Modulation and Deviation

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Modulation

- What is modulation?
- Why do we modulate?
- Spectrum: carrier and sidebands
- AM
- FM and PM
- Data modulations (PSK, QAM)
- DOs and DO NOTs

What is modulation?

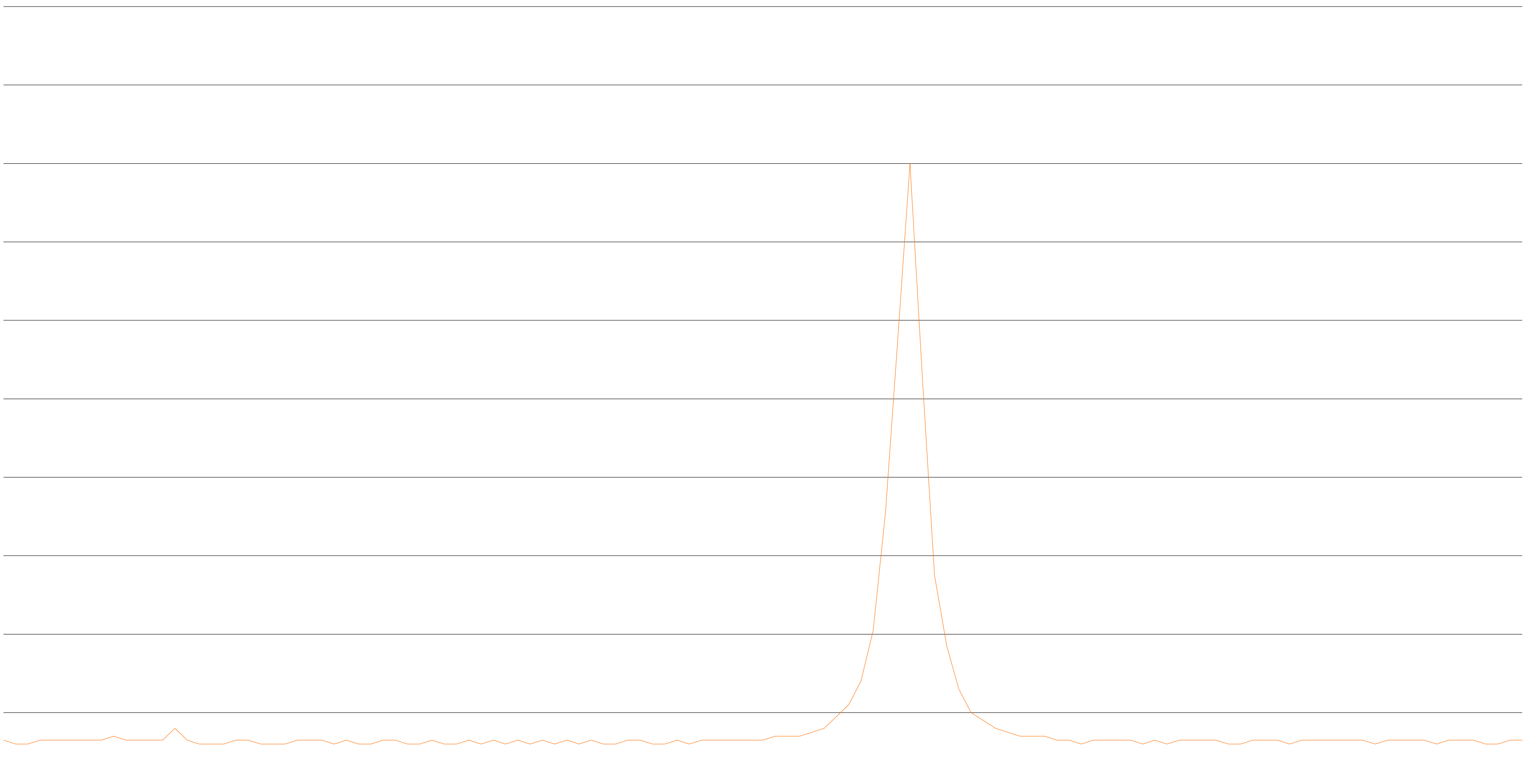
- Modulation is a change or alteration in a signal
- Any aspect of the signal can be changed: amplitude, frequency, phase, timing or repetition rate of pulses

Why do we modulate?

- We modulate because we wish to communicate
- An unmodulated signal conveys no information other than “Hi, I'm here”
- Changes in the signal convey information
- Interpreting the changes is a matter of convention: some may be significant, others can be ignored

Unmodulated (CW) carrier

Unmodulated (CW) carrier



Spectrum

- Most forms of RF modulation involve the generation of an RF carrier signal, which is then modified in some way
- Modifying (modulating) the carrier produces sidebands – other RF frequencies which carry some energy
- The specific sidebands created (frequency and amplitude) depend on the modulation type and the content of the signal

Spectrum and content

- The amount of information you can convey depends on the bandwidth of the transmission, the noise level of the transmission channel, and the amount of error you're willing to accept (the fidelity)
- There is a fundamental limit (the Shannon limit) beyond which you can't pack more information into the channel

Spectrum and content

- Some modern digital data transmission systems come very close to reaching the Shannon limit
- Ham voice (“phone”) modes don't come close
- Digital cellphone comes closer, thanks to digital coding/compression

Overcoming noise

- You can use more bandwidth
- You can reduce the noise level (more sensitive receiver, directional antennas, higher transmit power)
- You can live with it
- You can use less bandwidth and accept a lower information rate (e.g. CW, PSK31)
- It's all about tradeoffs

Amplitude modulation

- Change amplitude of a carrier signal
- Can be a simple on/off keying (amplitude is either “none” or “full on”), or more subtle.
- “AM” usually refers to a linear change in carrier amplitude, proportional to the amplitude of an intelligence signal (most commonly voice or music)

Amplitude Modulation

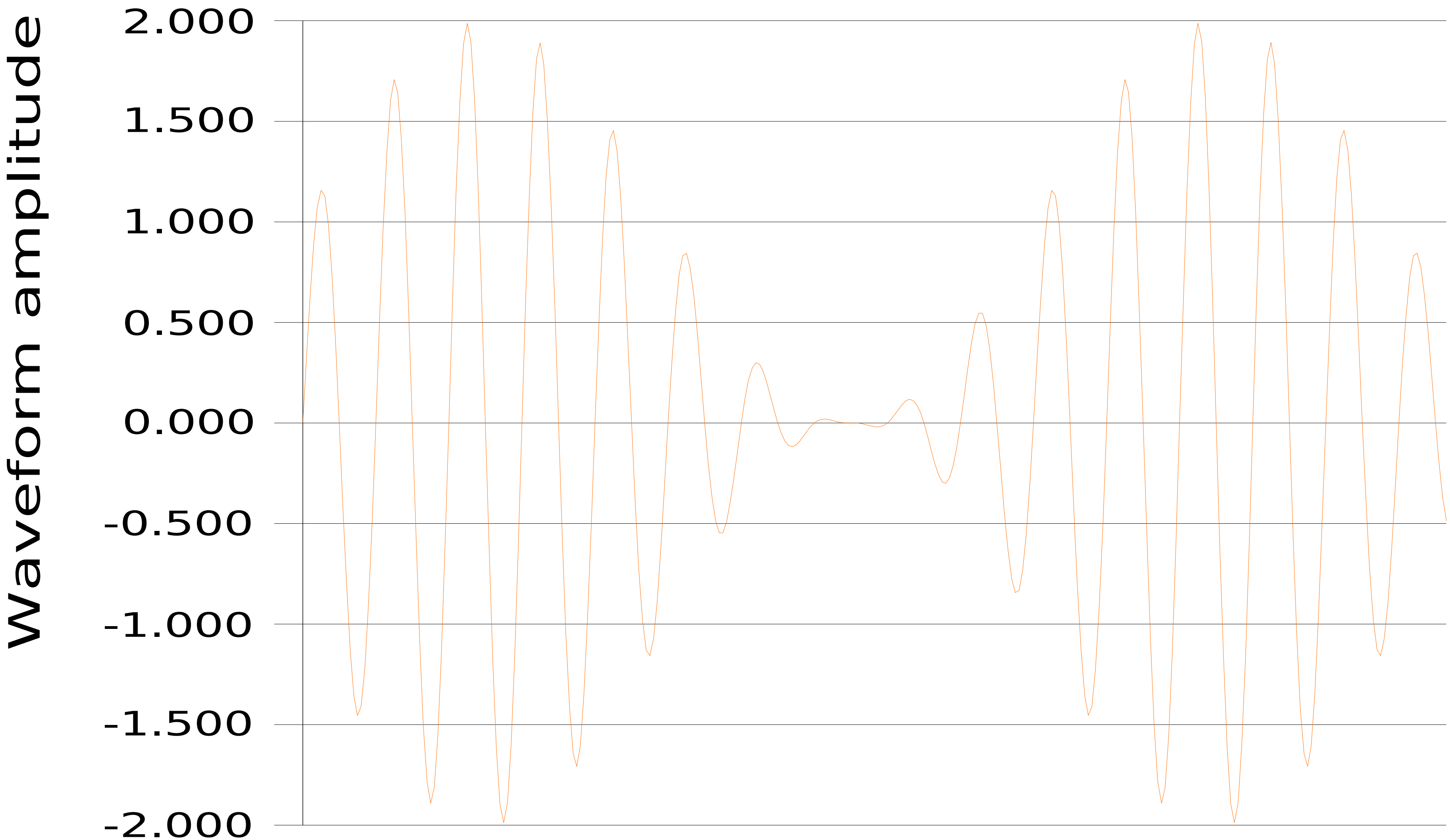
Multiplies the carrier's amplitude, by the amplitude of the modulating signal (plus a constant)

$$V_t = \sin(2\pi f_c t) \times (1 + m \times \sin(2\pi f_m t))$$

where m is the modulation level (0-100%)

AM – 50% modulation

AM – 100% modulation



Amplitude modulation

$$V_t = \sin(2\pi f_c t) \times (1 + m \times \sin(2\pi f_m t))$$

expands to the sum of three terms

$$\sin(2\pi f_c t)$$

$$\frac{m}{2} \times \sin(2\pi (f_c + f_m) t)$$

$$\frac{m}{2} \times \sin(2\pi (f_c - f_m) t)$$

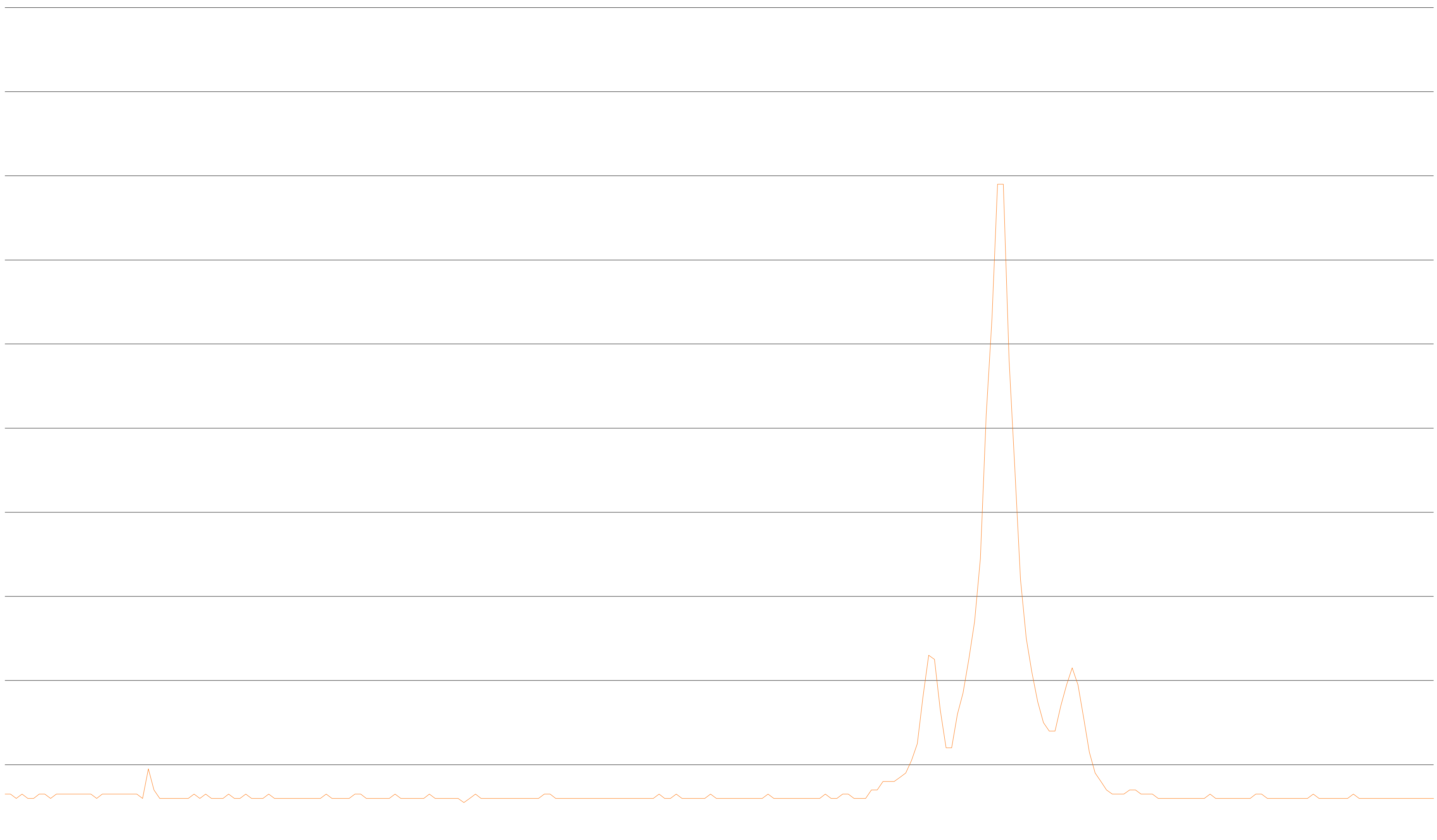
Amplitude modulation

The total signal consists of

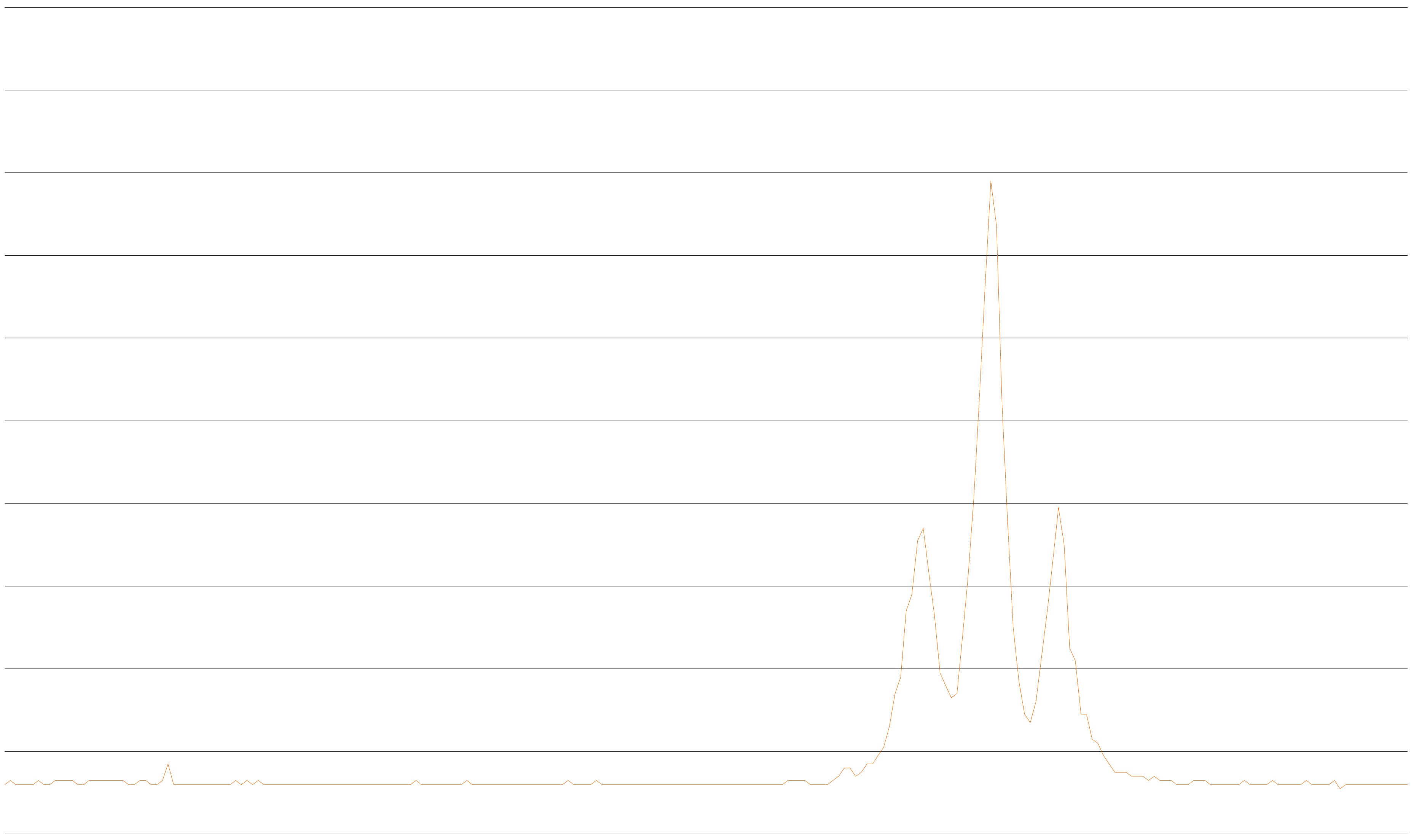
the original carrier (full amplitude), plus

two sidebands, located above and below the carrier frequency by a distance equal to the modulating frequency, each with an amplitude of up to half that of the carrier (and thus each has up to ¼ of the power in the carrier)

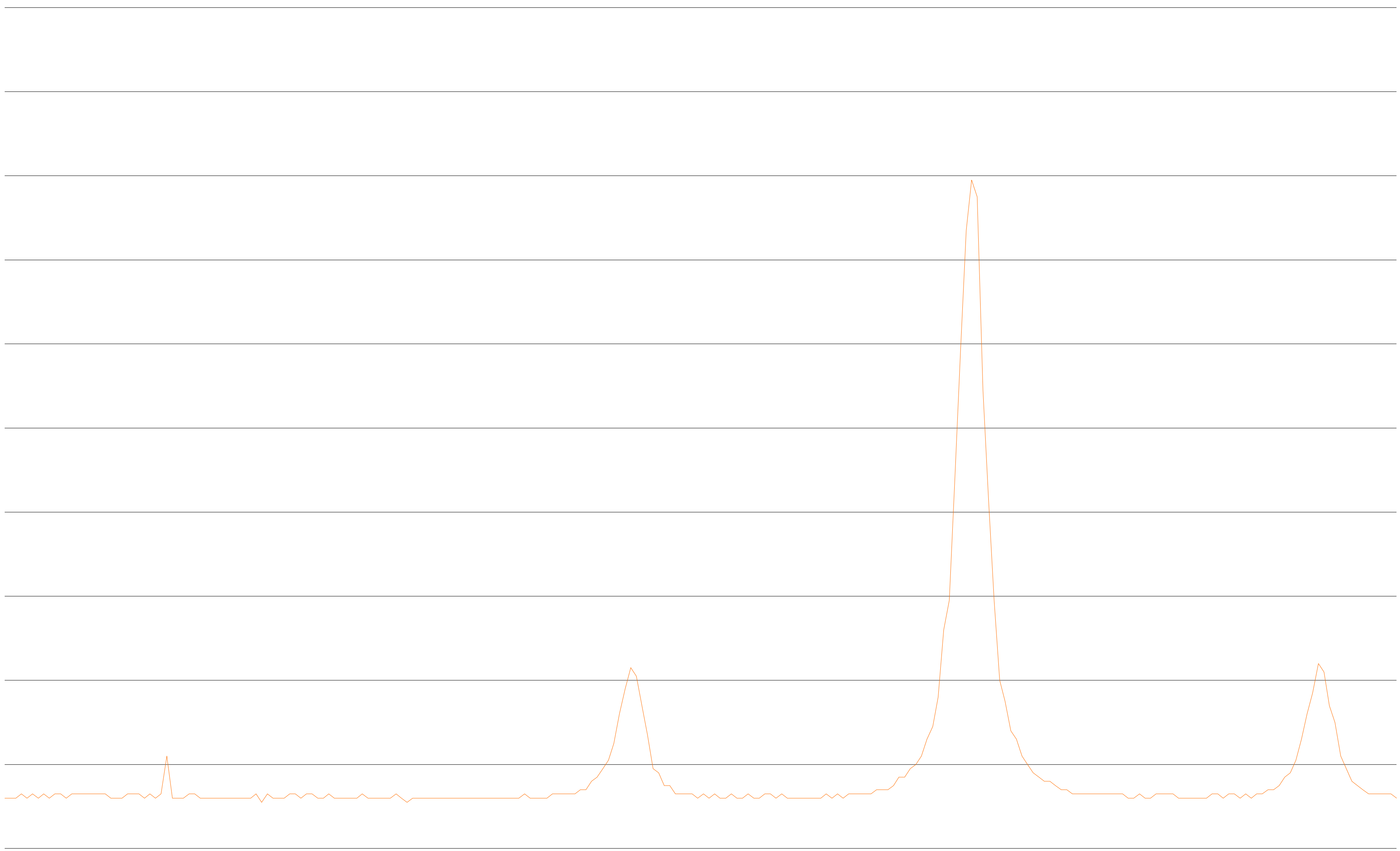
AM, 1kHz tone, 50% modulation



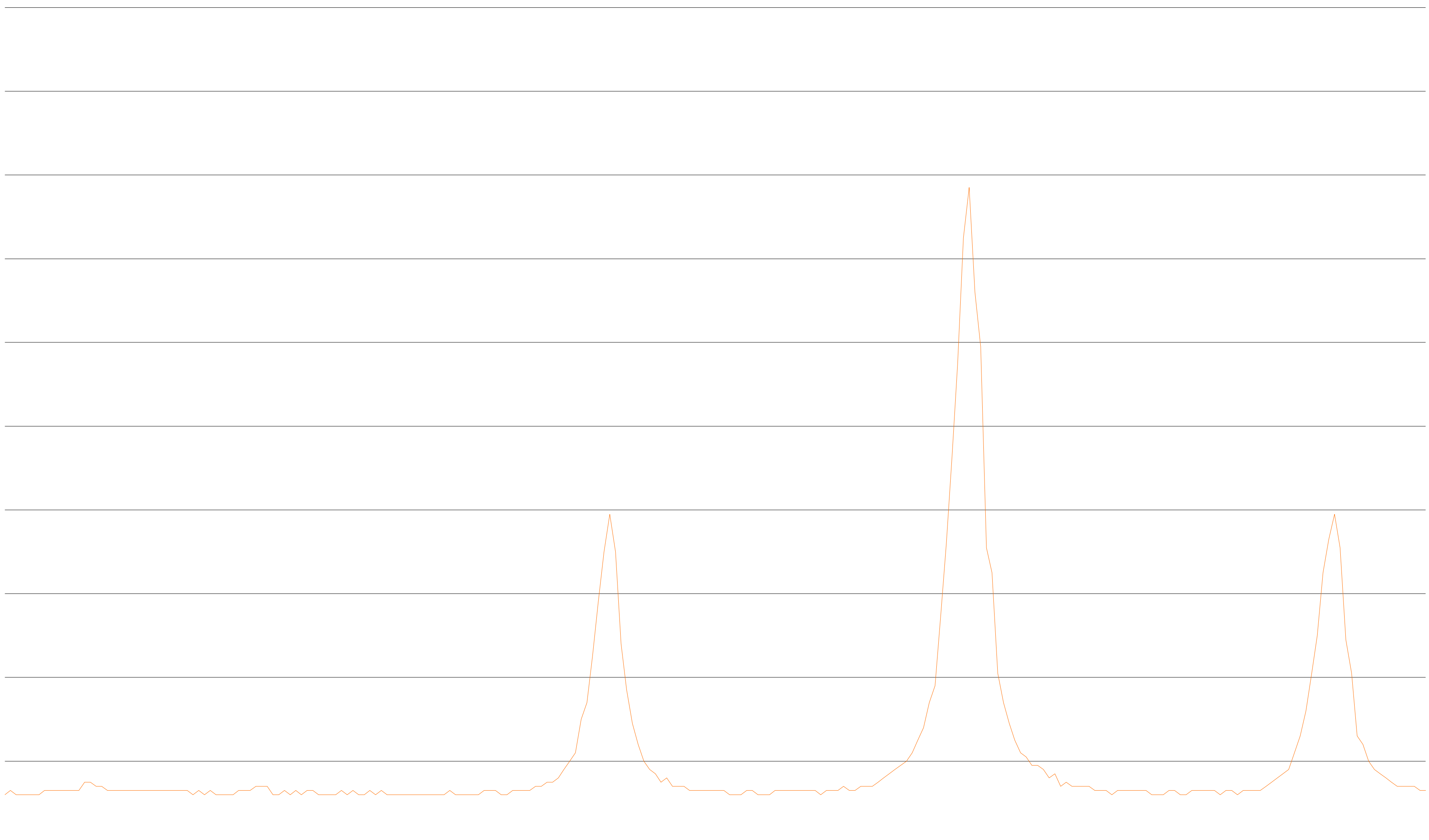
AM, 1 kHz, 100% modulation



AM, 5 kHz, 50% modulation



AM, 5 kHz, 100% modulation



Amplitude modulation

- AM creates an RF signal whose total power varies from moment to moment...
- ... but the power level at the carrier frequency doesn't change!
- At full modulation, total power is 50% more than the carrier power
- Peak power (top of the modulated-carrier waveform) is 4 times the average carrier power

Amplitude modulation

- Envelope maxima occur when the two sideband signals are in phase with one another and with the carrier
- Envelope minima occur when the sidebands are in phase with one another, but 180 degrees out of phase with carrier
- Envelope center occurs when sidebands are absent or are 180 degrees out of phase with one another

Amplitude modulation

- AM is easy to generate, either directly (plate modulation) or by amplifying a low-level AM signal (linear amp required!)
- Any non-linear method of combining two signals, or amplifying a signal containing multiple frequencies, has the effect of squaring or multiplying components and thus generates AM sidebands

Amplitude modulation

- Demodulating (detecting) AM uses the same technique, in reverse
- Multiplying the RF sidebands by the carrier frequency creates new sidebands, including a set down at the original audio frequency
- Since the RF signal contains both the sidebands, and the carrier, all we have to do is multiply it by itself!

Amplitude modulation

- As noted before, almost any nonlinear device will perform some amount of multiplication or squaring, and thus serve as a “product detector”
- Thus, AM is pathetically easy to detect – you can just follow the RF envelope with a rectifier (diode, crystal radio, razor-blade-and-pin, braces and fillings, corroded wire junction) and a low-pass filter

Amplitude modulation

- Prone to noise interference, precisely because it's amplitude sensitive
- Not very efficient. At least 2/3 of the power is in the carrier and carries no intelligence. Sidebands are identical (symmetrical) and therefore carry the same intelligence
- Not popular on HF because of wide bandwidth, heterodyne whistle noise

Sideband modulation

$$V_t = \sin(2\pi f_c t) \times \sin(2\pi f_m t)$$

expands to the sum of two terms

$$\frac{1}{2} \times \sin(2\pi (f_c + f_m) t)$$

$$\frac{1}{2} \times \sin(2\pi (f_c - f_m) t)$$

Single-sideband modulation

- Fundamentally similar to AM
- Generate a low-level AM signal, then eliminate the carrier and one set of sidebands, leaving only the components of the other sideband
- Amplify the remaining sideband signal and transmit
- Can use balanced mixers, crystal filters, etc. for carrier and sideband rejection

Single-sideband modulation

- More power-efficient than AM – all of the energy goes into information-carrying sidebands, none into the carrier
- Redundant sideband is filtered away before amplification, uses no power
- RF bandwidth same as baseband (audio) bandwidth – many QSOs fit into limited spectrum
- Requires linear amplification (like AM)

Single-sideband modulation

- Harder to demodulate than AM because there's no carrier.
- Must re-inject a carrier signal (local oscillator) to mix with the incoming RF, multiply, and thus shift the sideband signal down to the original audio frequencies
- If LO doesn't match original carrier frequency, say hello to Donald Duck!

Frequency modulation

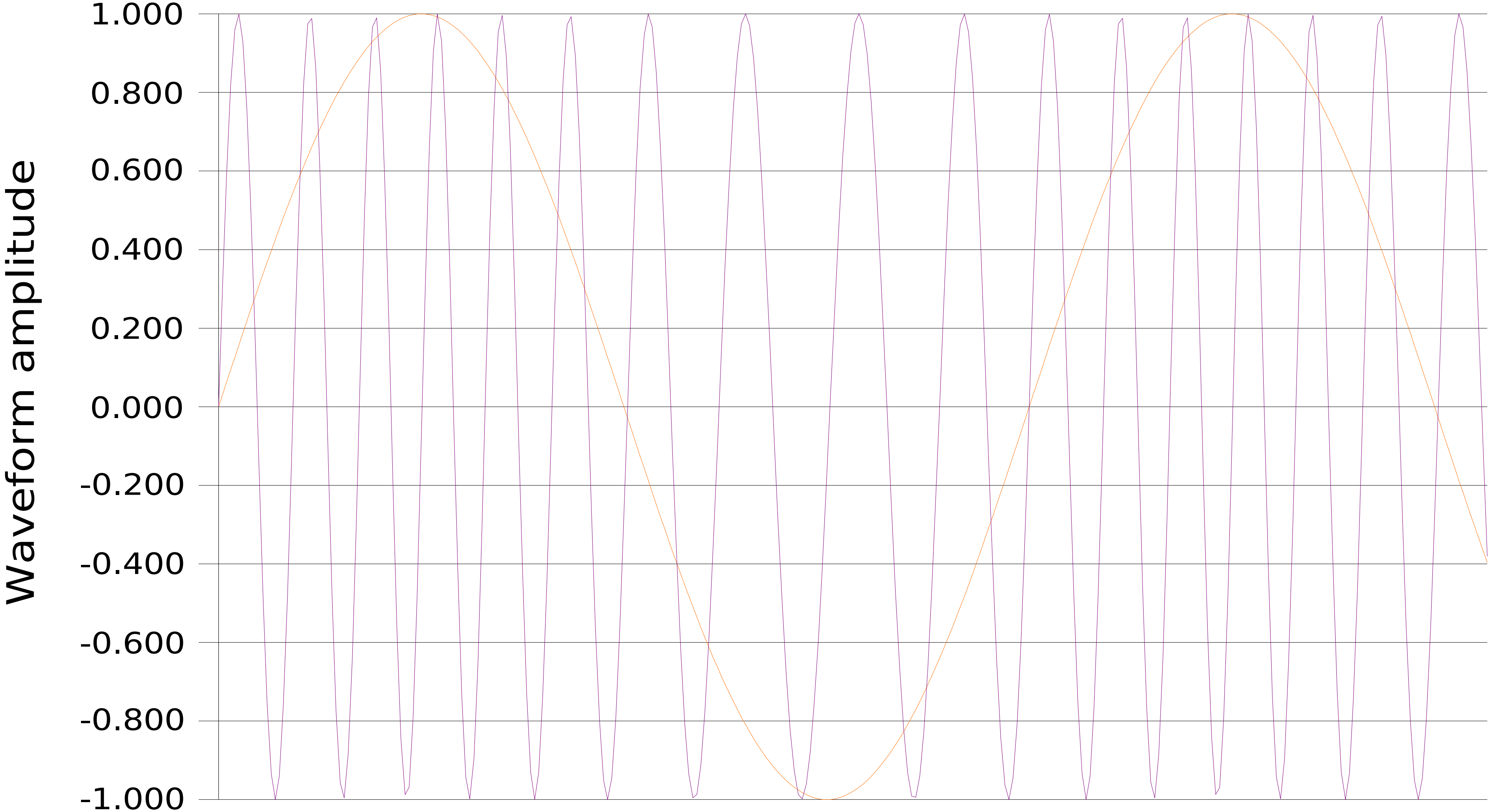
Frequency of carrier is varied, depending on modulating signal's value. Amplitude (envelope) of modulated signal does not change

$$V_t = \sin(2\pi(f_c + m\sin(2\pi f_m t))t)$$

This expands into an *infinite* series involving

$$\sin(2\pi(f_c \pm N f_m)t)$$

Frequency modulation



Frequency modulation

- Frequency modulation usually done by using a voltage to vary the value of a reactance (capacitor or inductor) in an oscillator or tuned-amplifier circuit
- Modulated signal is then amplified, multiplied up to a higher harmonic, and/or heterodyned to the final frequency
- Amplifier stages need not be linear!

Frequency modulation

- Like AM, FM creates sidebands both above and below the carrier frequency
- Each modulating frequency creates multiple sidebands, separated from the carrier by the modulating frequency and all of its multiples... all the way up to infinity (in theory)
- Sideband amplitude depends on amount of modulation – the “modulation index”

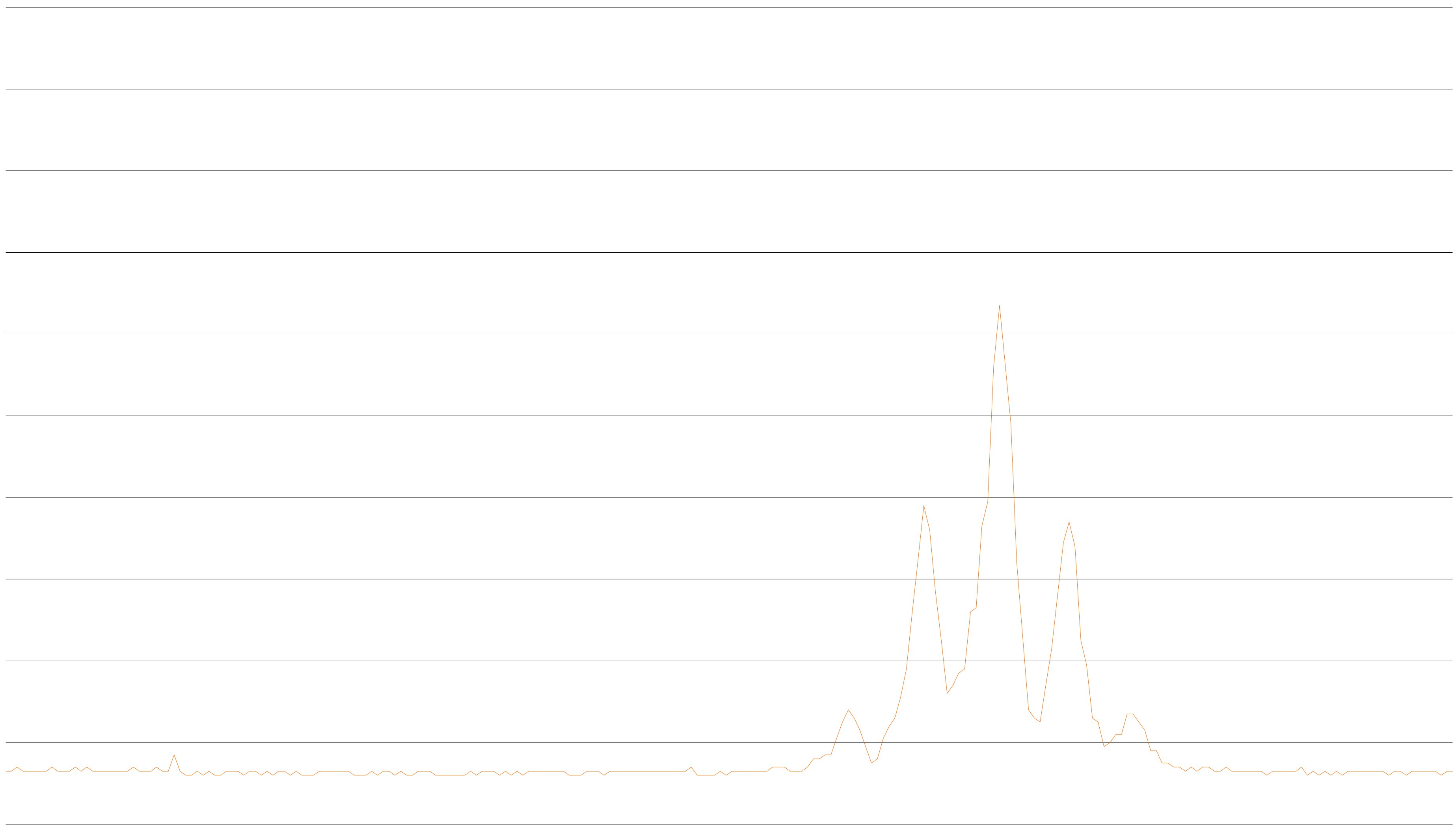
Frequency modulation

- Modulation index = peak carrier deviation divided by modulating frequency
- FM signals are inherently wider than AM signals having the same intelligence bandwidth, due to the presence of multiple sidebands
- At high modulation index, 3 – 5 sidebands may have significant power

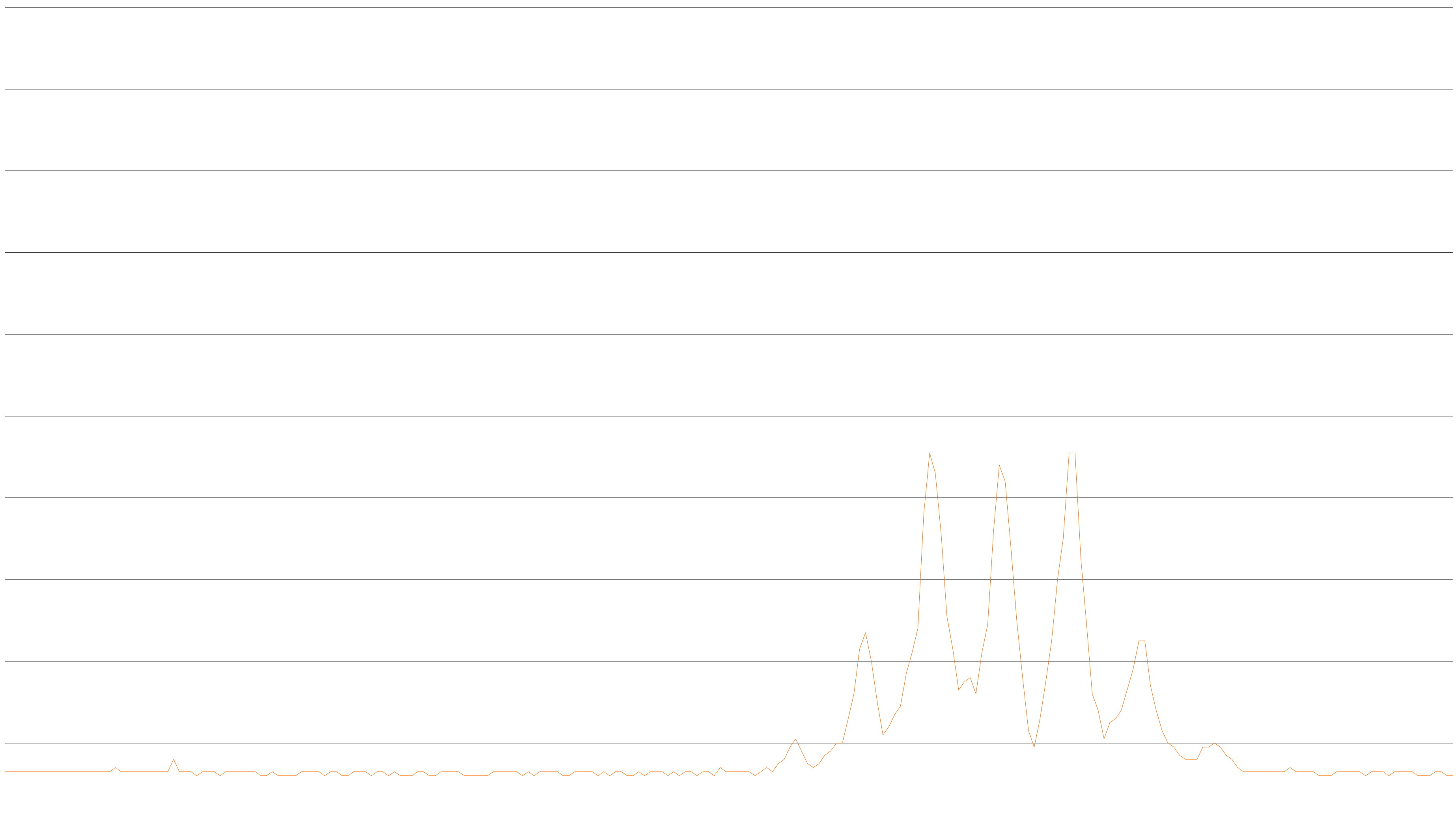
Frequency modulation

- Total signal power doesn't change... yet the power for the sidebands has to come from somewhere
- Frequency modulation shifts power away from the carrier frequency, into the sidebands
- At certain modulation indexes, the power at the carrier frequency actually drops to zero – all the power is in the sidebands!

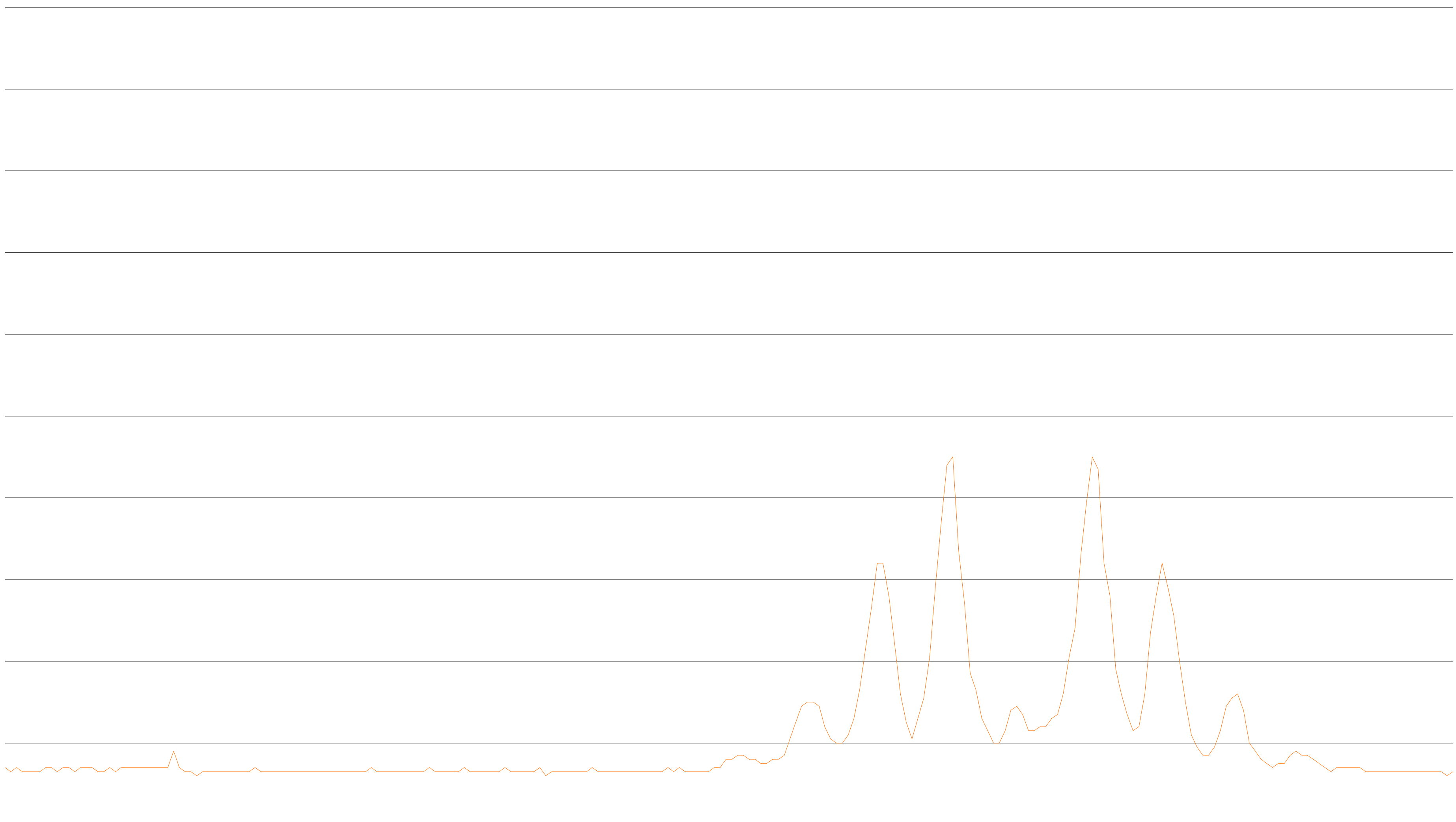
FM, 1 kHz signal, 1 kHz dev.



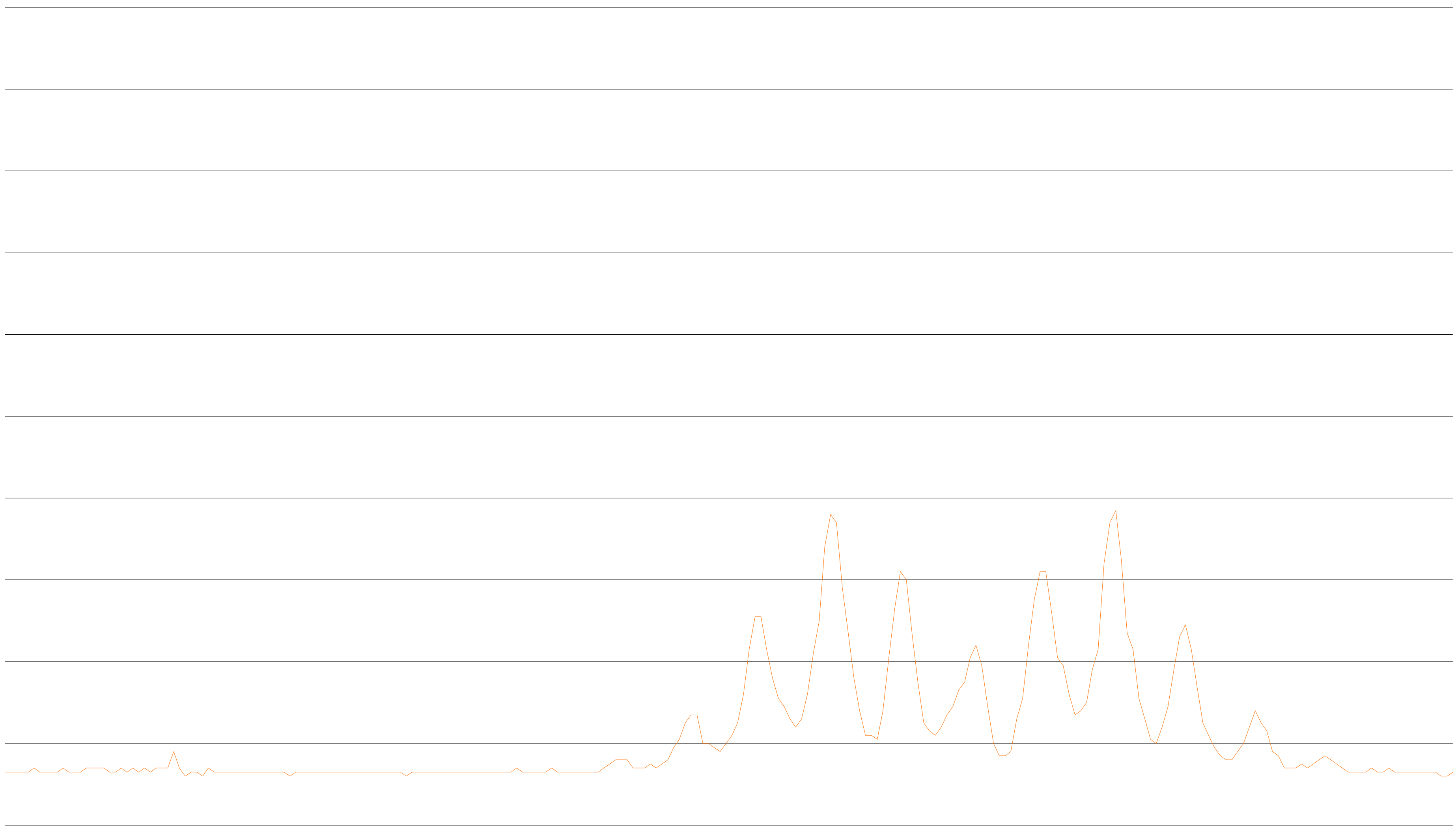
FM, 1 kHz signal, 1.5 kHz dev.



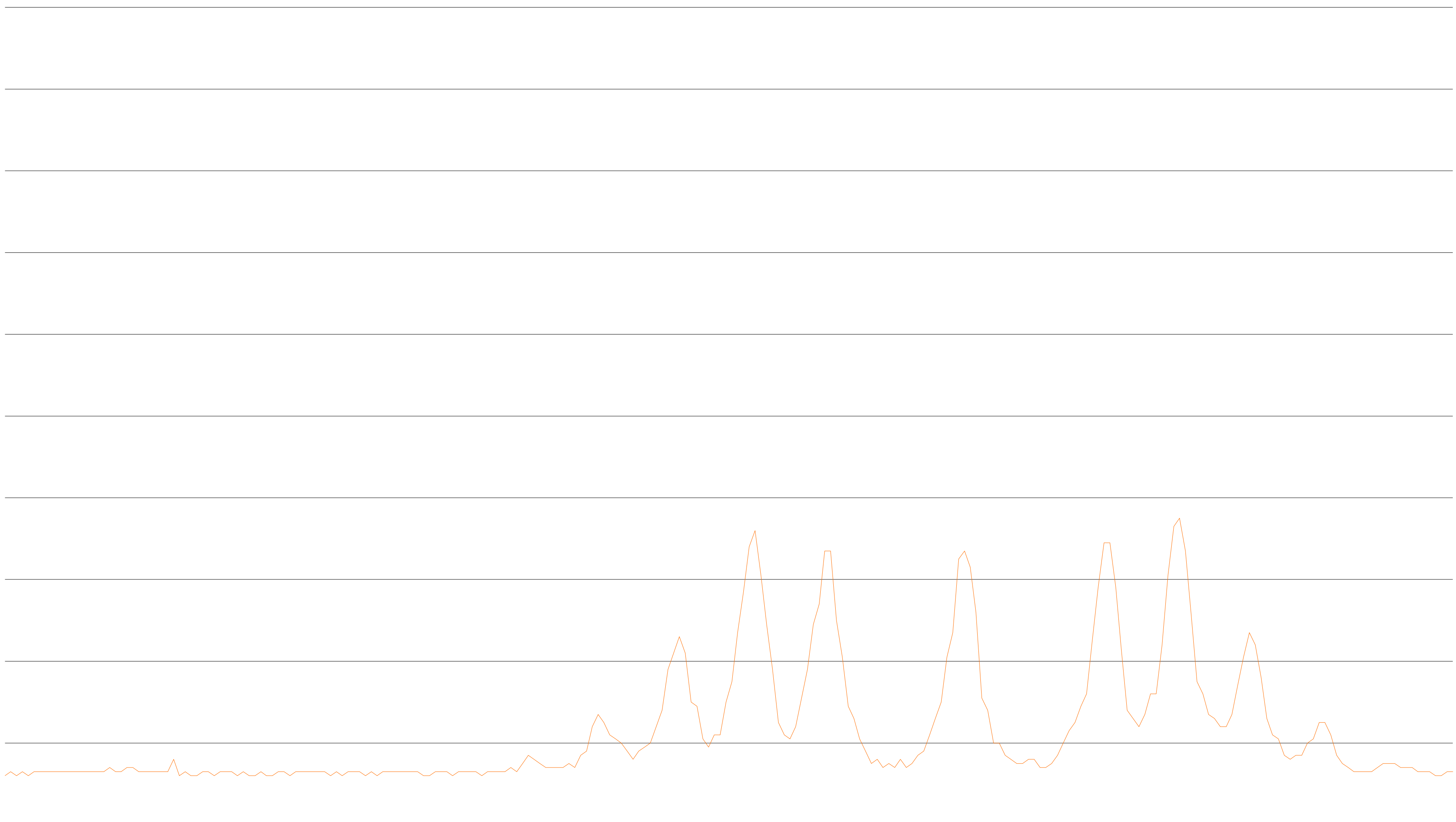
FM, 1 kHz signal, 2.0 kHz dev.



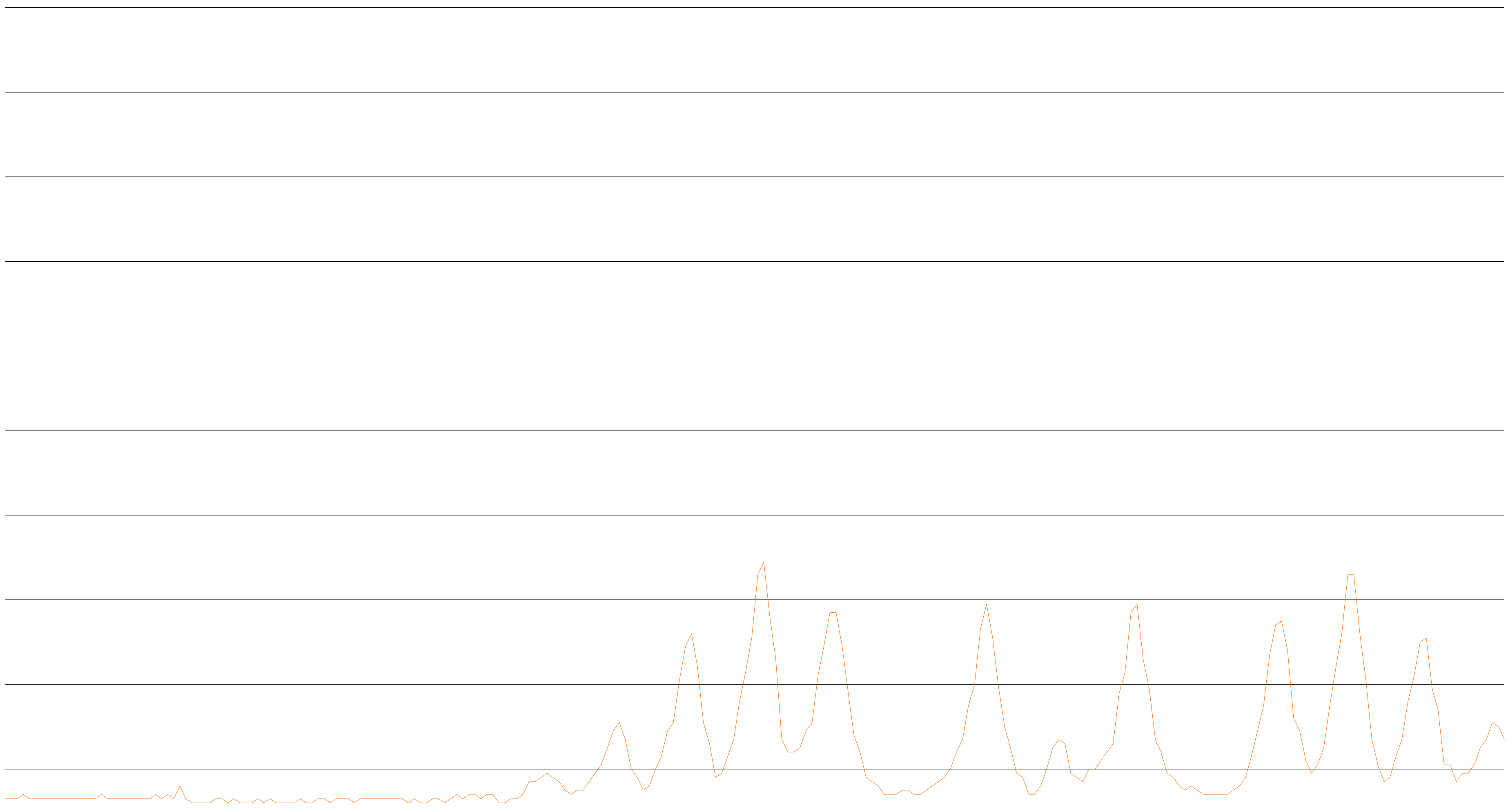
FM, 1 kHz signal, 3 kHz dev.



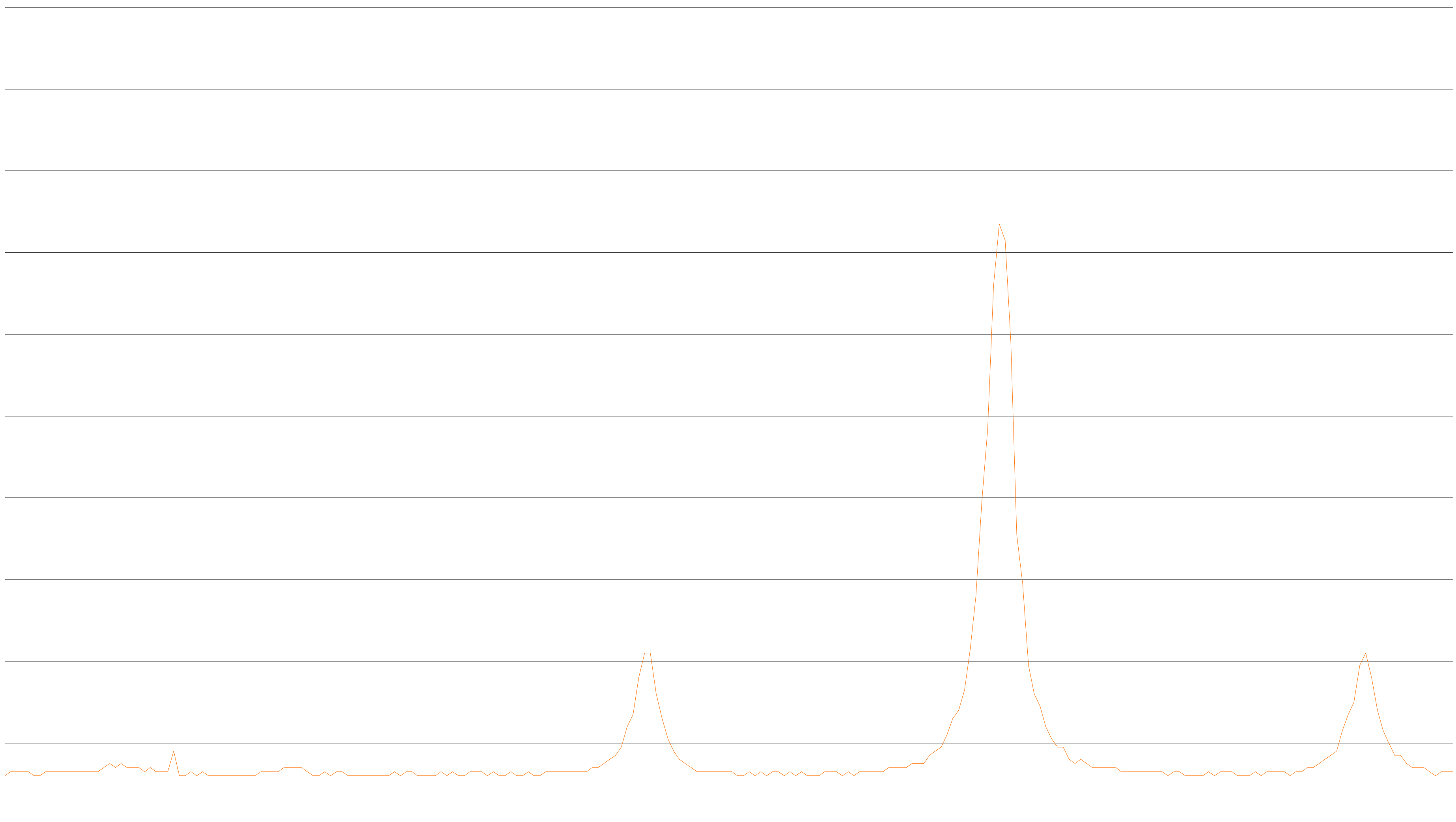
FM, 1 kHz signal, 4 kHz dev.



FM, 1 kHz signal, 5 kHz dev.



FM, 5 kHz signal, 2.5 kHz dev.



Receiving FM

- Amplify, mix RF down to convenient IF
- Bandpass filter (filter width roughly equal to channel spacing; sharp selectivity)
- Amplify / limit (~70 dB of gain)
- Frequency-to-voltage converter (phase-locked loop, tuned-transformer discriminator, crystal discriminator, pulse-counting zero-crossing detector)
- Slope detection works, but not well

Receiving FM

- High IF gain, limiting process eliminates most changes in signal amplitude
- RF noise doesn't interfere unless it's right at the zero-crossing or is nearly as strong as the signal
- Limiting also creates “capture effect” - weaker signals on the same or nearby frequency are largely eliminated

Wide and Narrow FM

- Wide information bandwidth (15 kHz)
- High maximum deviation (±75 kHz)
- Wide channel spacing (200 kHz)
- High modulation index

- Limited audio bandwidth (3 kHz)
- Small maximum deviation (±3-5 kHz)
- Narrow channel spacing (15 kHz)
- Low modulation index

Frequency modulation

- FM is legal for use in HF phone bands (except 60 meters) with limitations
- Modulation index at highest audio frequency must not exceed 1.0
- Total bandwidth may not exceed that of equivalent AM signal
- Has little benefit, hence almost nobody uses it (a few 10-meter repeaters?)

Commercial FM stereo

- Add left and right signals to create monaural signal (L+R)
- Subtract left and right signals to create stereo difference signal (L-R)
- Generate a 38 kHz audio subcarrier, frequency modulated by L-R
- Mix subcarrier, 19 kHz pilot signal, L+R monaural audio together
- Frequency-modulate RF carrier

Pushing it a bit too hard...

- Modulation level (AM or FM) corresponds to peak amplitude of audio signal.
- AM: sideband frequencies remain fixed. No additional sidebands until signal tries to exceed 100% modulation and the carrier is clipped or cut off.
- AM overmodulation creates audible intermodulation sidebands, and “splatter” outside of assigned frequency range.

Pushing it a bit too hard...

- FM: multiple sidebands ***always*** exist, although levels are insignificant at low modulation index
- Increasing modulation causes higher-order sidebands to gain strength. These sidebands can fall outside of the receiver's IF passband and are lost to the receiver (causes distortion), and...
- ... fall into adjacent channel's bandwidth (interference)

Avoiding overmodulation

- Best radios “turn down the gain” by watching peak levels (selective compression) – little added distortion
- Many radios simply clip audio signal (e.g. using diodes), then apply low-pass filter – adds more distortion
- Bad or poorly-adjusted radios don't limit enough or at all, may over-modulate

Talking too loudly is Bad

- Can overdrive HT mic and audio path
- Pushes HT into audio clipping/limiting, creates audio intermodulation
- Overmodulates the FM signal, deviates beyond desired channel bandwidth
- Can cause internal overdrive and distortion in the receiver due to design problems (discriminator clipping or nonlinearity)

PL/CTCSS tone issues

- Subaudible tone for repeater access is part of the signal modulating the carrier
- Typically adds 500-750 Hz of deviation
- Too much (or distorted) PL can be audible
- If injected before limiter (bad!), excessive audio level and clipping can suppress or mask PL tone, lead to “talking off” of the repeater (PL detector drops out)

Good practice for FM

- Check your transmitter's frequency accuracy
- Check transmitter's deviation limit (e.g. when talking loudly) and PL tone level
- Adjust / repair radio if necessary
- Talk softly enough that you don't push the HT into audio limiting
- Talk across the mic, not into it

Digital / data - RTTY

- Traditional RTTY on HF uses Frequency Shift Keying (FSK)
- Essentially a simplified form of FM, with only two deviation levels which correspond to 0 and 1 bits
- May be generated by “pulling” RF oscillator directly, or by FSK-modulating an audio signal and then using SSB modulation of RF

Digital / data – AX.25 packet

- AX.25 packet radio on HF is like faster (300-baud) RTTY
- AX.25 packet (1200-baud) on FM uses FSK of audio signal, fed into standard FM modulator
- AX.25 packet (9600-baud) uses FM (drives modulator directly) with carefully adjusted deviation levels and filtering

Digital/data - PSK31

- PSK31 uses Binary Phase Shift Keying. The phase of a single carrier frequency is reversed periodically to indicate transitions between bits
- Low baud rate (31 baud!), narrow bandwidth (under 100 Hz)
- Computer generates BPSK-modulated audio signal, fed to SSB modulator

Digital/data - PSK31

- Requires that receiver track carrier frequency exactly (± a few Hz)
- Fine-tuning is done by software, which uses phase error in received signal to lock onto center of carrier
- Can maintain lock on signal, tolerable error rate even when signal is buried so deeply in noise you can't hear it

Digital/data - PSK31

- Requires excellent linearity of the SSB transmit chain (including computer sound card and audio-isolation interface)
- Overdriving radio in any way causes splattering (excessively-wide sidebands) which will make the operator very unpopular!
- Best used with careful adjustment, low transmit power, signal-quality checks

Digital/data - MFSK

- Multiple-tone FSK – like RTTY but with 8 or 16 tones rather than 2 (carries multiple bits of data per symbol)
- Phase-continuous shifting between tones
- Fairly narrow bandwidth (~350 Hz)
- Convolutional forward error correction
- Sounds a bit like a calliope

Questions?