Modulation Techniques for Satellite Communications

Almost every communication industry — including broadcasting, navigation, transportation, and cellular — relies on satellite technology in some way. Applications and services for satellite communications include broadband communications, mobile satellite services, and weather forecasting. Emerging applications and services for satellite communications include in-flight connectivity, connected car, and 5G New Radio non-terrestrial network.

With strong demand for faster data throughput, satellite communications use complex modulation schemes to improve their spectral efficiency. The modulation techniques for satellite communications require not only faster data rates but also minimizing the impact of nonlinear amplification in the radio-frequency (RF) power amplifier.

This white paper focuses on modulation techniques for modern satellite communications from generating and analyzing the signals to the impacts of phase noise on modulation quality.

As network traffic increases exponentially due to rapidly evolving wireless communications systems, it will create strong demand for increased bandwidth to support next-generation wireless standards and technologies.
Modulation Schemes for Modern Satellite Communications

Amplitude, frequency, and phase are basic modulation methods that apply to a carrier signal. You can express modulating signals in polar form (vector) as a magnitude and phase. Digital modulation is often expressed in terms of I (in-phase) and Q (quadrature) components by removing carrier frequency. The left side of Figure 1 shows an I/Q diagram. I and Q signals mix with the same local oscillator (LO) but with a 90-degree phase shifter placed in one of the LO paths. The main advantage of I/Q modulation is the symmetric ease of combining independent signal components into a single composite signal for transmitting, then splitting that composite signal into its separate components for receiving.

![I/Q modulation diagram](image)

Figure 1. I/Q modulation

There are two main categories of modulation schemes: constant envelope and nonconstant envelope. “Constant envelope” means that all constellation points have a fixed distance from the center.

**Constant envelope digital modulation schemes**

The constant envelope modulation schemes are the most suitable for satellite communications because they minimize the effect of nonlinear amplification in the high-power amplifier. Those schemes include frequency-shift keying (FSK) and phase-shift keying (PSK). To achieve faster data rates, higher-order modulation schemes provide better spectral efficiency, but they are more sensitive to channel impairments. Figure 2 illustrates the constellation diagrams of binary PSK (BPSK), quadrature PSK (QPSK), and 8PSK. They transmit 1, 2, and 3 bits per symbol, correspondingly. For higher-order PSK, the constellation points are closer to each other, and the system is more sensitive to channel impairments.
Nonconstant envelope digital modulation schemes

Quadrature amplitude modulation (QAM) is a nonconstant modulation that changes both phase and amplitude to increase spectral efficiency. Figure 3 illustrates the constellation diagram of 16PSK and 16QAM. 16QAM increases the distance between the constellation points and has better resistance to signal impairments. However, 16QAM also increases the amplitude levels to three (rings) compared with 16PSK. RF power amplifiers require a wider linear range for nonconstant modulation.
In satellite transmission, RF power amplifiers often operate at their compression levels to maximize conversion efficiency. Operating at compression levels causes AM/AM and AM/PM distortion, as shown in Figure 4. For example, the I/Q constellation outer points have higher output power levels, and the compression is because of the saturated output power in the RF power amplifier. Thus, nonlinear amplifiers require a modulation scheme tolerant to distortion.

Figure 4. AM/AM and AM/PM effects on a 64QAM signal

Resist nonlinear distortion — using amplitude phase-shift keying

Satellite communications employ amplitude phase-shift keying (APSK) to resist nonlinear distortion. Figure 5 illustrates a constellation diagram for APSK and QAM modulation schemes. The APSK’s states are in rings such that the amplitude compression is the same in a specific ring. The 16APSK constellation has only two amplitudes (rings), whereas 16QAM has three amplitudes. The 32APSK constellation has three amplitudes versus five in 32QAM. More amplitude levels make the rings closer together and more difficult to compensate for nonlinearities.

Figure 5. Constellation diagrams for APSK schemes and corresponding QAM formats
Another advantage of APSK is to implement predistortion easily by varying the space between rings before transmission. In addition, by adjusting the spacing between rings, a designer can also reach a balance between lower peak-to-average power ratio (PAPR) and better resistance to distortion.

**Reduce PAPR — modulation variations**

A high PAPR of a transmitted signal requires a large dynamic range for a power amplifier in a satellite transmitter. Modulation variations can reduce PAPR and keep the same order modulation scheme, such as offset QPSK (OQPSK) and differential modulation.

OQPSK offsets the I and Q bit streams in their relative alignment by one bit period (one-half of a symbol period), as shown in Figure 6. The signal trajectories (blue lines) do not go through or near zero (the center of the constellation), reducing amplitude variations and allowing designers to use a more power-efficient, less linear RF power amplifier.

![Figure 6. I/Q diagrams of QPSK and OQPSK](image_url)
Enhance data rate using orthogonal frequency-division multiplexing

Orthogonal frequency-division multiplexing (OFDM) uses many closely spaced orthogonal subcarrier signals to transmit data in parallel. That process provides better spectral efficiency than traditional digital modulation schemes, such as QAM and PSK, and robustness against channel linear distortion. Figure 8 shows a single OFDM carrier (left plot) and multiple subcarriers (right plot). The peak of each subcarrier occurs at zero crossings of the others. The signal is orthogonal in the frequency domain, and each subcarrier does not interfere with the others. The subcarriers can apply different modulation formats, as shown in Figure 9, and channel coding, depending on the noise and interference level of individual sub-bands that provide a robust communication link.

Differential modulation means that the transition between state carries the information. For example, π/4 differential QPSK (DQPSK) uses two QPSK constellations offset by 45 degrees, as shown in Figure 7. The signal trajectories (blue lines) do not go through or near zero.
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![An OFDM constellation diagram with different modulation formats](image)

Figure 9. An OFDM constellation diagram with different modulation formats

However, OFDM signal has a higher PAPR than traditional modulation schemes, requiring a large back off to avoid the compression at a high output power level. Nonlinear effects generated by the high-power amplifier may introduce more distortions to a satellite system that cause a system failure. Therefore, characterizing the distortion performance of satellite RF components is essential for making a good system design.
Generate and Analyze Custom Modulation Schemes

APSK resists nonlinear distortion for satellite communications but also brings in test challenges — generating and analyzing custom, proprietary modulation schemes. Figure 10 illustrates a constellation editor for generating a 32APSK modulated signal. The custom signal-creation tool allows a user to enter the desired I/Q data, magnitude, phase, and symbol that corresponds to each point on the constellation diagram. The software tool lets you save setup files for configuring signal analysis measurement applications. That way, you do not need to edit the constellation map in the signal analysis tool again. Figure 11 shows the demodulation analysis of the 32APSK signal using a signal analyzer.

Figure 10. Edit a 32APSK modulated signal using PathWave Signal Generation for custom modulation

Figure 11. Demodulation analysis for a 32APSK signal with vector signal analysis software
Likewise, creating and analyzing custom OFDM waveforms requires a deeper background in OFDM technology. Fortunately, a custom signal-creation tool can accelerate the waveform generation and analysis of standard or proprietary OFDM signals. Figure 12 illustrates a custom OFDM setup for resource mapping, including subcarriers (frequency) and symbols (time), using a custom signal-creation tool. The signal analysis application can load the setup files in the creation tool and demodulate the signal with ease.

Figure 12. Simplify custom OFDM signal creation with PathWave Signal Generation
Impacts of Phase Noise on Modulation Quality

Phase noise performance is often the key factor in the selection of test instruments for demanding satellite test applications. It impacts the signal quality in many aspects and causes measurement uncertainty, such as high-order modulation schemes and OFDM modulation schemes. Figure 13 illustrates a measured single sideband (SSB) phase noise performance of a microwave signal generator. You need to ensure that the phase noise performance will not impact your measurement results and understand which frequency offsets matter the most to your test applications.

Figure 13. Measured SSB phase noise performance of the Keysight M9384B VXG

Impacts on Digital modulation

The phase noise of the LO signal is translated into the output of the I/Q modulator and demodulator mixers. The direct effect of phase noise on the constellation diagram is the radial smearing of the symbols, as shown in Figure 14. For a higher-order modulation scheme (for example, 256QAM), the symbols are closer. Symbol smearing results in bad receiver sensitivity and a higher bit error rate.

Figure 14. LO phase noise impairs the signal

For those interested in gaining deeper knowledge about OFDM frame and resource structure, download the application notes “Custom OFDM Signal Generation” and “Making Custom OFDM Measurements.”
Impacts on orthogonal frequency-division multiplexing

OFDM is a popular modulation scheme for broadband communications. During frequency conversion with a poor phase noise LO, the subcarrier with phase noise spreads into other subcarriers as interference, as shown in Figure 15. The phase noise degrades the modulation quality of the OFDM signal.

Figure 15. The impact on OFDM subcarriers for a poor phase noise LO

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- PathWave Signal Generation
- PathWave Vector Signal Analysis
- PathWave X-Series Applications
Simplify Custom Signal Generation and Analysis

Most communications systems optimize efficiencies in system designs, including spectral, power, and cost. The selection of modulation schemes for satellite communications depends on the communication channels, hardware limitations, and data throughput requirements. Generating and analyzing modulated signals for modern satellite communications brings challenges, as the signals are customized proprietary modulation schemes. A flexible custom modulation software tool reduces time spent on signal simulation and provides a setup file for configuring your signal analyzer for demodulation analysis.

To obtain accurate measurements, test instruments for satellite applications require excellent phase noise performance that does not impact the signal modulation quality for signal generation and analysis. Keysight offers an extensive line of test equipment with superior phase noise needed and widest bandwidth to test satellite communications equipment.

<table>
<thead>
<tr>
<th>Signal Analyzer</th>
<th>Signal Generator</th>
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<tbody>
<tr>
<td>UXA</td>
<td>PSG-D</td>
</tr>
<tr>
<td>N9042B</td>
<td>E8267D</td>
</tr>
<tr>
<td>N9041B</td>
<td>M9484C</td>
</tr>
<tr>
<td>N9040B</td>
<td>M9384B</td>
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<td>N9030B</td>
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<td>N9021B</td>
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- **Max. frequency**: 110 GHz (UXA), 110 GHz (PXA), 50 GHz (MXA), 44 GHz (PSG-D), 110 GHz (E8267D), 44 GHz (M9484C), 44 GHz (M9384B), 44 GHz (M9383B)
- **Max. bandwidth**: 4 GHz (UXA, 11 GHz), 1 GHz (PXA, 9.6 GHz), 1 GHz (MXA, 1.2 GHz), 2 GHz (PSG-D, 510 MHz), 2 GHz (E8267D, 510 MHz), 2 GHz (M9484C, 510 MHz), 2 GHz (M9384B, 80 MHz), 2 GHz (M9383B, 2.5 GHz)
- **Phase noise at 10 GHz, 10 kHz offset**: -126 dBc/Hz (UXA), -126 dBc/Hz (PXA), -126 dBc/Hz (MXA), -124 dBc/Hz (PSG-D), -121 dBc/Hz (E8267D), -129 dBc/Hz (M9484C), -129 dBc/Hz (M9384B), -127 dBc/Hz (M9383B)

1. Support maximum analysis bandwidth with wide IF output option and an external digitizer.
2. Get up to 4 GHz of RF bandwidth with wideband external differential I/Q inputs.
3. Get up to 4 GHz of RF bandwidth with dual-channel bonding.
4. Modular form factor

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