulation

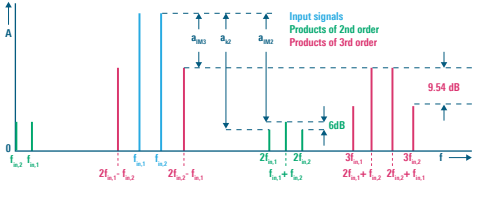


Typically, data sheets list the harmonics relative to the carrier signal in dBc (c: carrier). The harmonics are specified by the frequency as well as the output power up to which the specifications for the harmonics will apply. If the level offset of the harmonics to the carrier signal is not adequate for the application, optional filters can be used to further reduce the harmonics, as shown in this example.

Harmonics		
R&S®SMB-B101/-B102/-B103/-B106 -B112/-B112L[1]	1 MHz < f ≤ 6 GHz; level ≤ 13 dBm[6] f > 6 GHz; level ≤ 10 dBm[6]	< –30 dBc
R&S®SMB-B120/-B120L/-B140/-B140L[1]	standard; level ≤ 8 dBm[6]	
	f > 1 MHz	< –30 dBc
	with R&S®SMB-B25, R&S®SMB-B26 option low harmonic, low harmonic filter on, level ≤ 10 dBm[6]	
	1 MHz < f ≤ 150 MHz	< –30 dBc
	150 MHz < f ≤ 3 GHz	< –58 dBc
	3 GHz < f ≤ 20 GHz	< –50 dBc
	f > 20 GHz	< –60 dBc (meas)

Two-Tone Modulation

Signal generation also results in non-harmonic signal components. Because the isolation of the signal paths is limited, these components can be caused by crosstalk from internal power supplies or from other clock frequencies present in the signal generator, for example. This includes intermodulation products such as those that occur during two-tone modulation of non-linear components.

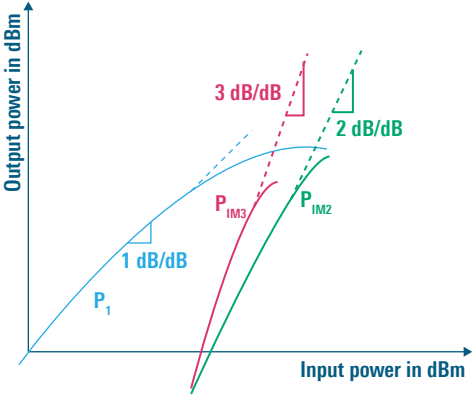


Intermodulation Products from Two-Tone Modulation

DC component	$a_2 \cdot 0.5(\hat{U}_{in,1}^2 + \hat{U}_{in,2}^2)$
Fundamentals	$a_1 \cdot \hat{U}_{in,1} \cdot \sin(\omega_1 t)$ $a_1 \cdot \hat{U}_{in,2} \cdot \sin(\omega_2 t)$
2nd harmonics	$a_2 \cdot 0.5 \cdot \hat{U}_{in,1}^2 \cdot \cos(2 \cdot \omega_1 t)$ $a_2 \cdot 0.5 \cdot \hat{U}_{in,2}^2 \cdot \cos(2 \cdot \omega_2 t)$
Intermodulation products of 2nd order	$a_2 \cdot \hat{U}_{e,1} \cdot \hat{U}_{in,2} \cdot \cos(\omega_1 - \omega_2)t$ $a_2 \cdot \hat{U}_{e,1} \cdot \hat{U}_{in,2} \cdot \cos(\omega_1 + \omega_2)t$
3rd harmonics	$a_3 \cdot 0.25 \cdot \hat{U}_{in,1}^3 \cdot \sin(3 \cdot \omega_1 t)$ $a_3 \cdot 0.25 \cdot \hat{U}_{in,2}^3 \cdot \cos(3 \cdot \omega_2 t)$
Intermodulation products of 3rd order	$a_3 \cdot \hat{U}_{in,1}^2 \cdot \hat{U}_{in,2} \cdot 0.75 \cdot \sin(2\omega_1 + \omega_2)t$ $a_3 \cdot \hat{U}_{in,1}^2 \cdot \hat{U}_{in,2} \cdot 0.75 \cdot \sin(2\omega_2 + \omega_1)t$ $a_3 \cdot \hat{U}_{in,1}^2 \cdot \hat{U}_{in,2} \cdot 0.75 \cdot \sin(2\omega_1 - \omega_2)t$ $a_3 \cdot \hat{U}_{in,1}^2 \cdot \hat{U}_{in,2} \cdot 0.75 \cdot \sin(2\omega_2 - \omega_1)t$

Characteristic Curves for Intermodulation Products

Characteristic curves for the fundamental (blue), second-order (green) and third-order (red) intermodulation products.



Data Sheet Specifications for Non-Harmonics

To ensure that the specification of non-harmonics for different signal generators can be compared, the level and the frequency offset to the carrier must be included in the specifications.

CW, level > -10 dBm (level > 0 dBm for instruments without step attenuator), offset > 10 kHz from carrier

f ≤ 23.4375 MHz	< -70 dBc
23.4375 MHz < f ≤ 3 GHz	< -70 dBc, < -84 dBc (typ.)
1500 MHz < f ≤ 3 GHz	< -64 dBc, < -78 dBc (typ.)
3 GHz < f ≤ 6.375 GHz	< -58 dBc, < -72 dBc (typ.)
6.375 GHz < f ≤ 12.75 GHz	< -52 dBc, < -66 dBc (typ.)
12.75 GHz < f ≤ 25.5 GHz	< -46 dBc, < -60 dBc (typ.)
25.5 GHz < f ≤ 40 GHz	< -40 dBc, < -54 dBc (typ.)

Data Sheet Specifications for Sub-Harmonics

To assess the spectral purity of a generator signal, not only the phase noise, harmonics and non-harmonics must be specified, but also the subharmonics. The frequencies of the subharmonics have an integer attenuation factor with respect to the carrier frequency:

- First subharmonic $1/2 \cdot f_c$
- Second subharmonic $1/3 \cdot f_c$
- Nth subharmonic $f_c/(n+1)$

Subharmonic frequency components arise in the signal generator exclusively through the use of frequency multipliers. The carrier output power reference is required as well as the comparison value in dBc. The signal generator in the example below does not use a frequency multiplier below 6.375 GHz, and no subharmonics occur in this range.

level > -10 dBm
(level > 0 dBm for instruments without step attenuator)

f < .375 GHz	none
6.375 GHz < f ≤ 20 GHz	< -55 dBc
20 GHz < f ≤ 40 GHz	< -50 dBc

Frequency Stability

The frequency accuracy of a signal generator is dependent on the frequency oscillator being used. A Temperature Compensated Crystal Oscillator (TCXO) is typically used as the reference oscillator for most signal generators. For applications demanding greater frequency accuracy, signal generators can usually also be equipped with an optional Oven Controlled Crystal Oscillator (OCXO). Beyond the advantage of higher frequency accuracy, an OCXO also provides a shorter warm-up time. When characterizing frequency stability, a distinction must be made between long-term stability and short-term stability.

Frequency Stability - Short-Term

Short-Term Stability is defined by statistical or deterministic fluctuations in frequency around an average value. The spectral line of a single frequency signal is expanded under its influence. A distinction must be made here between two types of frequency fluctuations: random and deterministic.

Deterministic Fluctuations (or systematic, periodic) can be traced back to discrete modulation frequencies. In other words, they appear as discrete, but adjacent lines close to the average frequency and can be tracked back to known causes, such as AC hum or intermodulation products.

Random Fluctuations (statistical) or fluctuations in the phase of a waveform are known as phase noise.

Frequency Stability - Long-Term

Long-term stability refers to a change in the average frequency, caused by slow changes in the components that determine the frequency (oscillators). For example, the expansion of a resonant structure due to change in temperature can cause a change in frequency. Long-term stability is often described by a relative frequency change per time unit. The specification of long-term stability is composed of several individual parameters.

Reference frequency

Frequency error	at time of calibration in production	$<1 \times 10^{-7}$
	with R&S® SMB-B1/SMB-B1H option	$<1 \times 10^{-8}$
Aging (after 10 days of uninterrupted operation)	standard	$<1 \times 10^{-6}$/year
	with R&S® SMB-B1 option	$<1 \times 10^{-9}$/day, $<1 \times 10^{-7}$/year
	with R&S® SMB-B1H option	$<5 \times 10^{-10}$/day, $<3 \times 10^{-8}$/year
Temperature effect (0° C to +50° C)	standard	$< 2 \times 10^{-6}$
	with R&S® SMB-B1 option	$<1 \times 10^{-7}$
	with R&S® SMB-B1H option	$<1 \times 10^{-8}$
Warmup time	to nominal thermostat temperature with R&S® SMB-B1/SMB-B1H option	≤ 10 min

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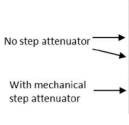
Level Accuracy and Level Setting Time

Level accuracy and level setting time depend on the synthesizer model being used, the type of step attenuator and whether Automatic Level Control (ALC) is used. Signal generators typically have less level error when they utilize mechanical step attenuators, which have a high degree of precision plus improved matching of the output jack.



Level error	ALC state on, temperature range +18 °C to +33 °C		
R&S®SMB-B101/-B102/-B103/-B106/-B112	9 kHz ≤ f ≤ 200 kHz [1]	< 1.0 dB	
	200 kHz < f ≤ 3 GHz	< 0.5 dB	
	f > 3 GHz	< 0.9 dB	
R&S®SMB-B112L	200 kHz < f ≤ 3 GHz	< 0.7 dB	
	f > 3 GHz	< 1.1 dB	
R&S®SMB-B120L/-B140L	200 kHz < f ≤ 3 GHz	< 0.7 dB	
	3 GHz < f ≤ 20 GHz	< 1.1 dB	
	20 GHz < f ≤ 40 GHz	< 1.2 dB	
R&S®SMB-B120/-B140		level > –90 dBm	level ≤ –90 dBm
	200 kHz < f ≤ 3 GHz	< 0.5 dB	< 0.5 dB
	3 GHz < f ≤ 20 GHz	< 0.9 dB	< 1.2 dB
	20 GHz < f ≤ 40 GHz	< 1.0 dB	< 1.5 dB

Level Accuracy and Level Setting Time

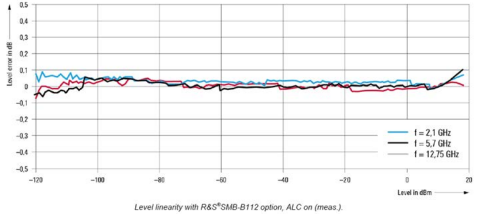
When an electronic step attenuator is used, a power amplifier is connected downstream in order to compensate the attenuation. This leads to a drop in the spectral purity and to an increase in the level error. If it becomes necessary to add a mechanical step attenuator, the setting time increases considerably.

Level setting times

Level deviation < 0.1 dB[5] from final value, with GUI update stopped, temperature range +18° C to +33° C, without switching of the mechanical step attenuator	
After IEC/IEEE bus delimiter	
ALC state on	< 2.5 ms
With switching of the mechanical step attenuator	
ALC state on	<25 ms

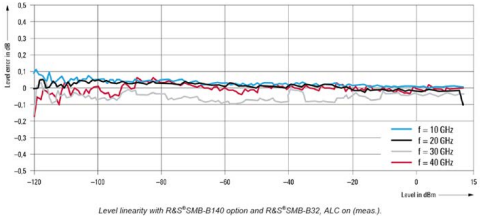
Level Accuracy and Level Setting Time

Level error with electronic step attenuator



Level linearity with R&S®SMB-B112 option, ALC on (meas.).

Level error with electronic step attenuator and power amplifier



Level linearity with R&S®SMB-B140 option and R&S®SMB-B32, ALC on (meas.).

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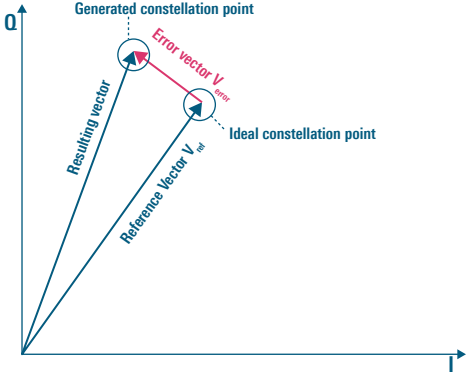
Error Vector Magnitude (EVM)

An important characteristic for the modulation quality of a vector signal generator is the error vector magnitude (EVM). The EVM is a measure of how much the generated symbols deviate from the ideal constellation and corresponds to the relationship between the error vector V_{error} and the ideal reference vector V_{ref}.



Error Vector Magnitude (EVM)

The error vector V_{error} in the complex I/Q plane extends from the ideal constellation point to the (real) constellation point generated by the signal generator. The reference vector V_{ref} extends from zero to the ideal constellation point. Typically, the EVM value is stated in decibels (dB) or as a percentage.

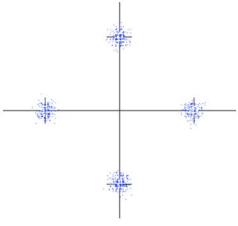
$$EVM(dB) = 10 \log \left(\frac{V_{error}}{V_{ref}} \right)$$

$$EVM(\%) = 100\ \% \cdot \sqrt{\frac{V_{error}}{V_{ref}}}$$

Error Vector Magnitude (EVM)

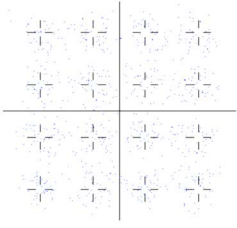
Higher-order modulation modes such as 16QAM with narrower symbol spacing react with more sensitivity to vector errors than simpler modulation modes with wider symbol spacing.

QPSK



S/N (or Carrier to Noise) 20 dB
EVM = 26%
Symbol recognition
not a problem

16 QAM



S/N (or Carrier to Noise) 20 dB
EVM = 47.9%
Symbol recognition more difficult, leading to a higher bit error probability

Error Vector Magnitude (EVM)

It is important that the signal generator produce a signal with a high modulation quality, i.e. a low EVM. The EVM of a vector signal generator depends on the baseband filtering, modulation mode, symbol rate and, for mobile radio signals on the selected mobile cellular standard.

Modulation performance for main digital standards

Measured values except otherwise stated.

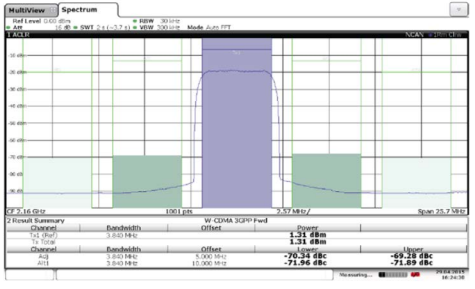
Standard	GSM	EDGE	WCDMA 3GPP		CDMA2000®	IEEE 802.11a/g	IEEE 802.11ac	WiMAX™	LTE
			1DPCH	TM1-64				BW = 10 MHz	
Frequency	400 MHz to 2000 MHz	400 MHz to 2000 MHz	1800 MHz to 2200 MHz	1800 MHz to 2200 MHz	800 MHz	2400 MHz to 2485 MHz; 5150 MHz to 5825 MHz	2400 MHz to 2485 MHz; 5150 MHz to 5825 MHz	5000 MHz	1800 MHz to 2200 MHz
EVM	–	0.25 % (typ.)	0.4 % (typ.)	0.4 %	0.4 %	0.6 %	0.44 %	0.4 %	0.4 %

Modulation performance for custom digital modulation

Deviation error with 2FSK, 4FSK	deviation 0.2 to 0.7 × symbol rate	
	Gaussian filter with B × T = 0.2 to 0.7	
	symbol rate up to 2 MHz	0.4 % (meas.)
	symbol rate up to 10 MHz	1.2 % (meas.)
Phase error with MSK	Gaussian filter with B × T = 0.2 to 0.7	
	bit rate up to 10 MHz	0.3° (meas.)
EVM with QPSK, OQPSK, π/4-DQPSK, 8PSK, 16QAM, 32QAM, 64QAM	cosine, root cosine filter with α = 0.2 to 0.7	
	symbol rate up to 5 MHz	0.5 % (meas.)
	symbol rate up to 20 MHz	2.0 % (meas.)

Adjacent Channel Power (ACP)

In order to ensure that transmitted information is received without interference by as many subscribers as possible, the adjacent channels in the frequency domain must always remain free of interference. One measure for this interference is the adjacent channel power, which should remain as low as possible and which is stated either as an absolute value (in dBm) or as a relative value referenced to the channel power in the transmission channel. The adjacent channel power (ACP) is also known as adjacent channel leakage power ratio (ACLR) or the adjacent channel power ratio (ACPR).



Digital standard 3GPP FDD test model 1, 64 DPCHs ACLR (meas.).

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Adjacent Channel Power (ACP)

The unwanted spurious emissions are primarily caused by amplifiers and their third-order intermodulation products in the first adjacent channel as well as by fifth-order intermodulation products in the second adjacent channel (the alternate channel). In order to test the amplifiers for generated disturbance power in the adjacent channel, it is important that the test signal produced by the vector signal generator itself have a very high adjacent channel power suppression.

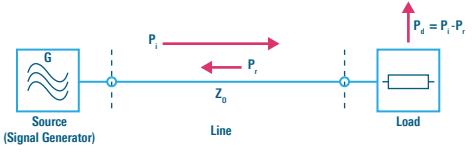
Modulation performance for main digital standards

Measured values except otherwise stated.

Standard	GSM	EDGE	WCDMA 3GPP		CDMA2000®	IEEE 802.11a/g	IEEE 802.11ac
			1DPCH	TM1-64			
Frequency	400 MHz to 2000 MHz	400 MHz to 2000 MHz	1800 MHz to 2200 MHz	1800 MHz to 2200 MHz	800 MHz	2400 MHz to 2485 MHz; 5150 MHz to 5825 MHz	2400 MHz to 2485 MHz; 5150 MHz to 5825 MHz
Adjacent channel power ratio (ACPR) in dB							
Channel spacing	200 kHz	200 kHz	5 MHz	5 MHz	30 kHz	20 MHz	160 MHz
In adjacent channel	–38	–38	–69	–67 (typ.)	–79 at 0.75 MHz	–42	–50
In alternate channel	–70	–70	–74	–71 (typ.)	–91 at 1.98 MHz	–55	–56
In 2nd alternate channel	–78	–78	–	–	–	–56	–56

Impedance Matching (VSWR)

Signal generators for the most part are designed for 50 Ω systems. To ensure that as much possible of the generated power can be used by the connected load or by the DUT, the signal generator output and the load input must be as close to 50 ohms as possible. A good impedance matching is ensured only if no signal reflection occurs and if the mismatch uncertainty is kept to a minimum.



Impedance Matching (VSWR)

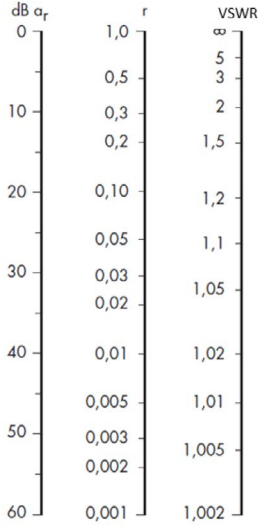
The interference pattern resulting from the superposition of forward and reflected waves is called a standing wave. It is periodic with one half of a line wavelength. At the positions where the voltage and current of both waves are either in phase or out of phase, maxima and minima values are produced. The ratio of maximum to minimum values is a measure of the magnitude of the load-side reflection coefficient.

$$VSWR = SWR = \frac{V_{max}}{V_{min}}$$

$$VSWR = \frac{1 + r_L}{1 - r_L}$$

Impedance Matching (VSWR)

For impedance matching where rL = 0, the result is VSWR = 1. For total reflection where rL = 1, the result is VSWR = ∞. The value range for VSWR therefore lies between 0 and ∞.



Impedance Matching (VSWR)

Because the type of step attenuators used in the signal generator can have an effect on the generator matching, the VSWR value is typically specified for several different instrument configurations.

VSWR

Output impedance VSWR in 50 Ω system, ALC state on		
R&S® SMB-B101/-B102/-B103/-B106/-B112	f > 200 kHz	< 1.8
R&S® SMB-B112L/-B30	f > 200 kHz	< 2.0
R&S® SMB-B120/-B140	1 MHz < f ≤ 20 GHz	< 1.6 (meas.)
	20 GHz < f ≤ 40 GHz	< 1.8 (meas.)

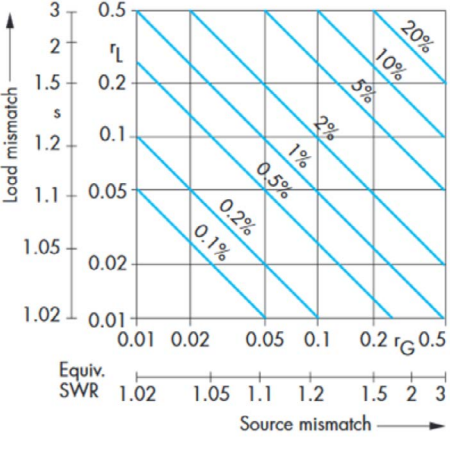
With electronic step attenuator

No step attenuator

With mechanical step attenuator

Impedance Matching (VSWR)

Mismatch uncertainty for the forward power and for the power available at Z_0.



Analog Modulation Methods

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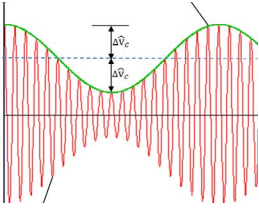
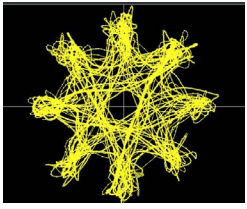
Modulation Methods

In order to transmit electrical information signals efficiently and with as little distortion as possible, the signals must be adapted to the physical characteristics of the transmission channel. To do this, the amplitude, frequency or phase angle of a carrier signal is modified by the wanted signal (voice, music, data) to permit efficient utilization of the transmission channel. This process is known as modulation. Within the carrier frequency range, the transmit signal occupies a bandwidth that is dependent on the wanted signal. The carrier signal itself has no significance with respect to the transmitted message and can be suppressed for certain modulation modes. Because only high-frequency signals can be radiated as electromagnetic waves over an antenna, the wireless transmission of signals requires a modulated, high-frequency carrier. On the receiver end, the wanted signal is restored by means of a demodulator.

Modulation Methods

Continuous-time modulation methods use a continuous signal, such as a sine-wave oscillation as the carrier. The two varieties of continuous-time methods are continuous value modulation and discrete value modulation. The continuous-value influence of a time-continuous carrier is better known as analog modulation, while a discrete-value influence of the carrier is known as digital modulation.





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Analog Modulation Methods

Analog modulations continuously process analog wanted signals such as voice, music or video signals without digitizing the transmission signal values. There are two main types of analog modulation; amplitude modulation and angle modulation. All other analog modulation methods are derived from these two modulation techniques.

Type of modulation	**Abbreviation**
Amplitude modulation	AM
Single-sideband modulation	SSB-AM
Vestigial-sideband modulation	VSB-AM
Double-sideband suppressed carrier	DSBSC-AM
Frequency modulation	FM
Phase modulation	PM

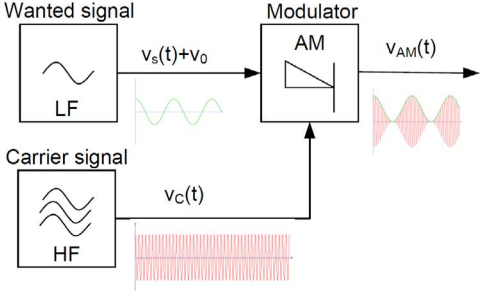
Amplitude Modulation (AM)

Amplitude modulation (AM) continuously applies the information from the wanted signal to the amplitude oscillations of the transmit signal. In the process, the low frequency wanted signal from the baseband is converted into a high frequency range, which causes the appearance of new frequency components. These result from the product of the modulated wanted signal and the carrier oscillation.

Important applications:

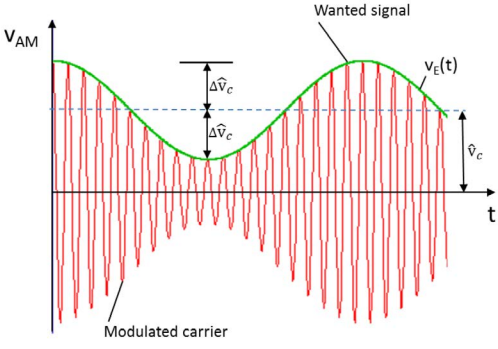
- Radio broadcasting across various frequency bands (long-wave, medium-wave, short-wave)
- Television broadcasting, depending on the broadcast standard
- Amateur radio (mostly in a modified format as single-sideband modulation)
- Flight navigation (ADF and VOR)
- Flight communications

Concept Behind AM Modulation



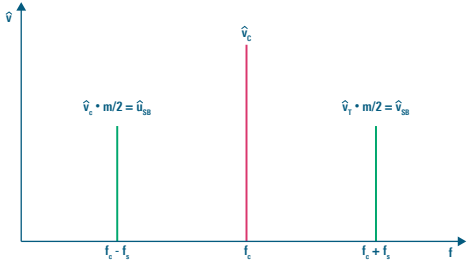
$$v_M(t) = v_{AM}(t) = (v_s(t) + V_0) \cdot \frac{v_c(t)}{\hat{v}_c(t)}$$

Time Characteristic of an AM Signal



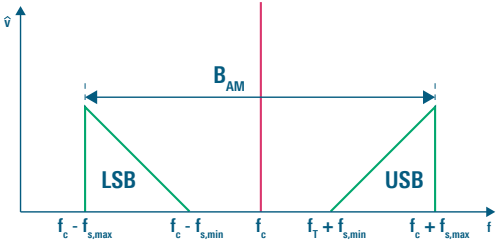
$$v_{AM}(t) = \hat{v}_{AM}(t) \cdot cos\omega_c t = \hat{v}_c \cdot (1 + m \cdot cos\omega_s t) \cdot cos\omega_s t$$

Frequency Spectrum of an AM Signal



$$v_{AM}(t) = \underbrace{\hat{v}_c \cdot cos\omega_c t}_{\text{Carrier oscillation}} + \underbrace{\hat{v}_c \frac{m}{2} \cdot \cos(\omega_c + \omega_s)\, t}_{\text{Upper sideband oscillation}} + \underbrace{\hat{v}_c \frac{m}{2} \cdot \cos(\omega_c - \omega_s)\, t}_{\text{Lower sideband oscillation}}$$

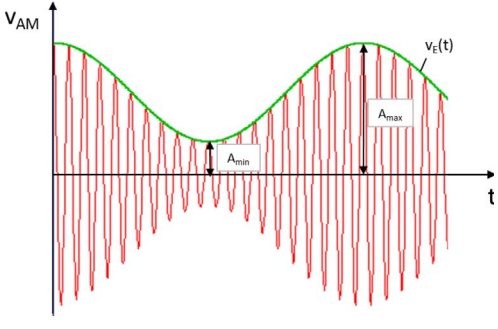
Sidebands of an AM Signal



The bandwidth required to transmit the AM signal is:

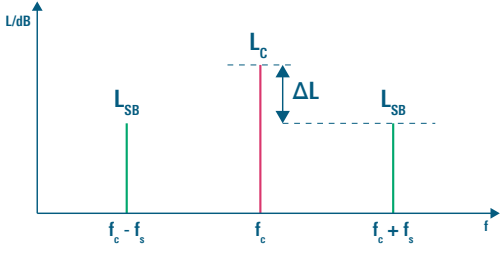
$$B_{AM} = 2 \cdot f_{s\,max}$$

Modulation Depth in the Time Domain



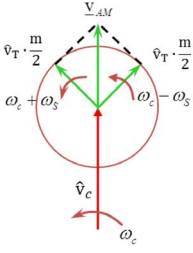
$$m = \frac{A_{max} - A_{min}}{A_{max} + A_{min}}$$

Modulation Depth in the Frequency Domain

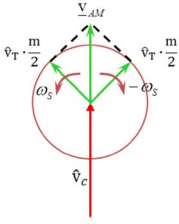


$$m = 10^{\left(\frac{6\,dB - \Delta L}{20\,dB}\right)}$$

Complex Display and Vector Diagram



AM oscillation with rotating carrier vector



AM oscillation with fixed carrier vector

$$v_{AM}(t) = \underbrace{\hat{v}_c \cdot cos\omega_c t}_{\text{Carrier oscillation}} + \underbrace{\hat{v}_c \frac{m}{2} \cdot \cos(\omega_c + \omega_s)\, t}_{\text{Upper sideband oscillation}} + \underbrace{\hat{v}_c \frac{m}{2} \cdot \cos(\omega_c - \omega_s)\, t}_{\text{Lower sideband oscillation}}$$

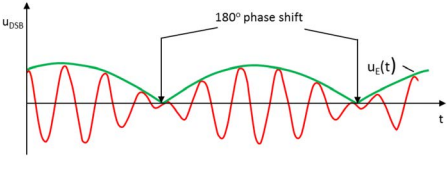
Types of Amplitude Modulation

An amplitude-modulated oscillation is made up of the carrier oscillation and two sidebands for the wanted signal. The disadvantage of this arrangement is that the carrier itself does not contain any information; instead, the information, or wanted signal, is divided equally onto two sidebands. This has clear disadvantages, in that the AM modulation requires a high output power (carrier + two sidebands) as well as a large bandwidth for a redundant sideband. The division of the power to the two sidebands alone reduces the power of each sideband by about 50%. These disadvantages are compensated by special variations in the amplitude modulation, such as amplitude modulation with suppressed carrier, single sideband modulation (SSB) or vestigial sideband modulation.

Dual Sideband Modulation with Carrier Suppression

To suppress the carrier, the modulator transfer function uses a value of zero for the DC component V_0. In the modulation product, this causes the carrier components to disappear, leaving a dual sideband amplitude modulation without carrier, also known as dual sideband modulation (DSB-AM).

By suppressing the constant carrier component $\hat{v}_c$, the envelope $u_E(t)$ experiences a phase shift of 180° at the zero crossing. The envelope now consists of half-sine waves with a repetition frequency that is double the signal frequency.



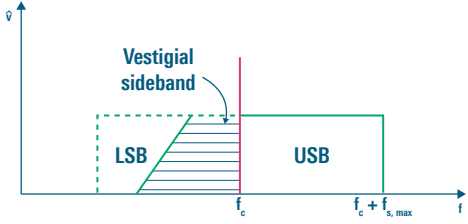
$$v_{DSB}(t) = \hat{v}_{SB}(t) \cdot \cos(\omega_c + \omega_s)t + \cos(\omega_c - \omega_s)t$$

Single Sideband Modulation

In order to reduce the required bandwidth, only one sideband is used for single sideband amplitude modulation (SSB-AM). This is done by suppressing the second sideband. This is possible because both sidebands contain the same information. In addition to the bandwidth advantage, a SSB modulation can apply all of the transmit energy to the information contained in the signal. The result is an increased coverage and a greater signal-to-noise ratio at the same transmit power. In many cases, the transmission includes not only the sidebands, but also a residual carrier as a reference quantity for the demodulation. The highly accurate transmit and receive oscillators available today make this type of modulation of little significance, however.

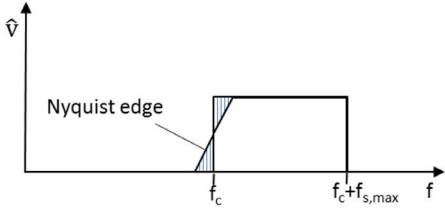
Vestigial Sideband Modulation

When vestigial sideband modulation is used to transmit information signals with very small frequency components, a filter with a very steep edge slope must be used to suppress the unwanted sidebands. Apart from the high technical effort to implement, steep-edged filters have the disadvantage that they exhibit strong group delay at the boundary to the passband. Pulsed signals in particular are strongly distorted during transmission. A vestigial sideband modulation (VSB-AM) can help. This is accomplished by using filters whose transfer function has a relatively flat falling edge. This ensures that a portion of the sideband that is to be suppressed (vestigial sideband) is included in the transmission.



Vestigial Sideband Modulation

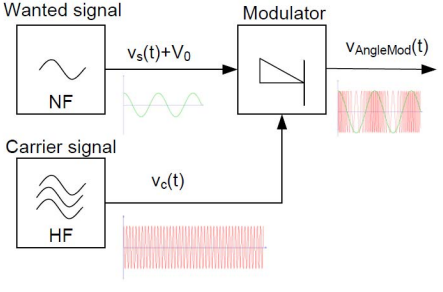
Because VSB-AM causes the entire upper sideband and a portion of the lower sideband to be transmitted, the signal amplitudes of the low and high frequencies are significantly different after demodulation. To compensate, a filter with a Nyquist edge is used before the demodulation. At high signal frequencies, this filter provides less amplification within the lower frequency range on the upper sideband than it does at the upper frequencies. This dissipation is eliminated by the portion of the lower sideband that lies below the Nyquist edge.



Angle Modulation

Unlike amplitude modulation where the amplitude is modified, angle modulation modifies the phase angle of a carrier oscillation dependent on the wanted signal.

Because this causes a simultaneous change in the carrier frequency, the angle modulation can be considered a type of phase modulation (PM) or frequency modulation (FM). Examples of applications for these technologies are found in analog VHF FM radio broadcasting.



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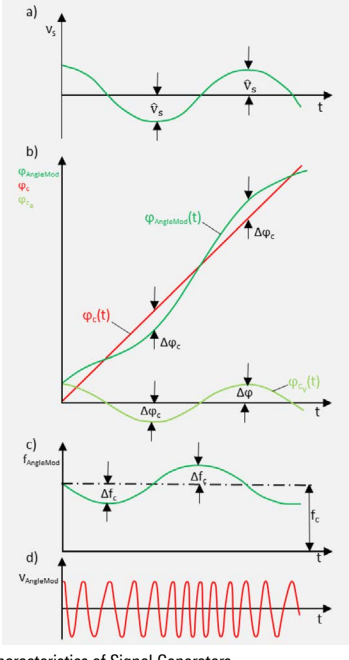
Time Function and Frequency Spectrum

Wanted Signal

Phase Angle

Frequency

Time Function of Angle Modulated Oscillation



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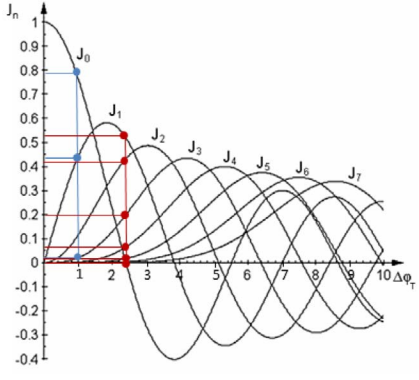
Bessel Function

The spectrum of an angle-modulated oscillation contains not only the carrier signal with frequency fc, but theoretically also an infinite number of discrete sideband oscillations. The amplitudes of the individual frequency components are calculated from the Bessel function values. Even where the Bessel functions have negative values, the amplitude values of the two side lines are displayed as positive numbers in the spectrum. In the phase diagram, this is indicated by a phase shift of 180°.



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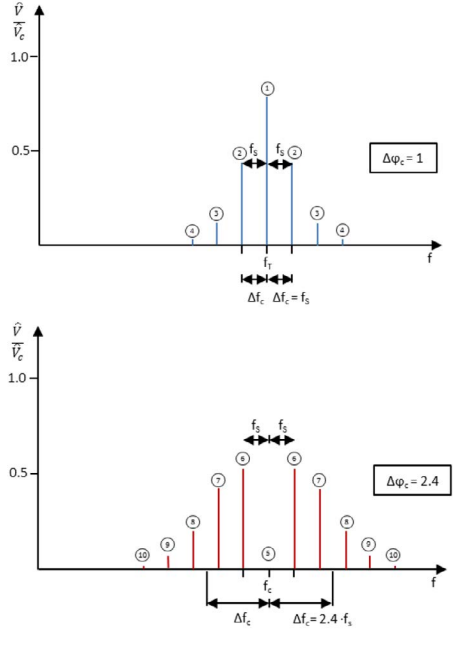
Frequency spectra for an angle-modulated oscillation



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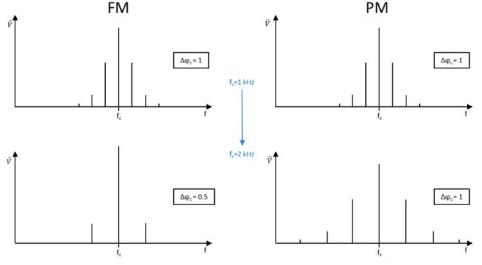
Differentiation of FM vs. PM in Angle Modulation



Frequency Modulation: After a change in the frequency of the wanted signal with constant amplitude, the frequency deviation remains constant and the phase deviation changes proportionately with the wanted signal frequency.

Phase Modulation: After a change in the frequency of the wanted signal with constant amplitude, the phase deviation remains constant and the frequency deviation changes directly proportionately with the wanted signal frequency.

Frequency Modulation with Predistortion

For FM at high frequencies for the wanted signal, the amplitudes of the two sideband oscillations are smaller, which results in a reduction of the signal-to-noise ratio during radio transmission.

In FM radio broadcasting, this disadvantage of a decreasing phase deviation at higher frequencies can be compensated by a transmitter-side pre-distortion of the signal using an RC high-pass before the modulator, called pre-emphasis. This ensures that the amplitudes of high frequencies are boosted nonlinearly.

Pros and Cons of Frequency Modulation vs. Amplitude Modulation

Because almost all spurious signals affect the signal amplitude during radio transmission, but do not change the frequency, a significant advantage of FM is a greater resistance to interference. In FM demodulation, the wanted signal is recovered from the sequence of signal zero crossings, which means that amplitude changes of the FM signal will have no effect as long as the receiver is not overdriven or operated at its sensitivity limit. In addition, the dynamic range for FM is greater than that for AM and is limited only by the distance to an adjacent transmitter. The relatively large spacing in transmitter carrier frequencies for VHF FM permits a good quality low frequency transmission, since almost the entire bandwidth can be used.

The disadvantage of FM is that the technical effort to implement the required signal pre-distortion is greater than for AM.

Digital Modulation Methods

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Digital Modulation Methods

Another, more efficient option of transmitting a signal as free of interference as possible is to use digital modulation methods. Only digital modulation provides methods such as coding that make it possible to regenerate a faulty information signal by means of an error correction during decoding at the receiver. The interference from some digital modulation methods can be analyzed using an eye diagram or by a constellation diagram, which displays transmit symbols in the complex plane (constellation diagram).

Some of the digital modulation methods are derived directly from the analog modulation methods. By studying a digitally modulated signal in the vector diagram, it becomes clear that digital modulation is nothing more than analog modulation with a finite number of discrete states.

A typical multi-carrier method is orthogonal frequency division multiplex (OFDM), which is used for the long-term evolution (LTE) mobile cellular standard. This also includes the coded orthogonal frequency division multiplex (COFDM) method, which is used for terrestrial digital television DVB-T, for example.

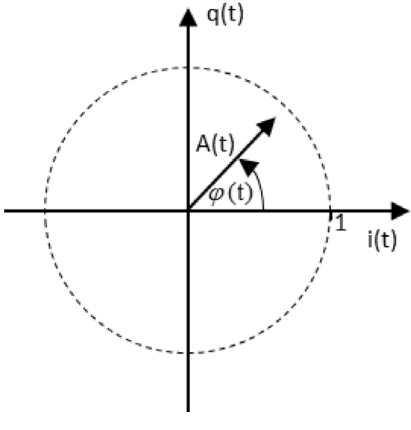
Digital Modulation Methods

Digital modulation methods transmit symbols that are uniquely defined for the transmitter and receiver. A symbol represents the smallest information element. Symbols combine – depending on modulation mode – n individual bits, where n is taken from the set of natural numbers. These symbols form the set of numbers used by a modulation mode. The throughput of the air interface is constrained by the symbol rate and the number of bits per symbol.

Analog signals (voice, music) must be digitized for transmission by means of a digital modulation method. The digital data is then mapped to the symbols to be transmitted. The digital modulation delivers valid values only at defined sample times and is therefore time discrete. The spacing in time between the sampling points is called the symbol rate.

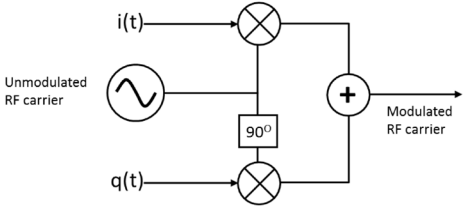
Principles of I/Q Modulation

State-of-the-art I-Q modulators vary the carrier signal in two dimensions. They synthesize the modulation signal from the sum of two baseband signals, i(t) and q(t), where i(t) represents the in-phase component and q(t) the quadrature component. Orthogonally applied in the I/Q plane, both extend over a vector with length A(t) and phase φ(t). i(t) and q(t) are normalized at a constant ≤ 1.



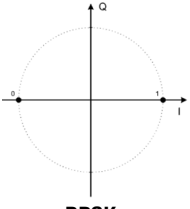
Principles of I/Q Modulation

The modulated signal is generated by adding one carrier modulated with i(t) and one modulated with q(t) – phase-shifted by 90°. By using two baseband signals, it is possible to determine the magnitude as well as the phase of the modulated signal at any given point in time. This also makes it fairly easy to implement analog modulation.

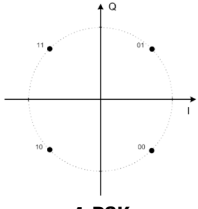


Constellation Diagram

The constellation diagram provides a graphical representation of the in-phase and quadrature-phase components of the digitally modulated signal. This displays a vector in a Cartesian system of coordinates, along with the amplitude and phase of a given carrier at the sampling point in time. Because the symbols to be transmitted represent complex numbers, they can be displayed as points in the constellation diagram, which corresponds to the complex plane. These points in turn correspond to the terminals of the respective I/Q vectors.



BPSK



4-PSK

Digital Modulation of a Sine-Wave Carrier

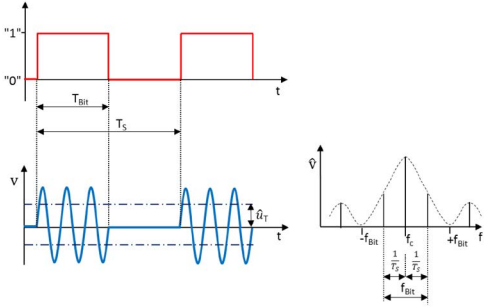
Like for analog modulation, the wireless transmission of a digital baseband signal also requires transition to a higher frequency range by modulating a sine-wave carrier. One or more parameters of the carrier oscillation, i.e. amplitude, frequency or phase, can still be influenced by the digital baseband signal. Because the digital signal oscillates only between two fixed signal values, this is not considered modulation, but rather a keying of the carrier oscillation. As such, there are three keying options:

- Amplitude shift keying (ASK)
- Frequency shift keying (FSK)
- Phase shift keying (PSK)

With a carrier that can assume M = 2n states for amplitude, frequency or phase, a group of n bits can be transmitted simultaneously in one clock step. This is included in the method names, e.g. 2-ASK, 4-PSK or 8-FSK.

Amplitude Shift Keying (ASK)

If a digital bit sequence changes only the carrier amplitude, this is considered to be amplitude shift keying. For a digital high bit “1”, the maximum carrier amplitude is transmitted. For a low bit “0”, the carrier switches off. ASK can be performed with multiple increments of the carrier amplitude. For example, with four amplitude increments, it is possible to transmit 2 bits (00, 01, 10, 11) simultaneously at double the rate. Because interference in the transmission channel is almost always exhibited as amplitude interference, the multi-value ASK is more prone to interference.



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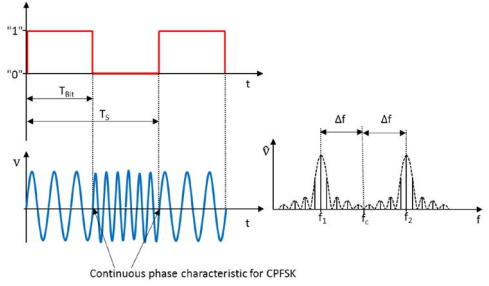
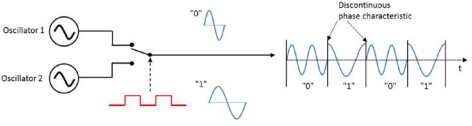
Frequency Shift Keying (FSK)

Frequency shift keying takes place when a digital bit sequence changes only the carrier frequency. In this case, the frequency of a carrier oscillation changes erratically during digital data transmission. For example, with a 2-FSK method, the binary states "0" and "1" are transmitted with frequencies f_1 and f_2. These two identification frequencies are placed in symmetry to the carrier frequency fc. In the case of 4-FSK, each symbol frequency transmits two bits simultaneously, whereby the each of the symbols 00, 01, 10 or 11 is assigned one frequency.



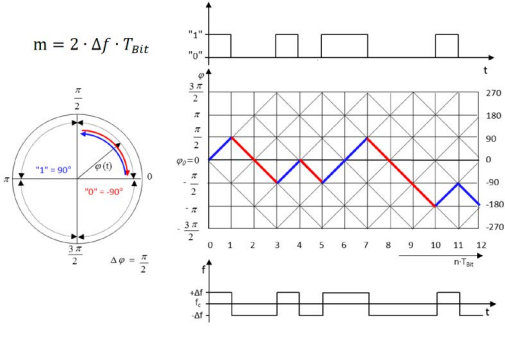
Frequency Shift Keying (FSK)

The switchover between the individual frequencies can be done in any of several different ways. The simplest method is to switch the digital information directly between two separate oscillators with frequency f_1 and f_2. This method is known as "hard FSK keying". Because the individual oscillators can have a random phase angle to one another, typically a discontinuous transition takes place at the individual switching times, resulting in a discontinuous phase characteristic.



Minimum Shift Keying (MSK)

The smallest possible value of m that still permits an orthogonal FSK is 0.5. It is only with an orthogonal FSK and an integer multiplier of m = 0.5 that the intersymbol interference between two individual symbols remains at a minimum, with the result that the mutual influence is also minimal. The method that uses m = 0.5 is known as minimum shift keying (MSK), or fast frequency shift keying (FFSK). For MSK, Δf between binary "1" and "0" is exactly one half the data rate.



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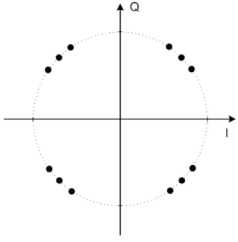
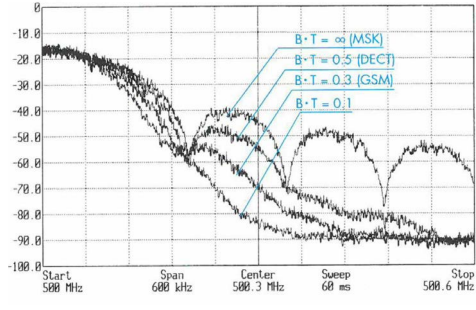
Gaussian-Filtered Minimum Shift Keying (GMSK)

To save bandwidth, the digital data stream is filtered using a Gaussian filter before the modulation, and the MSK is transformed into a Gaussian-filtered minimum shift keying (GMSK). This filter flattens the steep edges of the square-wave digital signals and eliminates high frequency signal components. Like 2-FSK, GMSK transmits only one bit per symbol. Because the modulation is performed by means of a phase shift of ± π/2, exactly four possible states result. GMSK significantly reduces the sidelobes in the spectrum, which can interfere with adjacent channels. An example application for GMSK is the global system for mobile communications (GSM) mobile cellular standard for data transmission.



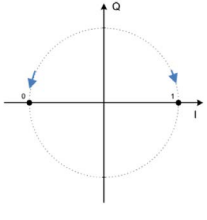
Gaussian-Filtered Minimum Shift Keying (GMSK)

The sidelobes become less pronounced as the value of the bandwidth time product decreases, and the intersymbol interference increases as the required bandwidth decreases. These superpositions and the resulting misinterpretation of adjacent bits in the receiver can be compensated by means of an error correction after the demodulation.



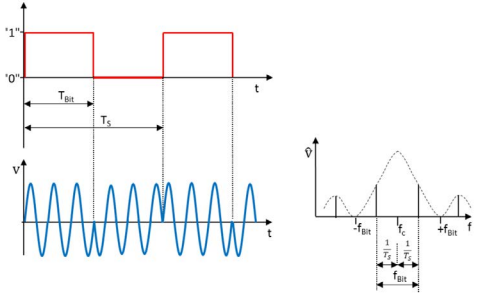
Phase Shift Keying (PSK)

In phase shift keying, the phase of a carrier oscillation is shifted in accordance with the digital bit sequence. Each symbol to be transmitted is assigned an absolute phase angle. For better differentiation, the phase states are typically equally divided over 360°. All phase shift keying is based on binary phase shift keying (2-PSK), which is also known as binary shift keying (BSK). Two phase states are available in 2-PSK for displaying the binary "0" or "1". BPSK thus transmits only one bit per symbol.



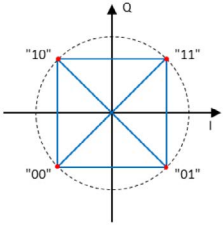
BPSK

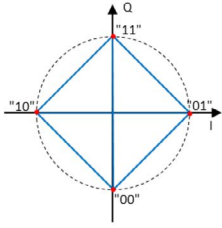
Phase Shift Keying (PSK)



2-PSK

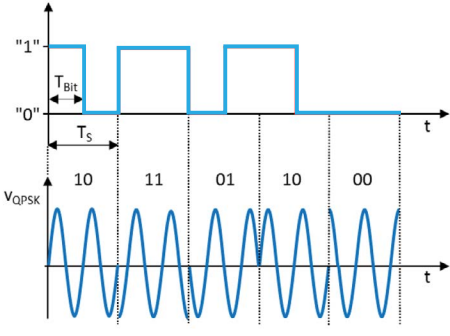
Quadrature Phase Shift Keying (QPSK)





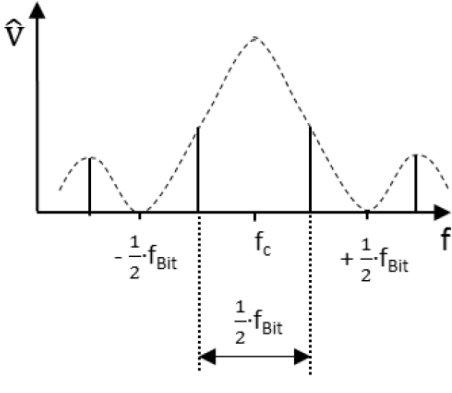
Symbol (Dibit)	Δφ
1 1	+45°
0 1	+135°
0 0	–135°
1 0	–45°

Quadrature Phase Shift Keying (QPSK)



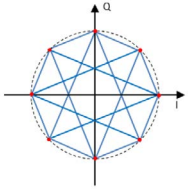
Quadrature Phase Shift Keying (QPSK)

For QPSK, the duration of a signal step T_s is: $T_s = 2T_{bit}$. The width of the QPSK spectrum is reduced by one-half compared to 2-PSK. In other words, in the 2-PSK spectrum f_{bit} is replaced by $f_{bit}/2$.



Quadrature Phase Shift Keying (QPSK)

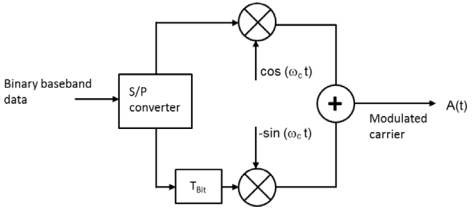
The transition between two diagonally placed transmit symbol points (10 to 01 and 11 to 00) in the complex plane passes through the zero crossing. This means that the carrier power fluctuates strongly and returns to zero at the zero crossing. The result is an undesirably strong AM modulation of the carrier. It is undesirable because modulation methods without a constant envelope, such as GMSK, cannot use non-linear class C amplifiers with a high degree of efficiency and low energy consumption.
This problem can be alleviated with π/4-DQPSK modulation. Independent of the user data, an additional phase shift of π/4 (45°) is performed after each transmit symbol. This ensures that the transition between two symbols never transverses the origin and always only one carrier amplitude is transmitted.



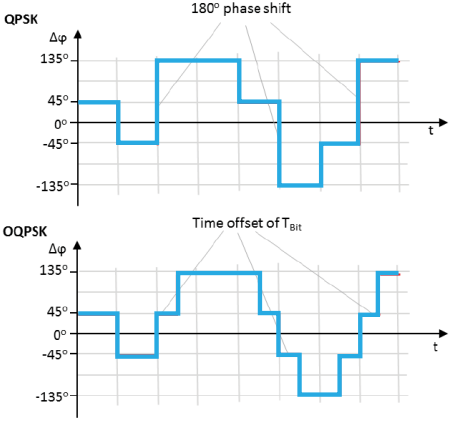
π/4-DQPSK

Offset Quadrature Phase Shift Keying (OQPSK)

Another option for preventing zero crossings and the associated reduction in amplitude is offered by offset QPSK (OQPSK). To achieve this, the maximum phase change for OQPSK is only 90° instead of the 180° for conventional QPSK. With QPSK, the two bit streams used to generate the I and Q signals are synchronous, i.e. their sign changes occur simultaneously. If both binary signals change state at the same time in QPSK, a phase shift of 180° occurs. In the case of OQPSK, the two data streams are shifted toward one another at half a step length of T_S or at a bit time of T_{Bit} and then applied to the modulators for I and Q, ensuring that they no longer change simultaneously.



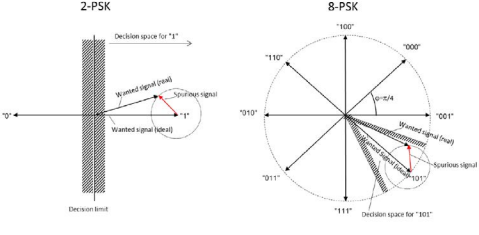
Offset Quadrature Phase Shift Keying (OQPSK)



Offset Quadrature Phase Shift Keying (OQPSK)

At a constant signal-to-noise ratio, the 2-PSK method provides the lowest bit error probability. The susceptibility to noise increases steadily as the PSK order increases. However, because more bits are transmitted per symbol, the data rate also increases.

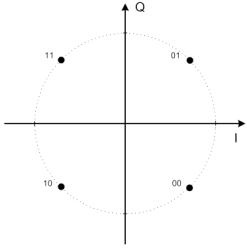
For example, with an 8-PSK with eight possible carrier states, 3 bits are transmitted per step or symbol.



Quadrature Amplitude Modulation (QAM)

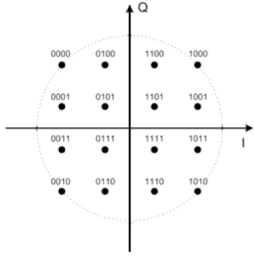
The preceding sections introduced digital modulation methods for data transmission in which only one parameter (amplitude, frequency or phase) of a carrier oscillation was changed by a modulating binary signal. An increase in the transmission rate is achieved by modulating the amplitude and phase of a high-frequency carrier. The method that combines amplitude and phase modulation is known as quadrature amplitude modulation (QAM). While the signal states lie in a circle for PSK, this is no longer the case when the amplitude is changed. The only exception is 4-QAM, which is identical to 4-PSK/QPSK. Four bits are transmitted per symbol. The result is 24 = 16 symbols. The symbol rate is ¼ the bit rate. This symbol placement in the constellation diagram includes three different amplitudes, one with eight different phase values and two with four phase values.

Quadrature Amplitude Modulation (QAM)



4-QAM or 4-PSK (QPSK)

16-QAM



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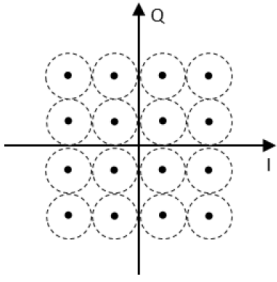
Quadrature Amplitude Modulation (QAM)

A QAM requires less power than PSK at the same weighting M and the same bit error probability. However, as the number of symbols increase, the spacing of adjacent states of necessity are reduced. As a result, the symbols are more difficult to isolate on the receiver end, especially when they are accompanied by noise from a poor radio link.



Applications for Digital Modulation Methods

Standard	Transmission Method	Modulation
GSM	Single carrier	GMSK
EGPRS	Single carrier	8-PSK (3pi/8 rotation)
TETRA	Single carrier	Pi/4-DQPSK, 16-QAM, 64-QAM
UMTS, HSPA, HSPA+	CDMA	QPSK, 16-QAM, 32-QAM
LTE	COFDM	QPSK - 64-QAM
DVB-S	Single carrier	QPSK
DVB-S2	Single carrier	QPSK, 8-PSK, 16-APSK, 32-APSK
DVB-T	COFDM	QPSK, 16-QAM, 64-QAM
DVB-C	Single carrier	64-QAM, 256-QAM
WLAN	COFDM	DBPSK - 64-QAM
DAB	COFDM	DQPSK

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Comparing Different Phase Shift Keying Methods

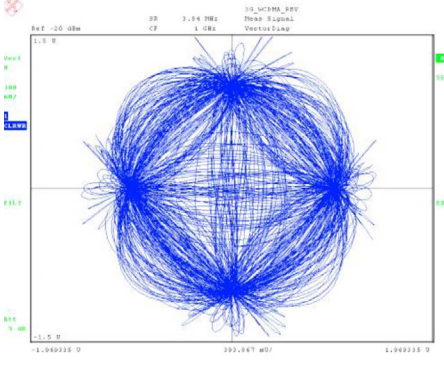
Modulation	2-PSK	4-PSK	8-PSK	16-PSK	16-QAM	32-QAM	64-QAM
Amplitude states	1	1	1	1	3	5	9
Phase states	2	4	8	16	12	28	52
Carrier states	2	4	8	16	16	32	64
Theoretical maximum bandwidth utilization in (bit/s)/Hz	1	2	3	4	4	5	6
Practical bandwidth utilization in (bit/s)/Hz	0.7	1.4	2.1	2.8	2.8	3.6	4.2
C/N in dB for BER = 10^{-6}, in practice	10.7	13.7	18.8	24	20.5	24	27

Crest Factor / Linearity Requirements

The amplitude of the modulated transmit signal is always proportionate to the corresponding vector length in the baseband – including between the symbol points in time. When considered in this light, it is clear that the unit circle is frequently violated by the transitions between the symbols. The ratio of peak value to average value is called the crest factor. It determines the power margin that must be reserved at the TX output stage.

Crest Factor / Linearity Requirements

For an error-free demodulation on the receiver end, it is important that the signal characteristic be transmitted totally without distortion. The transmit output stage must therefore not only maintain some headroom for high power levels, but must also exhibit very high linearity over the entire power range from 0 watts to the maximum power.



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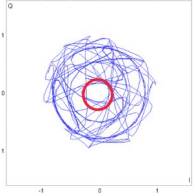
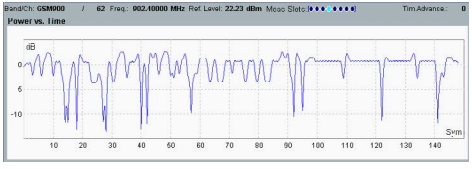
Crest Factor / Linearity Requirements

With 8-PSK, the zero crossings required during hops between opposing symbols in the I/Q diagram are avoided by rotating the constellation diagram by 3π/8 between the symbol clocks. As a result of the rotation, about 16 symbol states will be recalculated at the receiver end during demodulation.





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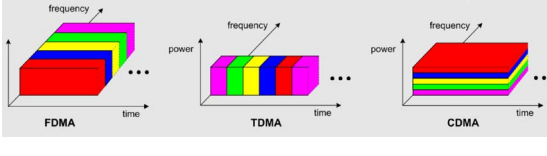
Access Methods

Digital wireless communications networks are organized into cells. Because radio waves have a limited range, it is possible to define an area – called a cell – inside of which service to wireless subscribers is provided by a single base station (BS). At the reception boundaries, a mobile phone (also called a mobile station, MS or user equipment, UE) is automatically switched to the adjacent cell that is most suitable (handover). This typically also involves a change in frequency. The original frequency might then be available again in the next cell over (frequency reuse).



Access Methods

Because every cell is limited to a specific area, it can handle a finite number of wireless subscribers or, stated conversely: The size of a wireless communications cell is determined primarily by its required capacity. Because the available resources of frequency, time and – as we will see later – code are limited, locations with a large potential number of subscribers must have many base stations with correspondingly low power. Regions with fewer subscribers can have large cells with powerful base stations. The point is to ensure that multiple subscribers have access to a fixed percentage of the resources frequency, time and code – independent of the uplink / downlink duplex.

The three most frequently used methods are:
- Frequency-division multiple access (FDMA)
- Time-division multiple access (TDMA)
- Code-division multiple access (CDMA)

Modern vector signal generators are able to offer these methods for standard-compliant generation of signals.

Signal Generators

Baseband, RF and microwave signal generators from Rohde & Schwarz excel in signal quality, flexibility and usability. Rohde & Schwarz signal generators offer wide frequency ranges up to 43.5 GHz (up to 170 GHz with frequency multipliers), feature modulation bandwidths up to 2 GHz and support all major mobile communications and wireless digital standards.

The portfolio ranges from ultracompact and unexcelled fast analog and digital signal sources, optimized for use in production and automated solutions, to premium class vector signal generators with multichannel and fading simulation capabilities for most demanding applications.

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Signal & Spectrum Analyzer

All Rohde & Schwarz signal and spectrum analyzers, from basic value and handheld models to benchtop instruments up to 85 GHz, set standards in accuracy, RF performance and usability. We support performance-oriented, cost-conscious users during the development, production, installation and servicing of RF systems.

For production and monitoring systems, we also offer specially designed remote controlled ultra-compact spectrum analyzers that require minimal rack space.

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Power Sensors

Power meters, power sensors and volt meters from Rohde & Schwarz stand for highest measurement accuracy and reliability – and have done so for decades.

Rohde & Schwarz power sensors are intelligent stand-alone instruments with a flexible connection concept. The comprehensive USB-capable sensor portfolio is designed to operate with the power meter base unit or a PC/laptop. The latest power sensor family can also be controlled via LAN.

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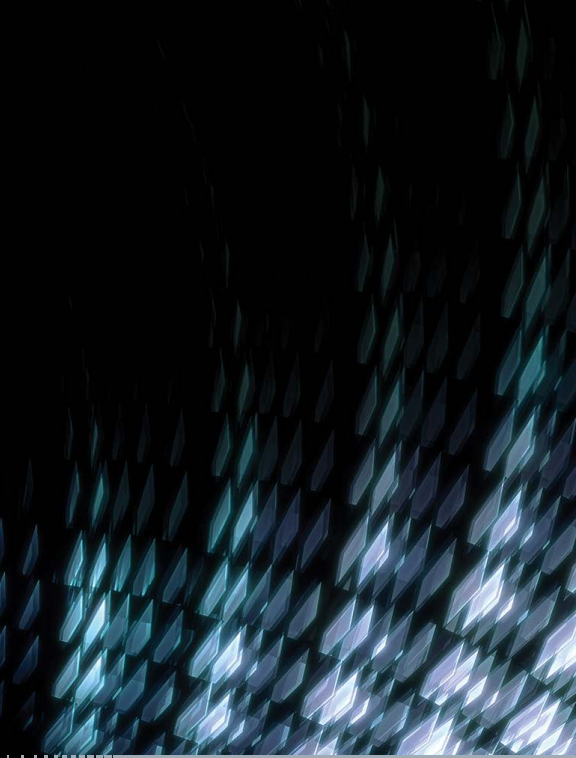

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