KEYSIGHT

Welcome to the Keysight Technologies Students Workshop

08 November 2022
Universität Stuttgart

If you want to get a **certificate of the workshop completion**, please register here:

Workshop

Fundamentals of Arbitrary Waveform Generation (AWG)

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Solutions Engineering
Keysight Technologies

Agenda

AWG Workshop

Arbitrary Waveform Generation Fundamentals

Frequency Response Correction

In-System Calibration

Conclusion & Summary

Agenda

AWG Workshop

- Arbitrary Waveform Generation Fundamentals
- Frequency Response Correction
- In-System Calibration
- Conclusion & Summary

History of Arbitrary Waveform Generators

From analog to digital signal generation

Sep 1950

Signal Generator with internal and external modulation capabilities

April 1988

Arbitrary Waveform Synthesizer with digital architecture and analog output, 50 MHz

Sep 2018

Arbitrary Waveform Generator with 120 GSa/s 45 GHz analog bandwidth

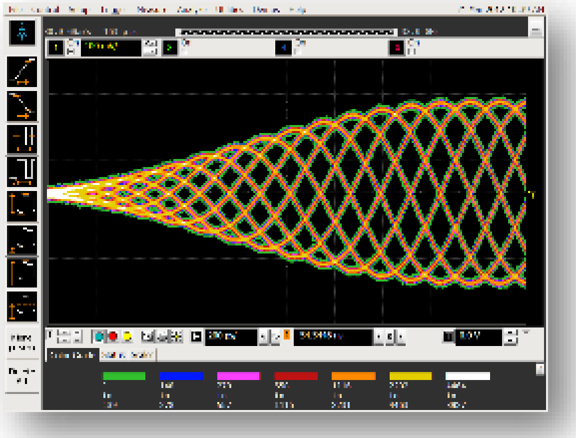
HP 618

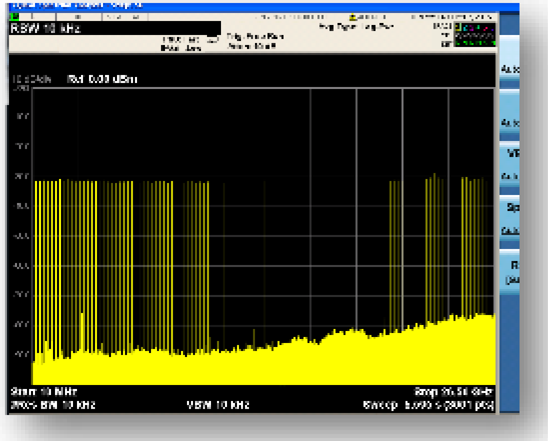
HP 8770A back view

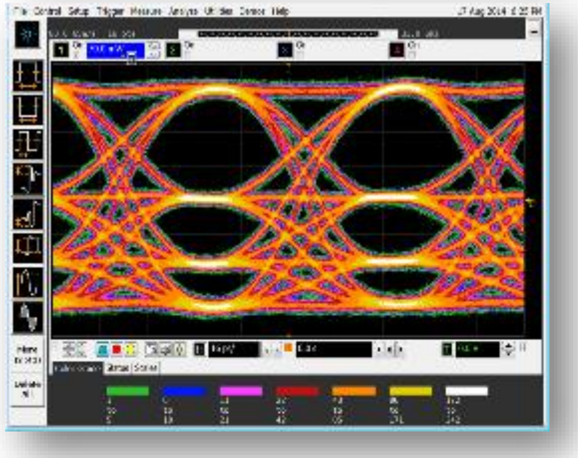
Keysight M8194A

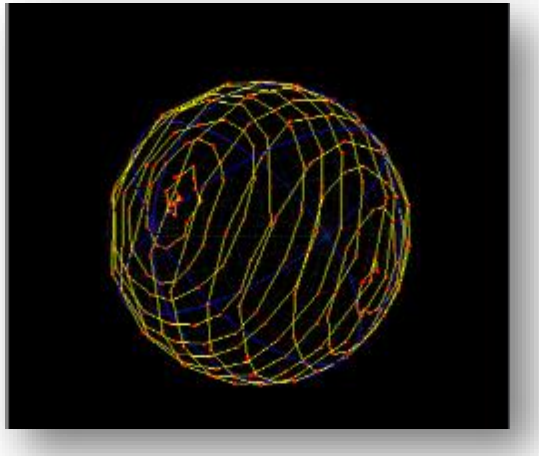
An ARBITRARY Waveform Generator

The most versatile signal scenario generator possible





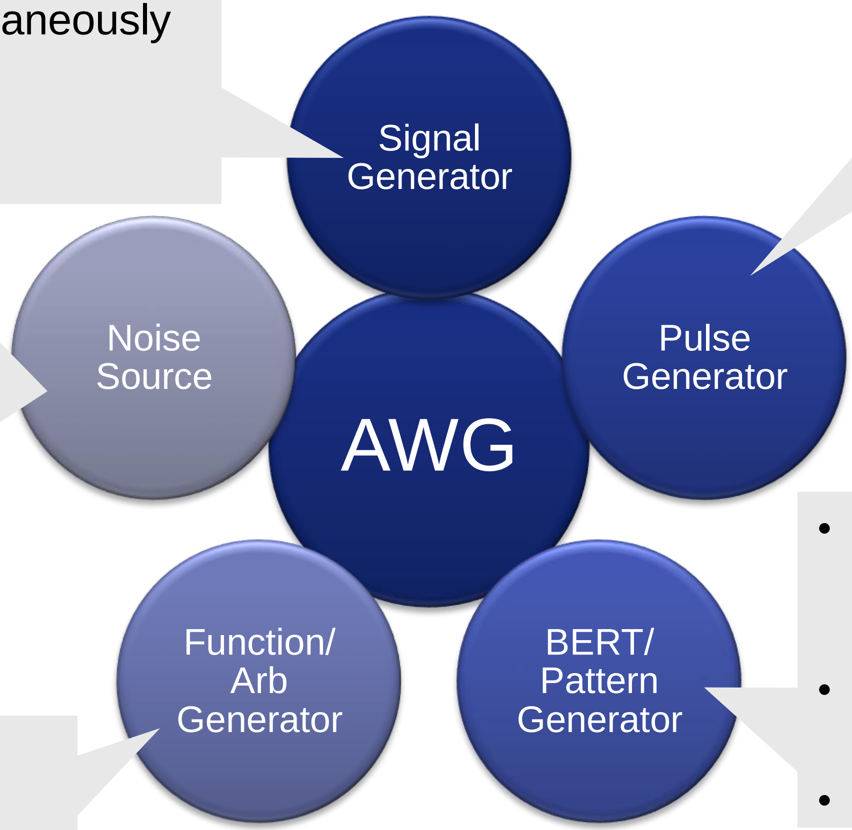




It demonstrates the flexibility you can have with an AWG. Whatever you can described mathematically you can generate.

…you are only limited by your imagination!

AWG in Comparison to Other Instruments



- AWG offers wider modulation BW
- Generate multiple carriers simultaneously
- Fast hopping
- BUT: less dynamic range

- AWG offers more flexibility, e.g. different pulse shapes or adding pre-distortion
- BUT new waveform required for every pulse parameter change

- AWG offers more flexibility, e.g. custom spectral “shapes”, notches, narrowband noise, etc.
- BUT: not as “random” as true noise sources

- AWG offers more flexibility, e.g. variable rise times, multi-level signals, pre-distortion
- BUT can not do true RJ and limited pattern length
- No error detector included

- AWG has typically a superset of functionality
- BUT is typically more expensive (for same bandwidth)

Find the AWG That’s Right For You

Push your design to the limit

The M8100 Series arbitrary waveform generators (AWGs) offer a level of versatility that enables you to set up complex real-world signals — whether you need precise signals to characterize the performance of a design or need to stress a device to its limits. From low-observable radar to high-density communications, testing is more realistic with our precision arbitrary waveform generators.

M8190A
12 GSa/s

M8195A
65 GSa/s

M8196A
92 GSa/s

M8194A
120 GSa/s

Keysight M8199A, 256 GSa/s, up to 70 GHz The World’s Highest Performing AWG

Push your design to the limit

In order to create next generation technology, advanced research engineers require a new level of stimulus performance. Whether testing the discrete components of a coherent optical system or experimenting with terabit transmission, you need the highest speed, bandwidth, precision, and flexibility to meet the challenges of industry-leading applications. The unmatched capabilities of the M8199A enable you to take your designs to a new level.

Keysight M8190A Arbitrary Waveform Generator

High-quality signal generation is the foundation of reliable and repeatable measurements. No matter the application, you must be confident that you are testing your device, not the signal source. The **high dynamic range and excellent vertical resolution** of the M8190A provides the accuracy and repeatability required to achieve the most reliable measurements possible.

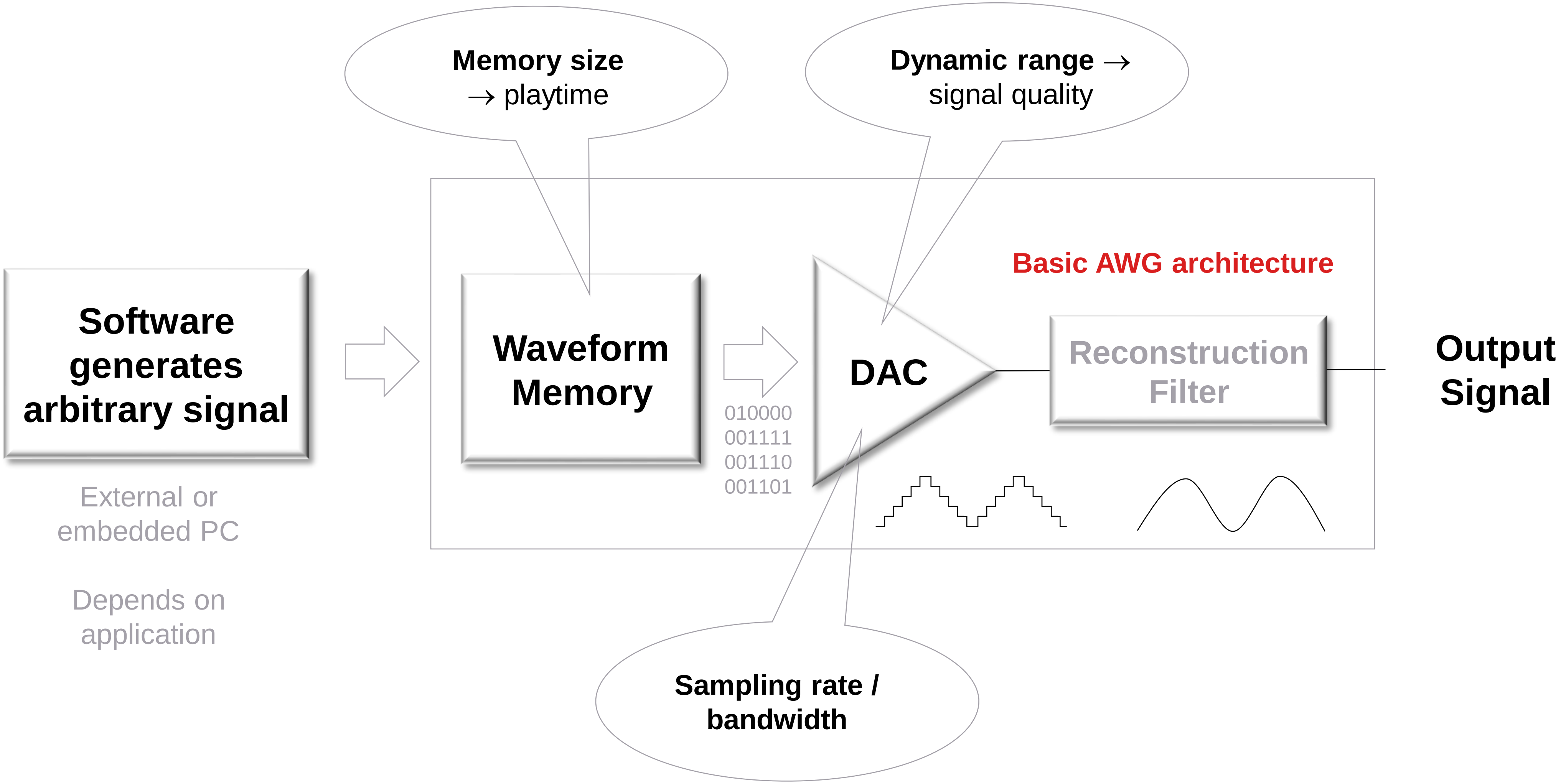
Key Benefits of the M8190A AWG

Get the resolution you need

- Precision AWG with two DAC settings to **handle multiple applications**
  - **14-bit resolution** at 8 GSa/s – used to achieve highest vertical resolution
  - 12-bit resolution with up to 12 GSa/s – used to achieve highest sample rate
- Spurious-free-dynamic range (SFDR) up to 90 dBc ensures **tones clearly stand out**
- Analog bandwidth up to 5 GHz allows you to **mimic analog imperfections** with custom ISI
- 3 selectable output amplifier paths:
  - **Direct DAC** – optimized for best SFDR & high definition
  - **DC** – optimized for serial/data time domain applications
  - **AC** – optimized to generate high voltage, high bandwidth signals
- 1 or 2 channels per 2 slot module (sync up to 12 channels)

Theory of AWG Operation

Key Blocks and Specifications



Memory size
→ playtime

Dynamic range →
signal quality

Basic AWG architecture

Software generates arbitrary signal

External or
embedded PC

Depends on
application

Waveform Memory

010000
001111
001110
001101

DAC

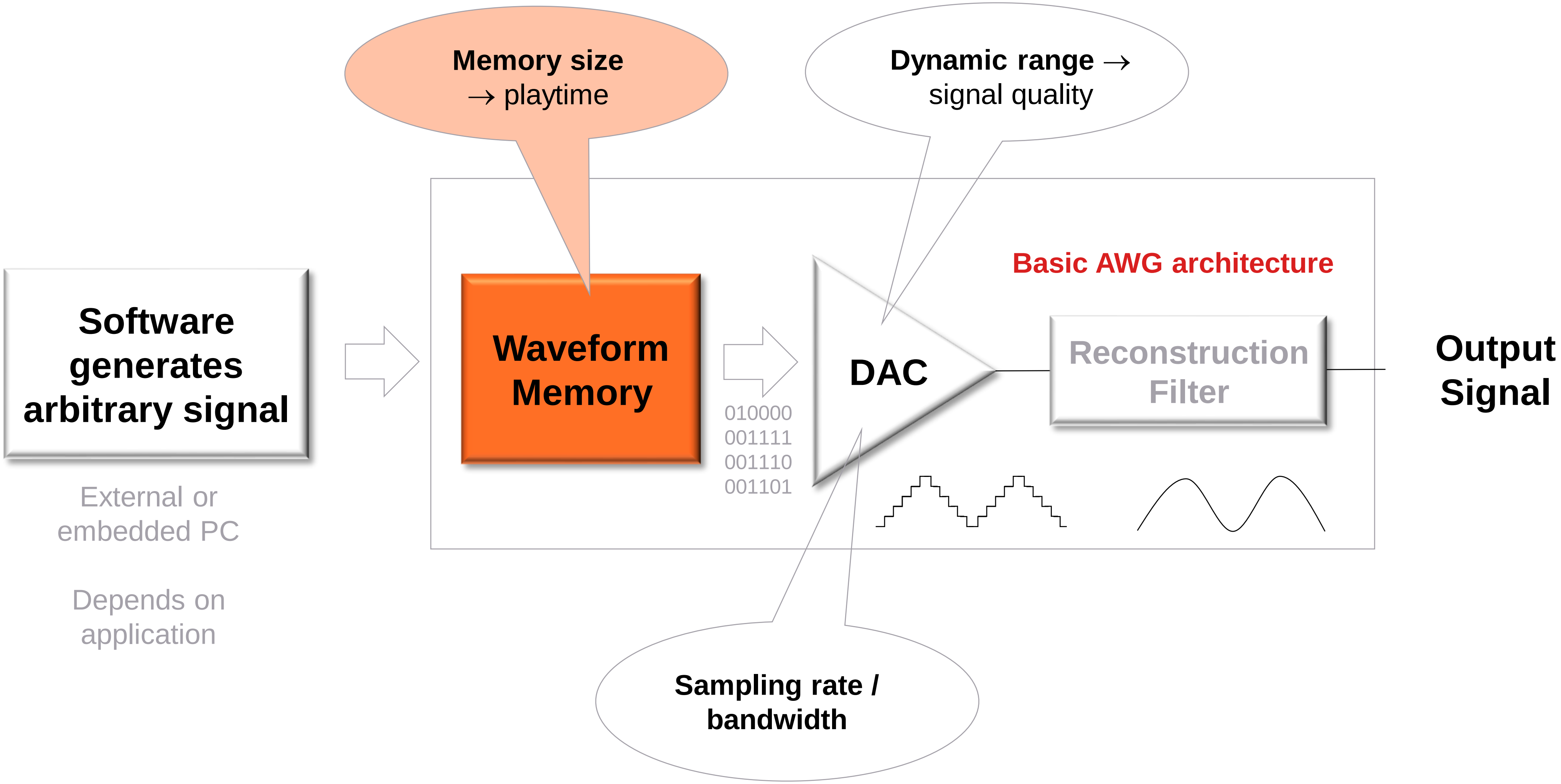
Reconstruction Filter

Output Signal

Sampling rate /
bandwidth

Theory of AWG Operation

Key Blocks and Specifications: Memory



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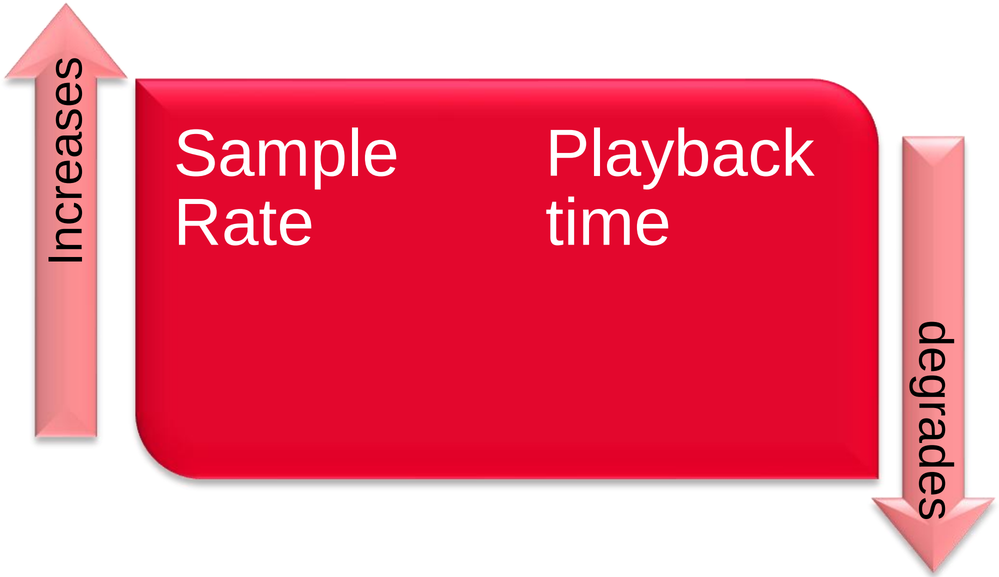
AWG Basics: Memory

Theory of AWG operation

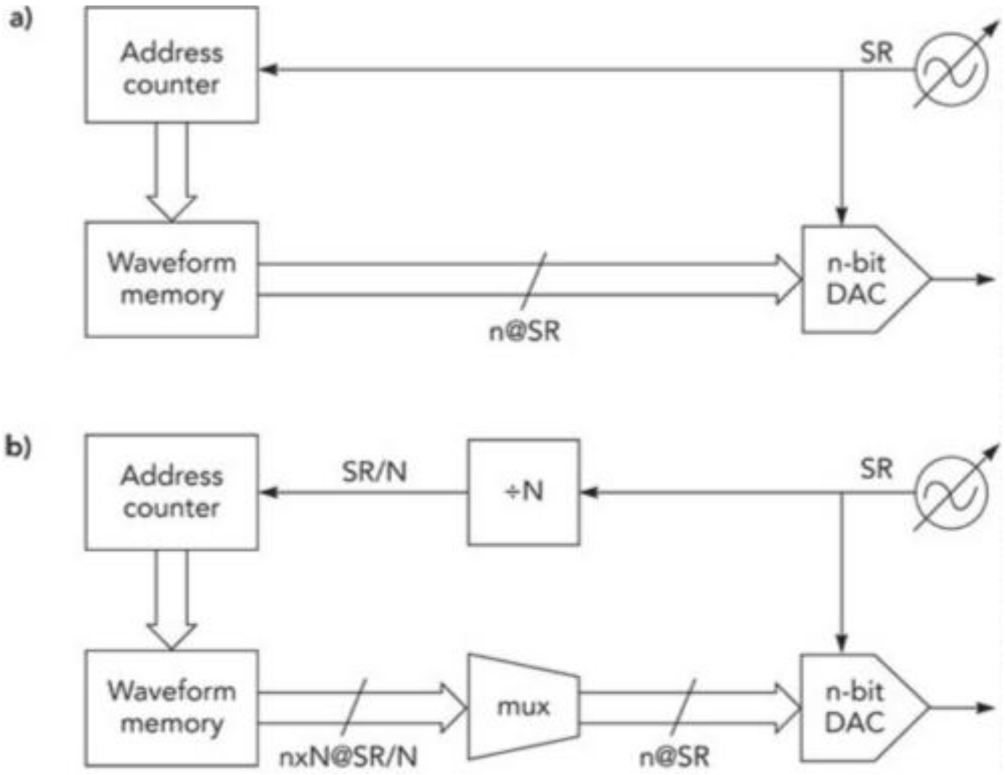
Memory ÷ sample rate = play time
For example, 128 MSa ÷ 12 GSa/s = 10 ms
For example, 2 GSa ÷ 12 GSa/s = 166,67 ms



Waveform is defined in samples, which defines values in a given time interval.
The AWG outputs discrete output voltage levels
=> allows any different waveforms

AWG Memory and Granularity

Theory of AWG operation



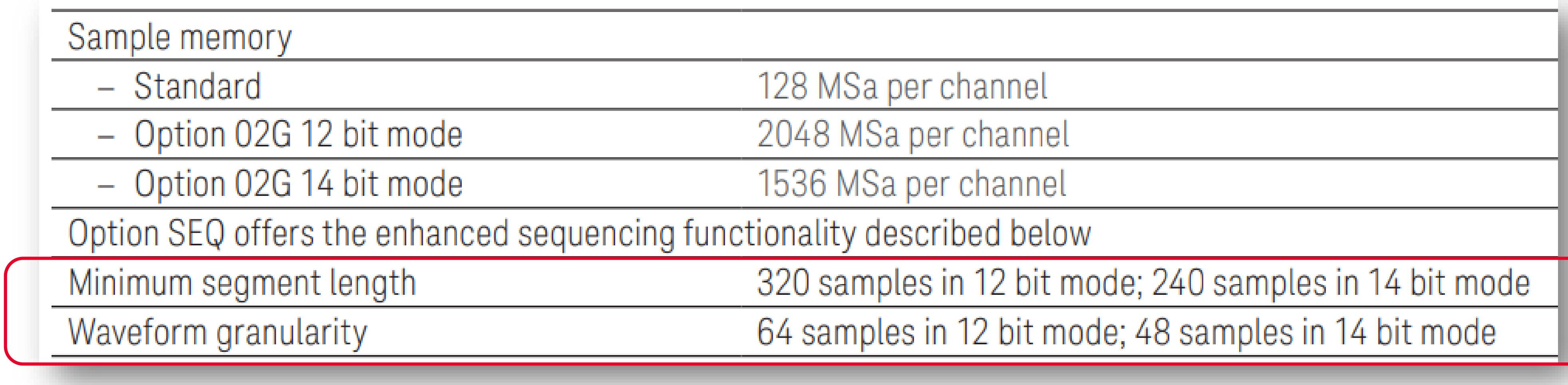
Waveform memory access architectures are influenced by memory technology and access speed.

a) Fast enough SRAM can be directly connected to the DAC

b) If conversion speed is too high then it is possible to transfer more than one sample in a memory access cycle by widening the bus and using a multiplexer close to the DAC

Granularity → The granularity reflects the number of sample that transfered in parallel from Memory to DAC

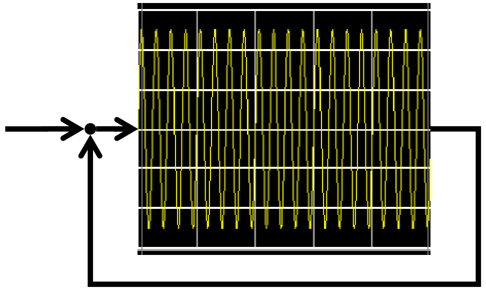
Granularity and Min Length of Sample Memory of M8190A



Sample memory	
– Standard	128 MSa per channel
– Option 02G 12 bit mode	2048 MSa per channel
– Option 02G 14 bit mode	1536 MSa per channel
Option SEQ offers the enhanced sequencing functionality described below	
Minimum segment length	320 samples in 12 bit mode; 240 samples in 14 bit mode
Waveform granularity	64 samples in 12 bit mode; 48 samples in 14 bit mode

AWG without Sequencing

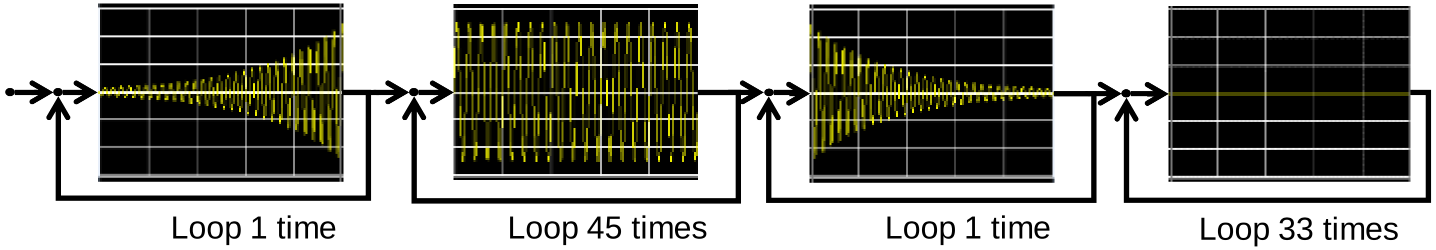
- Only a **single** waveform segment is available
- Waveform segment can be up to full memory size



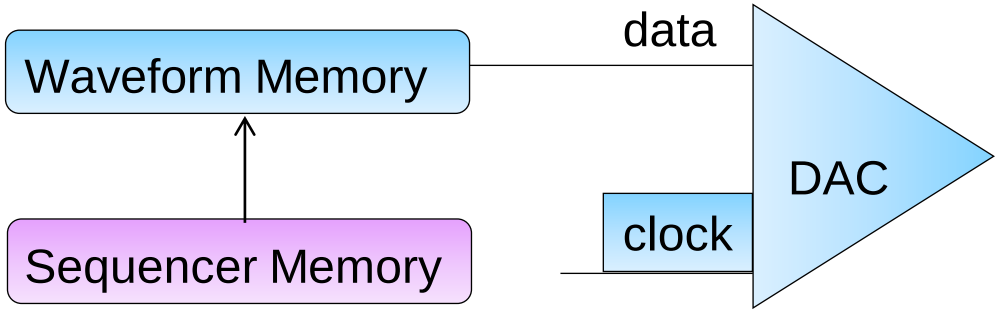
Infinite loop

AWG with Sequencing

How do we achieve longer playtimes?



Waveform segments are stored in memory



Waveform Memory

Sequencer Memory

data

clock

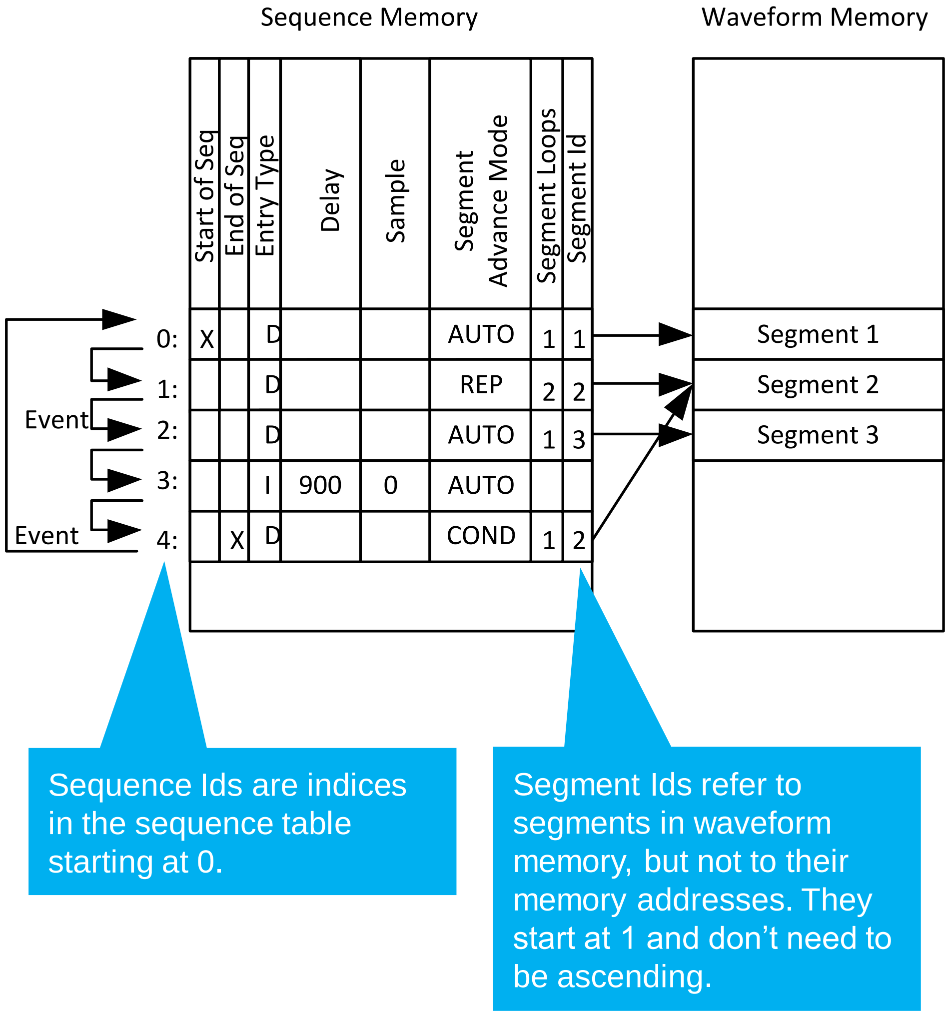
DAC

The Waveform Sequencer is where the waveform segments are arranged (sequenced) to create the desired waveform

<u>Memory ÷ sample rate ≠ playback time</u>

Sequencing – Theory of Operation

- Start-of-Sequence and End-of-Sequence frame the sequence
- Data entries refer to a waveform segment
- Idle entries implement a sample-accurate delay with a defined sample value
- Advance modes determine how execution proceeds from one entry to the next
- Loop counts determine number of repetitions per segment

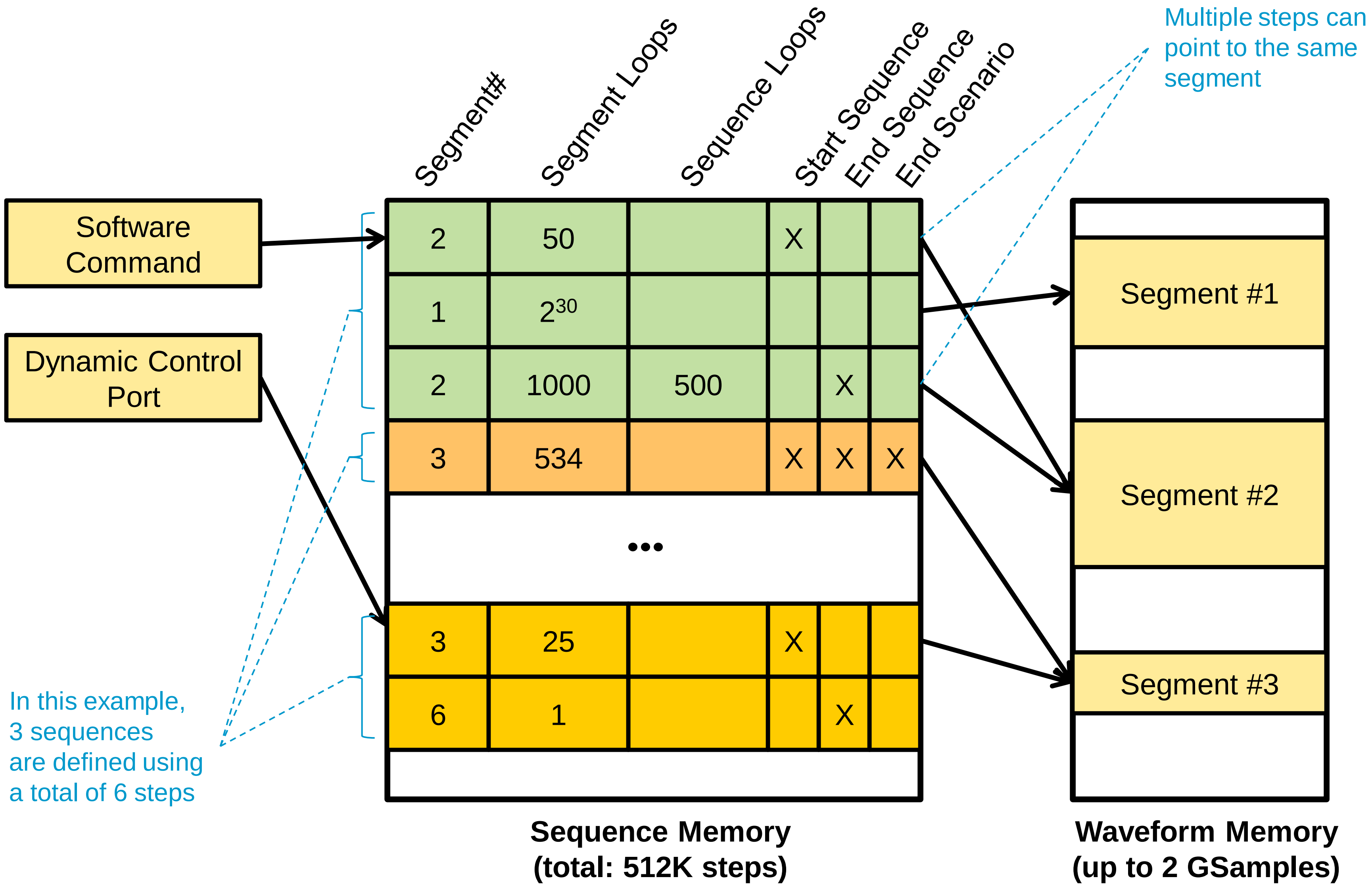


	Start of Seq	End of Seq	Entry Type	Delay	Sample	Segment Advance Mode	Segment Loops	Segment Id
0:	X		D			AUTO	1	1
1:			D			REP	2	2
2:			D			AUTO	1	3
3:			I	900	0	AUTO		
4:		X	D			COND	1	2

Sequence Ids are indices in the sequence table starting at 0.

Segment Ids refer to segments in waveform memory, but not to their memory addresses. They start at 1 and don’t need to be ascending.

…and how does it work internally?



Segment#	Segment Loops	Sequence Loops	Start Sequence	End Sequence	End Scenario
2	50		X		
1	2^{30}				
2	1000	500		X	
3	534		X	X	X
•••					
3	25		X		
6	1			X	

Multiple steps can point to the same segment

In this example, 3 sequences are defined using a total of 6 steps

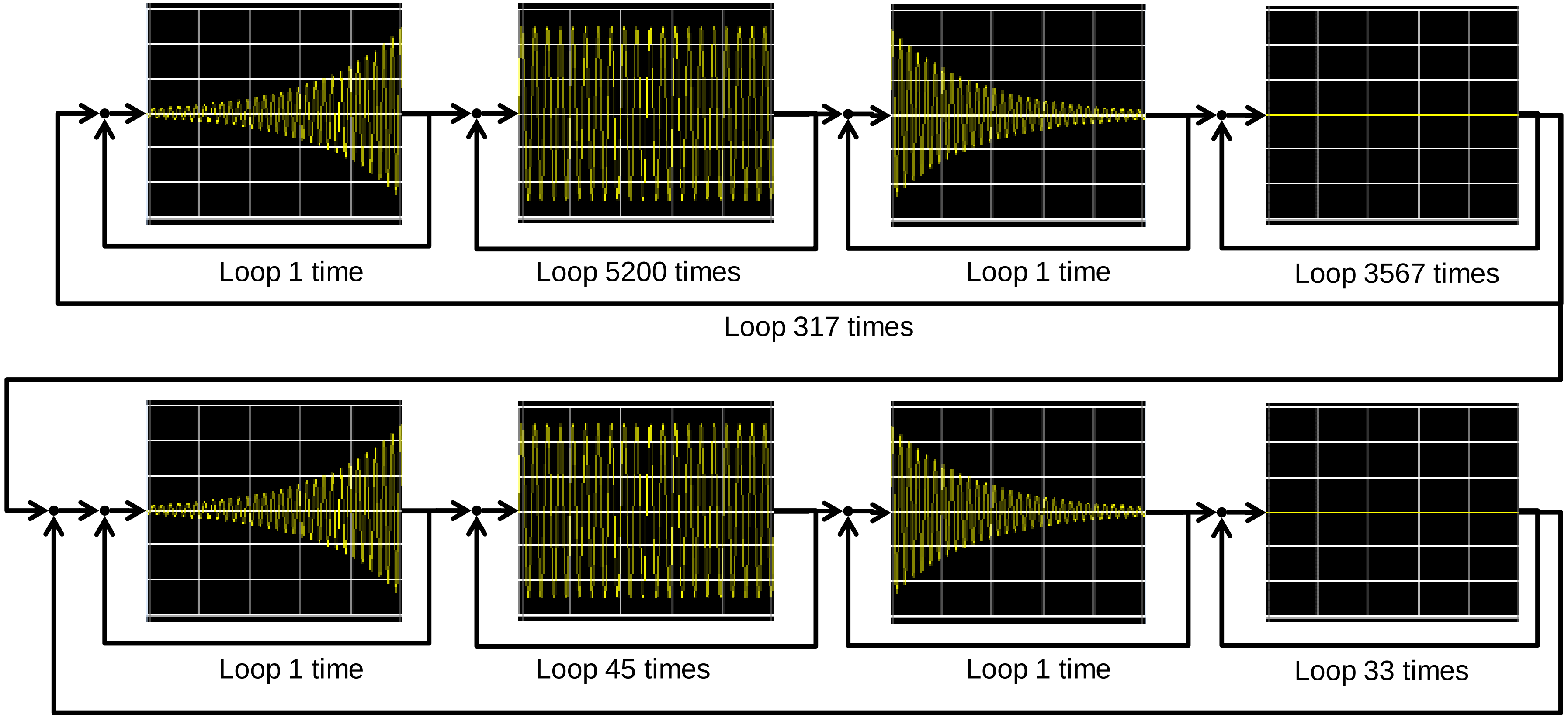
Sequence Memory (total: 512K steps)

Waveform Memory (up to 2 GSamples)

AWG with Sequencing

Using Scenarios to increase playback time

A **scenario** consists of a list of sequences

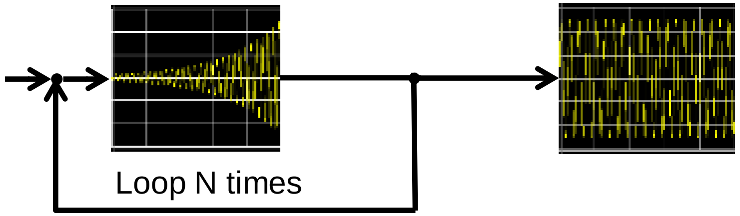


Loop 5 times

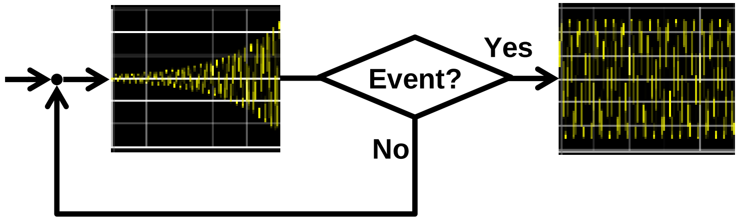
Advancement Modes of Sequencing

Advancing from one segment/sequence to the next can be…

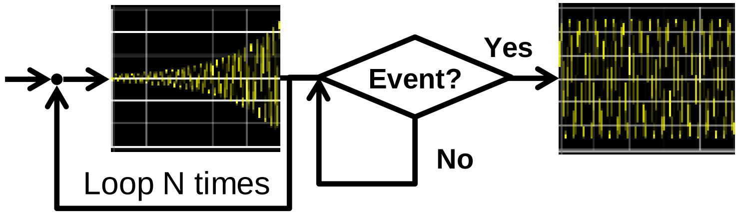
- **Automatic**
  - Loop N times, then go to next segment/sequence (un-conditional)



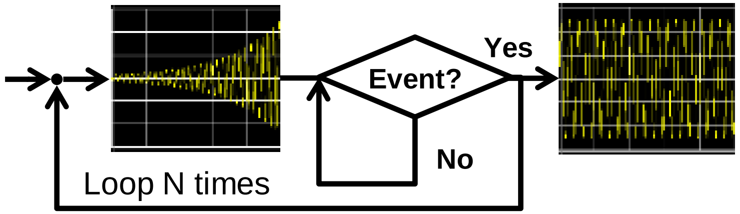
- **Conditional**
  - Loop until an event occurs, then go to next segment/sequence



- **Repeat**
  - Loop N times, then wait until an event occurs before going to the next segment/sequence



- **Single**
  - Same as “Repeat”, but wait for an event on every loop



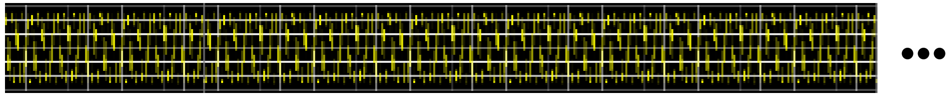
All transitions are “seamless”. Event can be an external signal or a software command

It’s time for a demo…

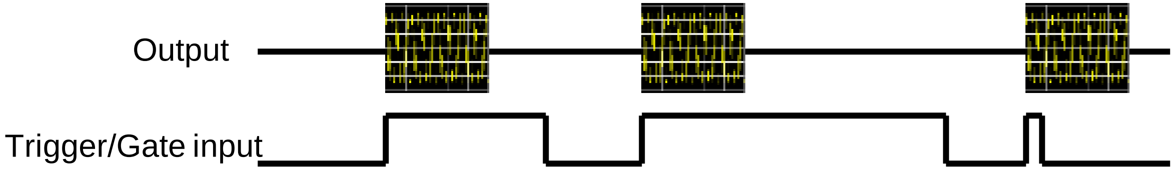
Trigger Modes of Sequencing

All of the previously mentioned cases can be combined with the following trigger modes. This applies to **segments** or **sequences**.

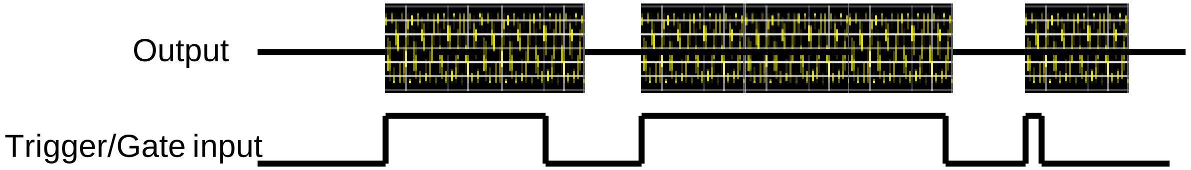
- Continuous



- Triggered
  - Each edge of the trigger signal starts the selected segment/sequence



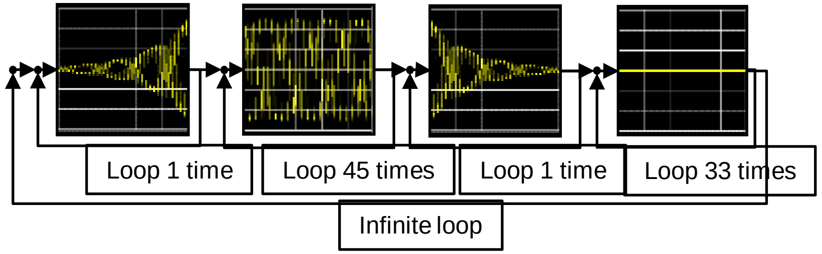
- Gated
  - Segments are always completed



Selection of segment/sequence to be generated

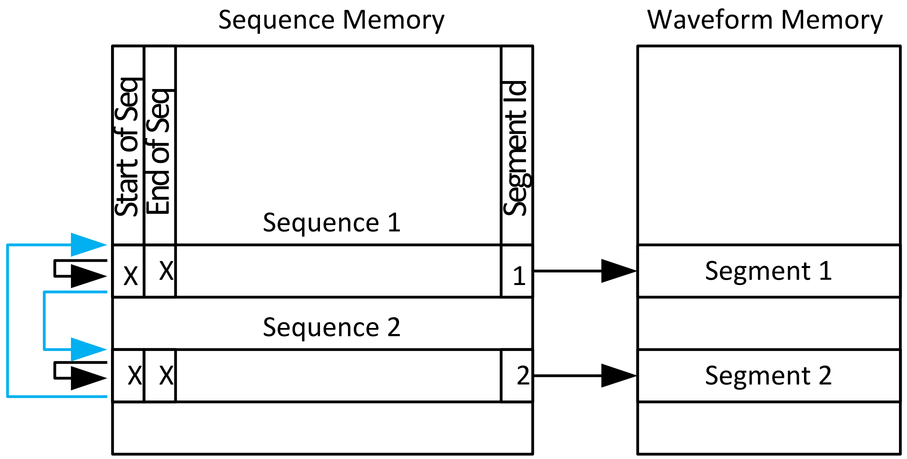
Selection of segment/sequence can be determined by…

- **Pre-defined sequence**
  - If the **order** of waveform segments is known ahead of time, it can be set up as a “sequence”
- **Dynamic Control Port**
  - The dynamic control port on the front panel allows you to select one of 2^{13} (2^{19}) segments/sequences **dynamically at runtime** by applying a digital pattern to the dynamic control port connector
- **Software**
  - Instead of applying a digital pattern to the dynamic control port, you can also select a segment/sequence using software by sending a command to the firmware



In all cases, transitions are “seamless” - without any gaps

Sequencing – “Memory Ping-Pong”



Execute alternately Segment 1 and 2. When one segment is played the other one is loaded with a new waveform.

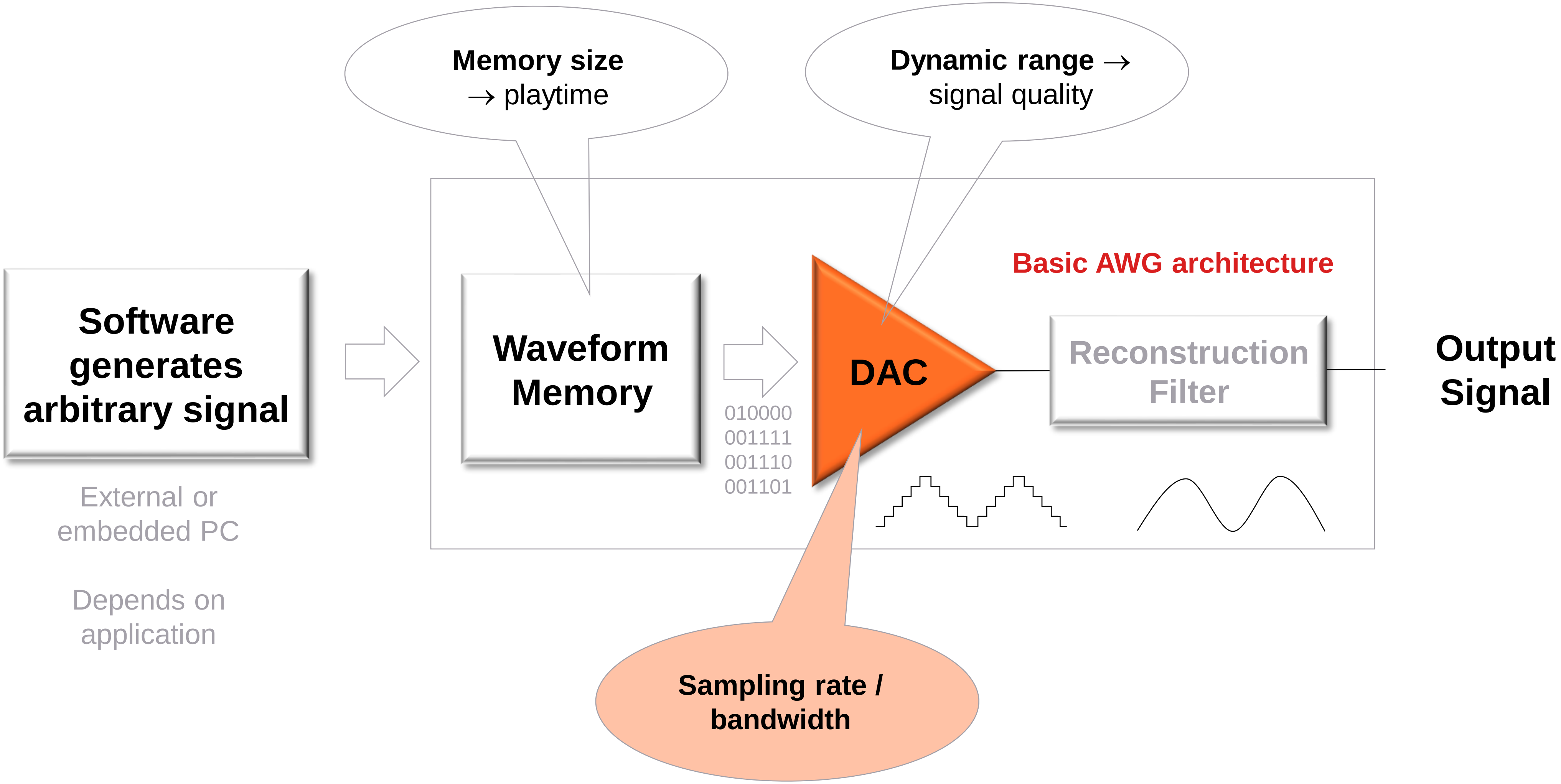
Load Segment 1. Start signal generation in dynamic mode. → Segment 1 is played (Looped until next is selected or played once in triggered mode).

Repeat:

Load Segment 2.
Switch to play Segment 2.
Load Segment 1.
Switch to play Segment 1.

Theory of AWG Operation

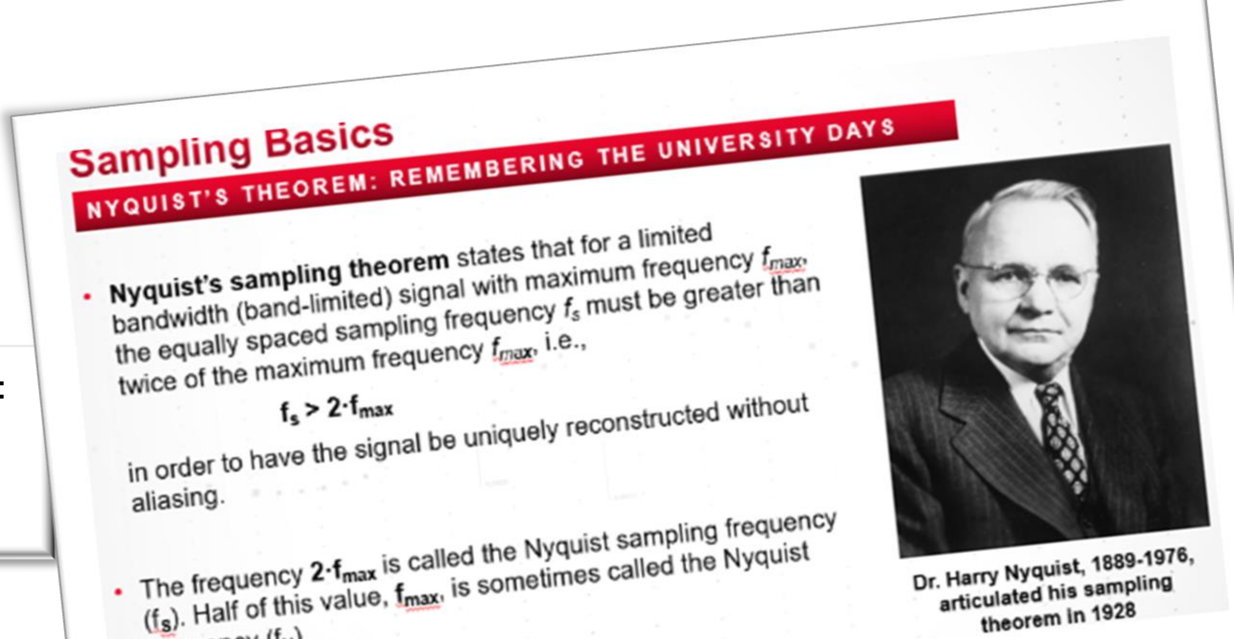
Key Blocks and Specifications: Sampling rate



AWG Sampling Basics

Sampling Factor

Sample Rate determines **Modulation Bandwidth** = typically less than 1/2 of sample rate,
e.g. 12 GSa/s → 5 GHz BW



Sampling Basics

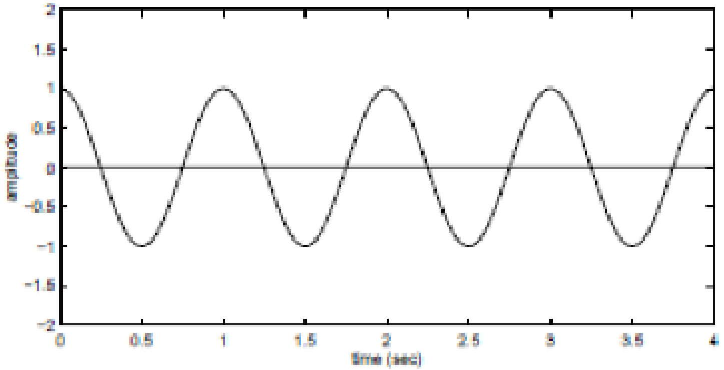
NYQUIST'S THEOREM: REMEMBERING THE UNIVERSITY DAYS

- **Nyquist's sampling theorem** states that for a limited bandwidth (band-limited) signal with maximum frequency f_{max}, the equally spaced sampling frequency f_s must be greater than twice of the maximum frequency f_{max}, i.e.,

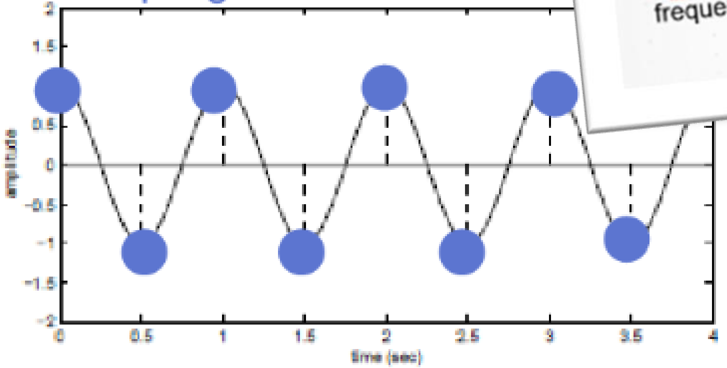
  $$f_s > 2 \cdot f_{max}$$

  in order to have the signal be uniquely reconstructed without aliasing.
- The frequency $2 \cdot f_{max}$ is called the Nyquist sampling frequency (f_s). Half of this value, f_{max}, is sometimes called the Nyquist frequency (f_N).

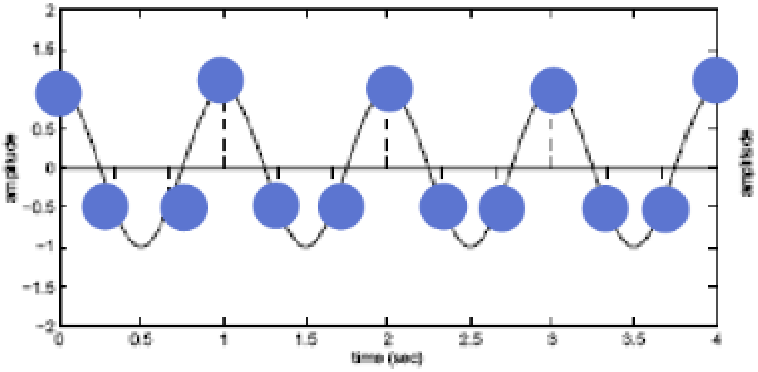
Dr. Harry Nyquist, 1889-1976, articulated his sampling theorem in 1928



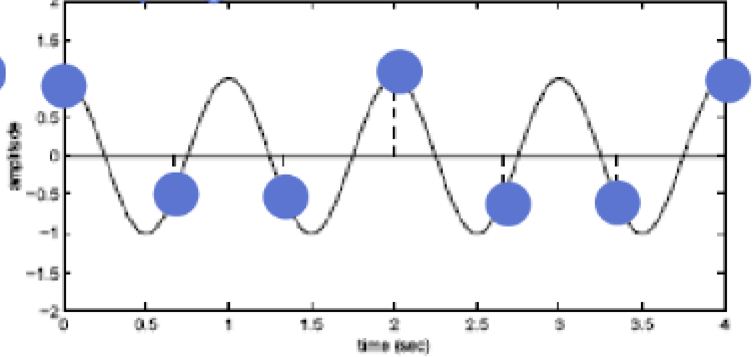
sampling factor 2



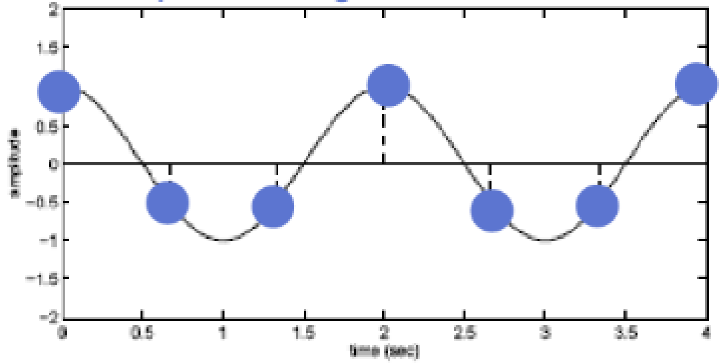
sampling factor 3



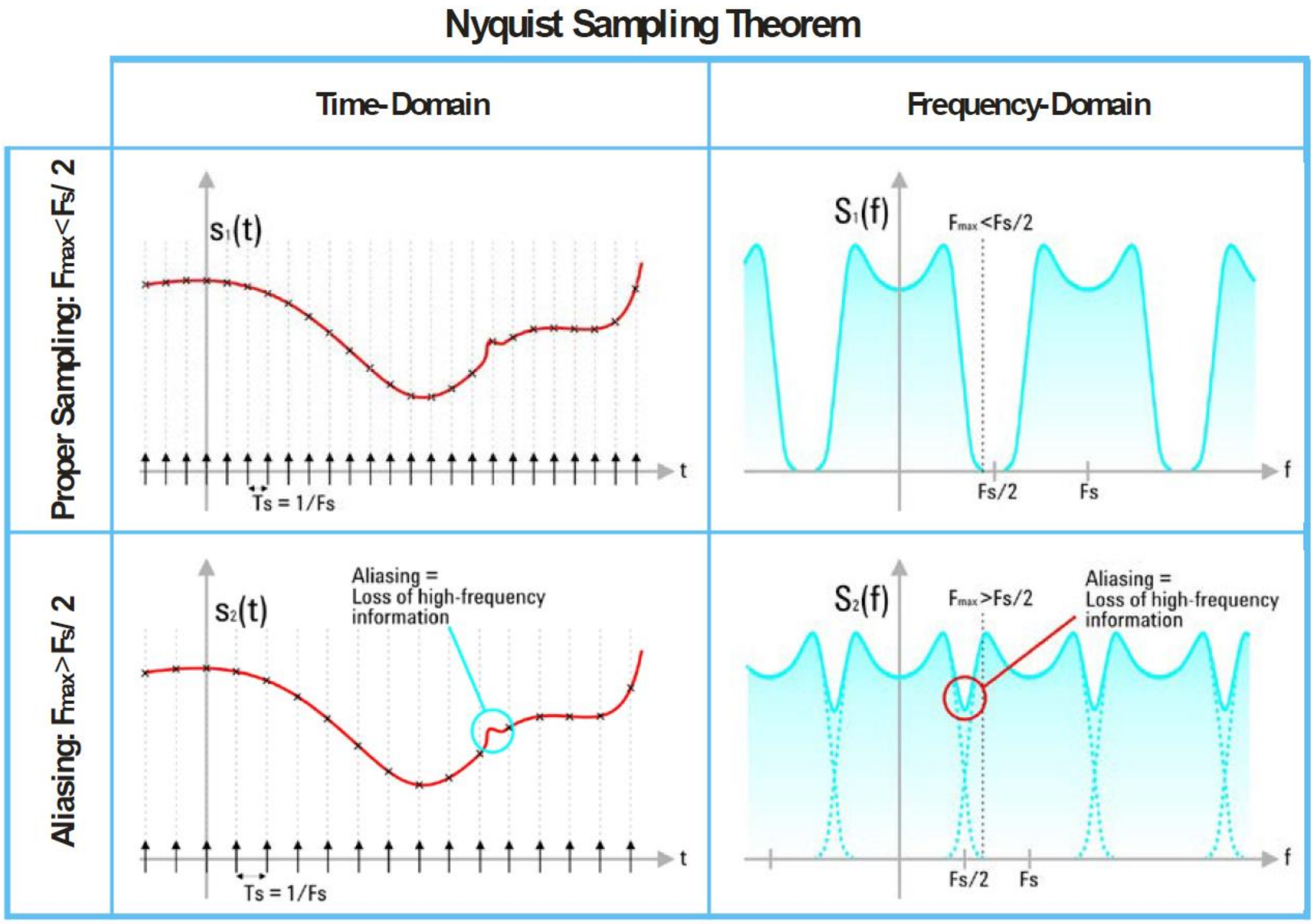
sampling factor 1.5



example aliasing



Nyquist Theorem in the Time and Frequency Domains



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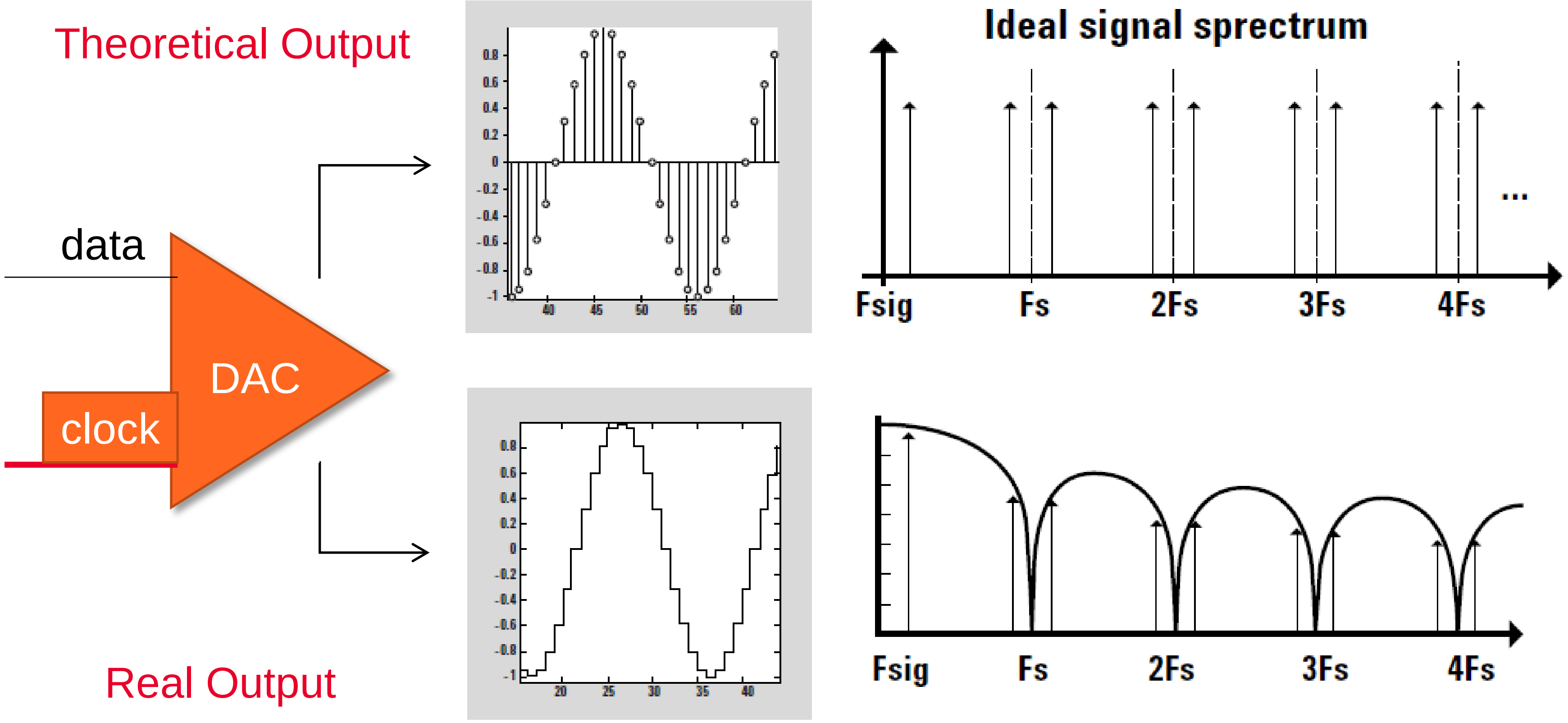
AWG Sampling Basics

Theoretical vs. Real output



Theoretical Output

data

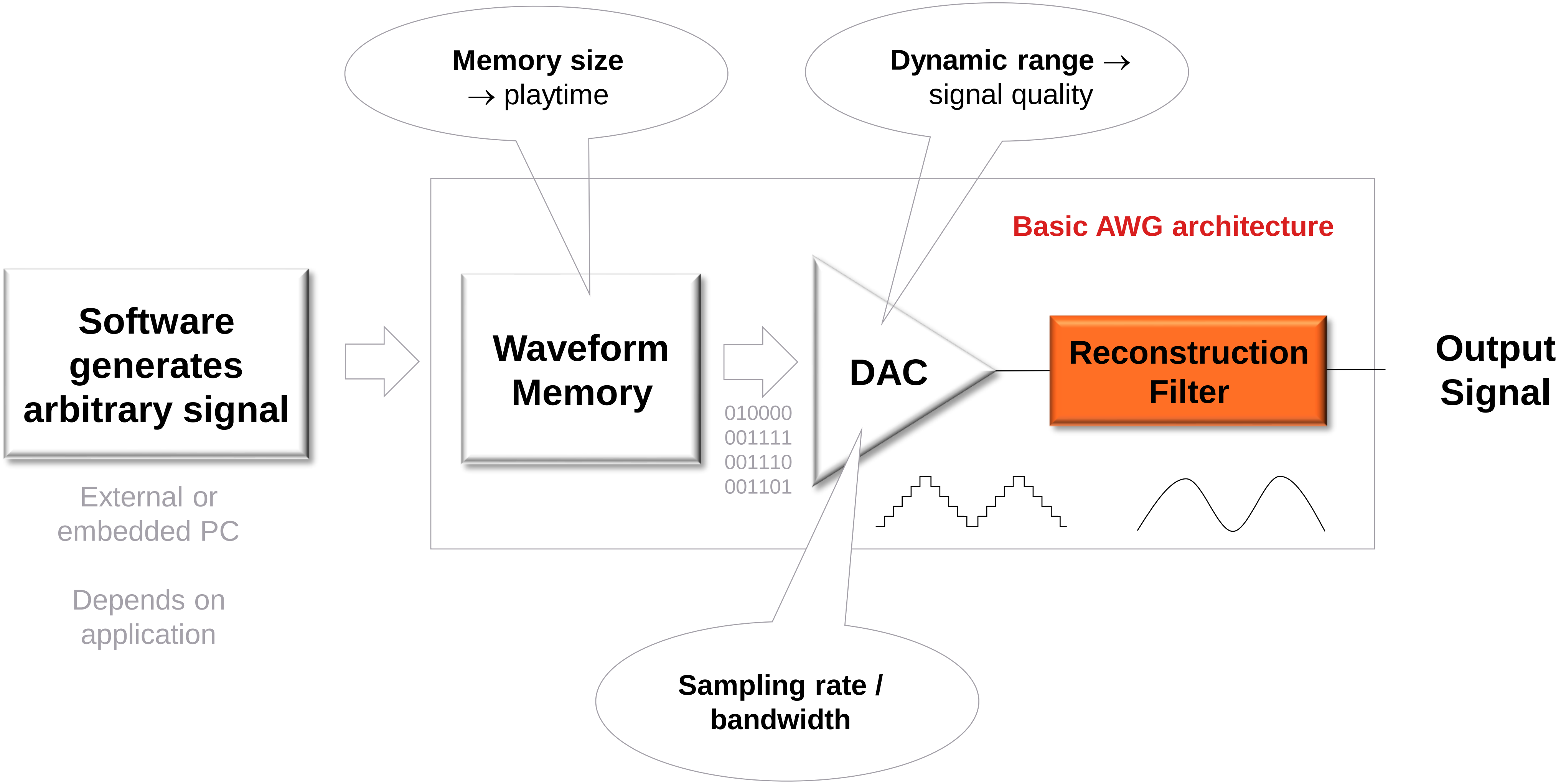
DAC

clock

Real Output

Theory of AWG Operation

Key Blocks and Specifications: Reconstruction Filter



Memory size
→ playtime

Dynamic range →
signal quality

Basic AWG architecture

Software generates arbitrary signal

Waveform Memory

010000
001111
001110
001101

DAC

Reconstruction Filter

Output Signal

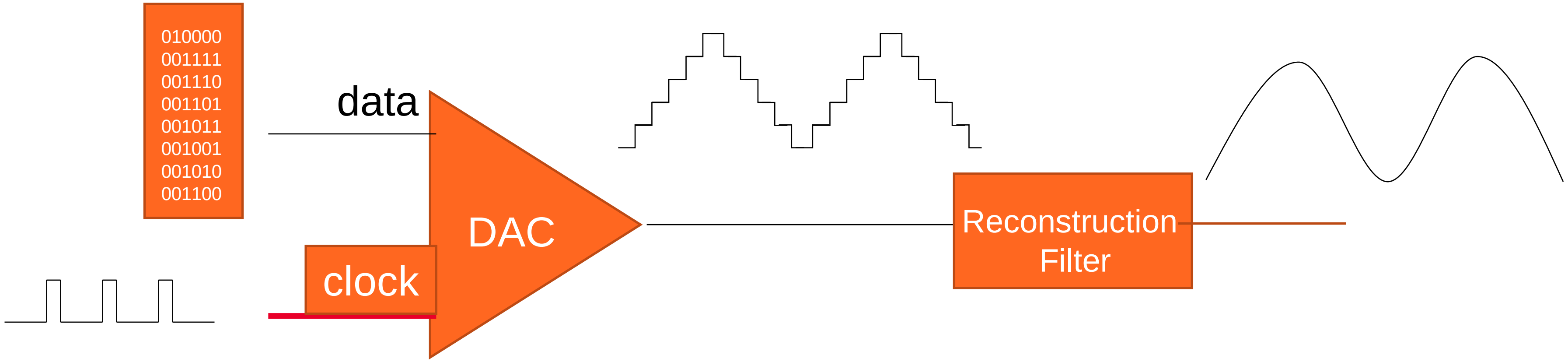
External or embedded PC

Depends on application

Sampling rate / bandwidth

AWG Sampling Basics: Reconstruction Filter

Theory of AWG operation

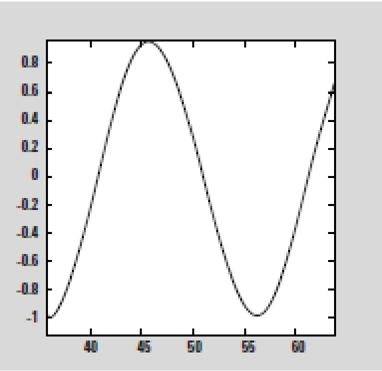

010000
001111
001110
001101
001011
001001
001010
001100

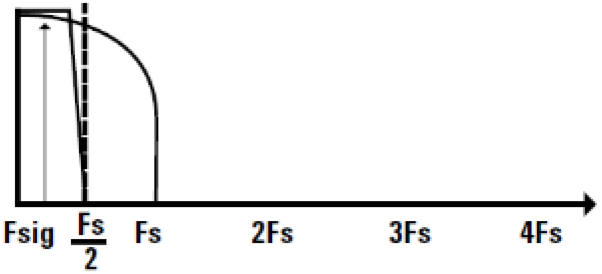
data

clock

DAC

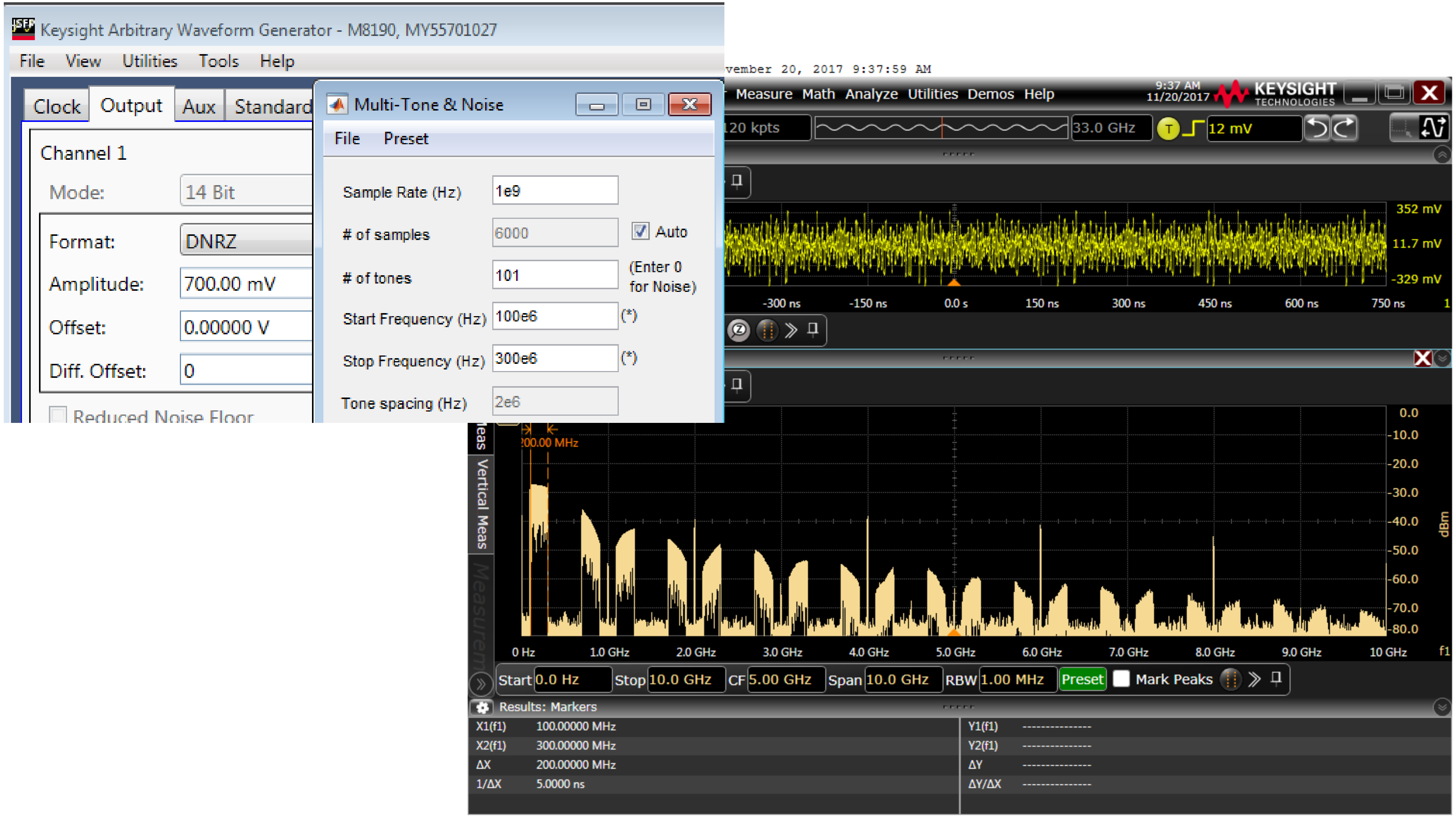
Reconstruction Filter





Why is a high sampling frequency always good?

100 to 300 MHz multitone & 1 GSample/s sample rate



Keysight Arbitrary Waveform Generator - M8190, MY55701027

Channel 1

Mode: 14 Bit

Format: DNRZ

Amplitude: 700.00 mV

Offset: 0.00000 V

Diff. Offset: 0

☐ Reduced Noise Floor

Multi-Tone & Noise

Sample Rate (Hz): 1e9

# of samples: 6000 ☑ Auto

# of tones: 101 (Enter 0 for Noise)

Start Frequency (Hz): 100e6 (*)

Stop Frequency (Hz): 300e6 (*)

Tone spacing (Hz): 2e6

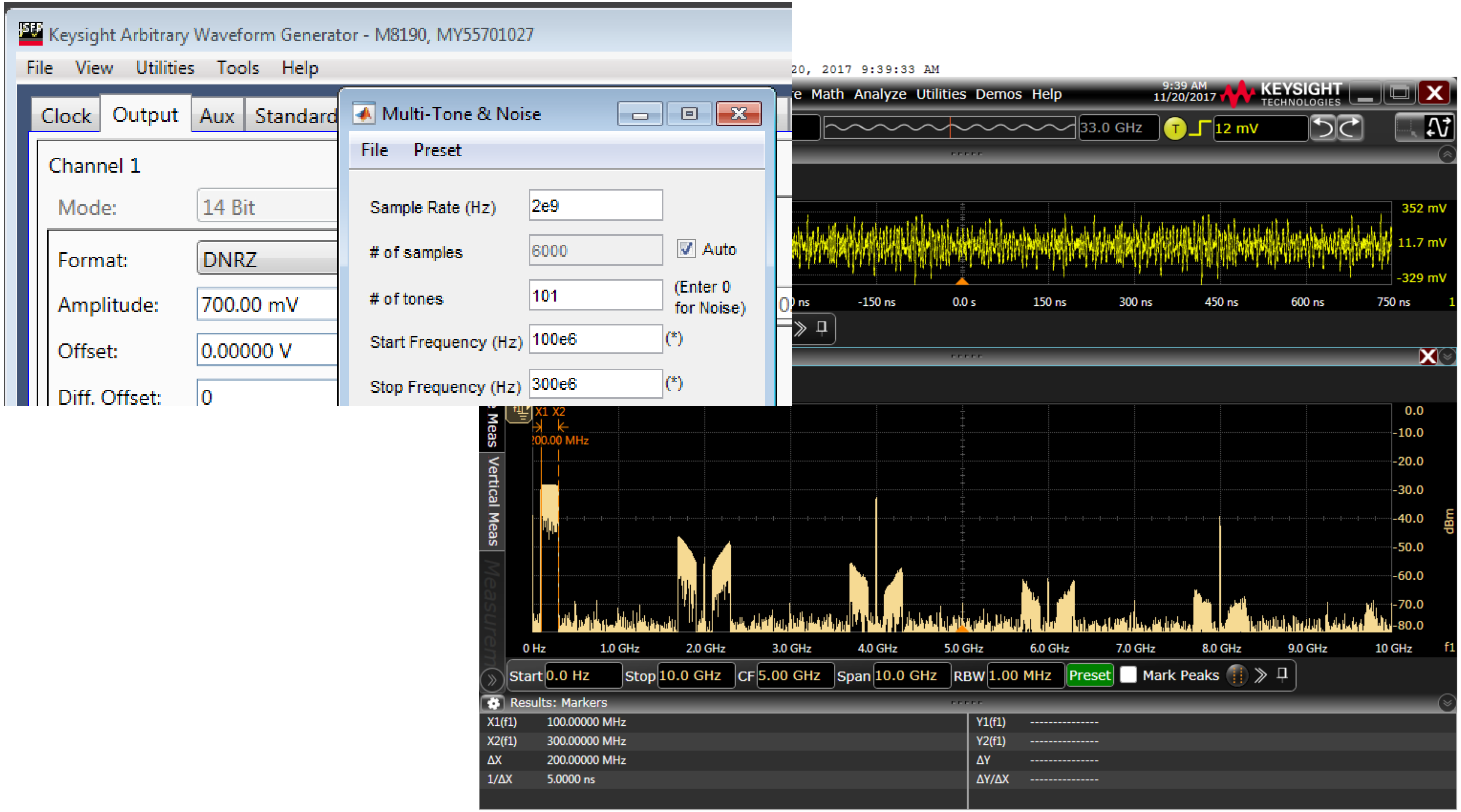
vember 20, 2017 9:37:59 AM

Start 0.0 Hz | Stop 10.0 GHz | CF 5.00 GHz | Span 10.0 GHz | RBW 1.00 MHz

Results: Markers

X1(f1)	100.00000 MHz	Y1(f1)	---------------
X2(f1)	300.00000 MHz	Y2(f1)	---------------
ΔX	200.00000 MHz	ΔY	---------------
1/ΔX	5.0000 ns	ΔY/ΔX	---------------

100 to 300 MHz multitone & 2 GSample/s sample rate



Channel 1

Mode: 14 Bit

Format: DNRZ

Amplitude: 700.00 mV

Offset: 0.00000 V

Diff. Offset: 0

Sample Rate (Hz) 2e9

# of samples 6000 ☑ Auto

# of tones 101 (Enter 0 for Noise)

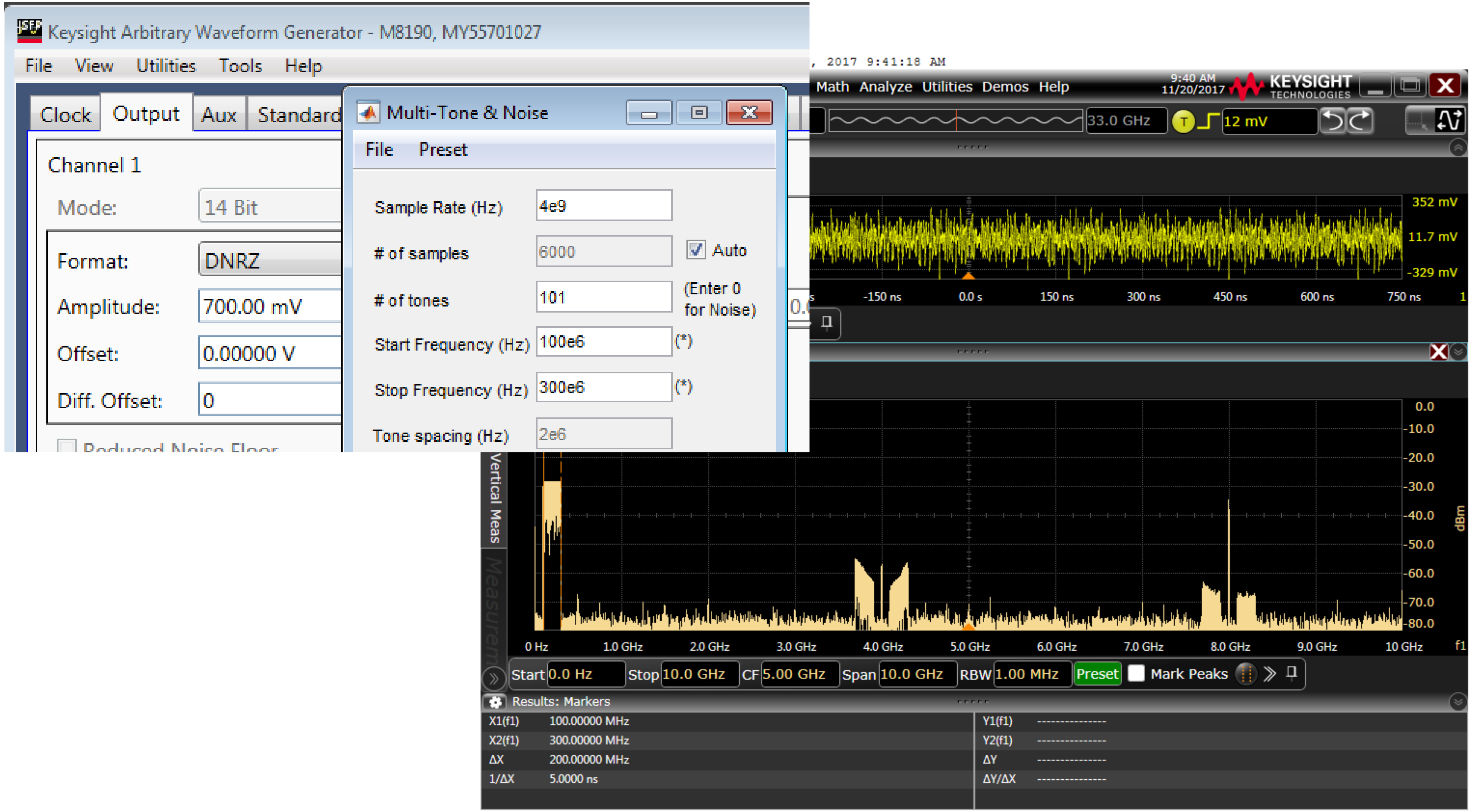
Start Frequency (Hz) 100e6 (*)

Stop Frequency (Hz) 300e6 (*)

Start 0.0 Hz Stop 10.0 GHz CF 5.00 GHz Span 10.0 GHz RBW 1.00 MHz

X1(f1)	100.00000 MHz	Y1(f1)	---------------
X2(f1)	300.00000 MHz	Y2(f1)	---------------
ΔX	200.00000 MHz	ΔY	---------------
1/ΔX	5.0000 ns	ΔY/ΔX	---------------

100 to 300 MHz multitone & 4 GSample/sec sample rate



Channel 1

Mode: 14 Bit

Format: DNRZ

Amplitude: 700.00 mV

Offset: 0.00000 V

Diff. Offset: 0

☐ Reduced Noise Floor

Sample Rate (Hz): 4e9

# of samples: 6000 ☑ Auto

# of tones: 101 (Enter 0 for Noise)

Start Frequency (Hz): 100e6 (*)

Stop Frequency (Hz): 300e6 (*)

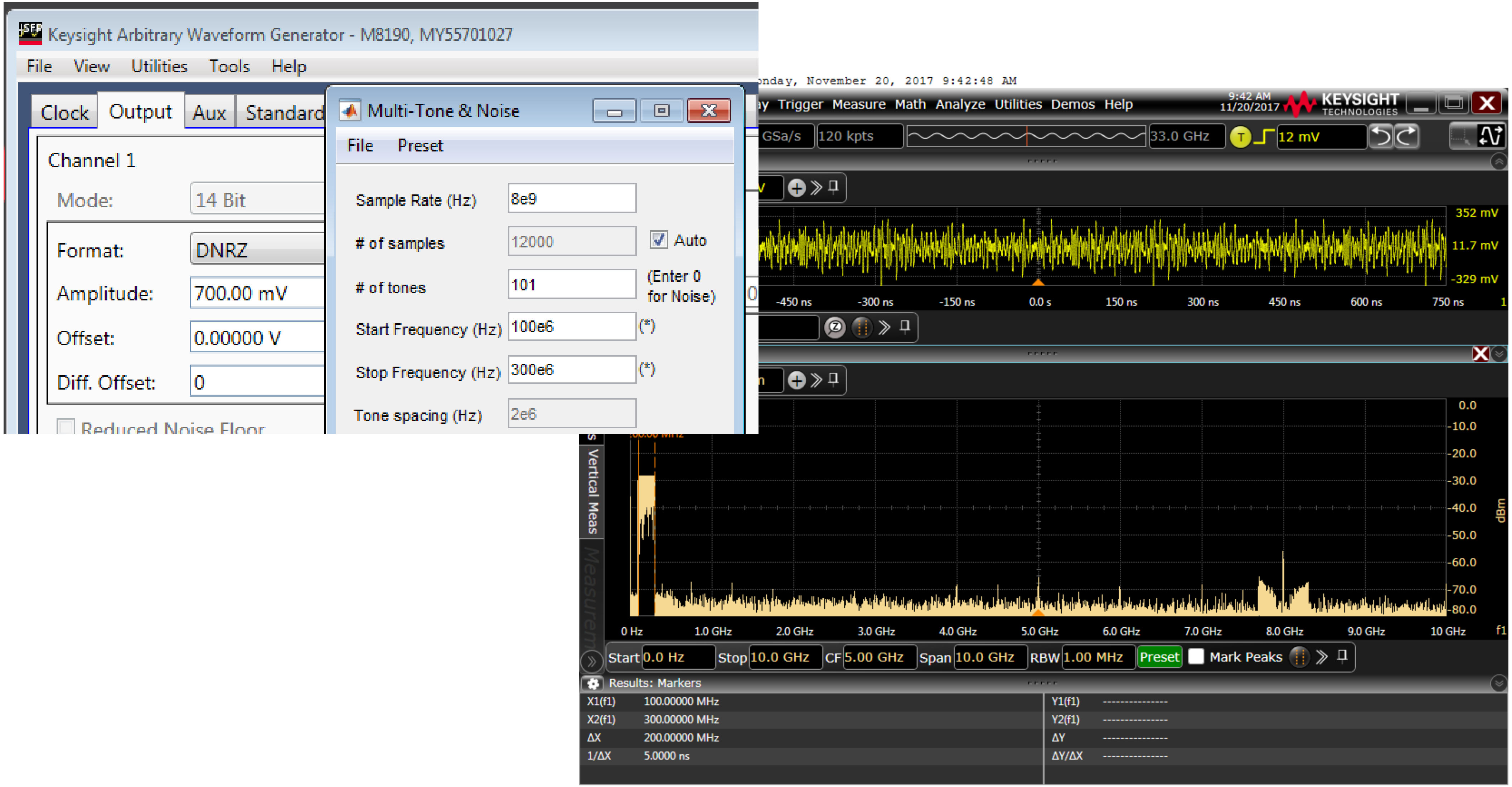
Tone spacing (Hz): 2e6

Start 0.0 Hz Stop 10.0 GHz CF 5.00 GHz Span 10.0 GHz RBW 1.00 MHz Preset

Results: Markers

X1(f1)	100.00000 MHz	Y1(f1)	---------------
X2(f1)	300.00000 MHz	Y2(f1)	---------------
ΔX	200.00000 MHz	ΔY	---------------
1/ΔX	5.0000 ns	ΔY/ΔX	---------------

100 to 300 MHz multitone & 8 GSample/s sample rate



Keysight Arbitrary Waveform Generator - M8190, MY55701027

Channel 1

Mode: 14 Bit

Format: DNRZ

Amplitude: 700.00 mV

Offset: 0.00000 V

Diff. Offset: 0

☐ Reduced Noise Floor

Multi-Tone & Noise

Sample Rate (Hz): 8e9

# of samples: 12000 ☑ Auto

# of tones: 101 (Enter 0 for Noise)

Start Frequency (Hz): 100e6 (*)

Stop Frequency (Hz): 300e6 (*)

Tone spacing (Hz): 2e6

nday, November 20, 2017 9:42:48 AM

Start 0.0 Hz | Stop 10.0 GHz | CF 5.00 GHz | Span 10.0 GHz | RBW 1.00 MHz

Results: Markers

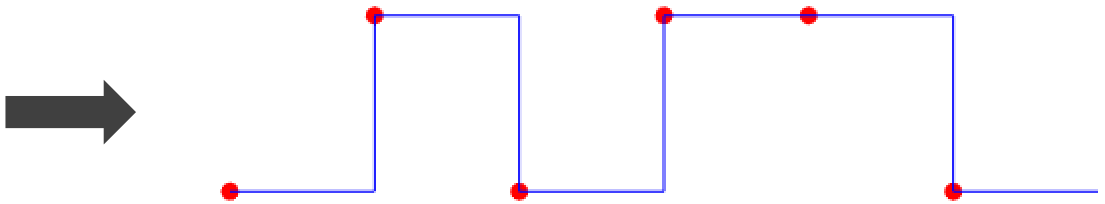
X1(f1)	100.00000 MHz	Y1(f1)	---------------
X2(f1)	300.00000 MHz	Y2(f1)	---------------
ΔX	200.00000 MHz	ΔY	---------------
1/ΔX	5.0000 ns	ΔY/ΔX	---------------

It’s time for a demo…

How To Get From a Bit/Symbol Pattern To Samples

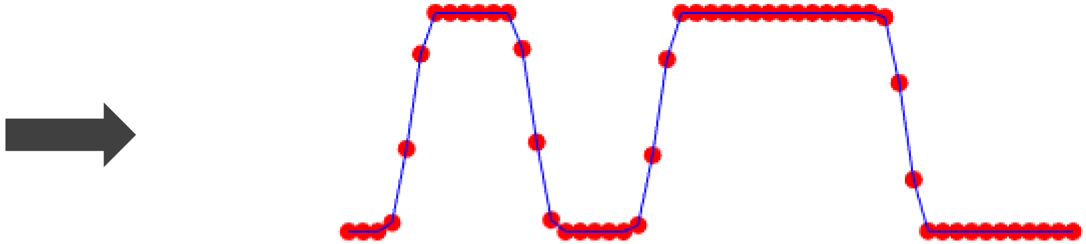
- In a “one-sample-per-symbol” architecture (e.g. in a BERT-PG), it is straight forward:

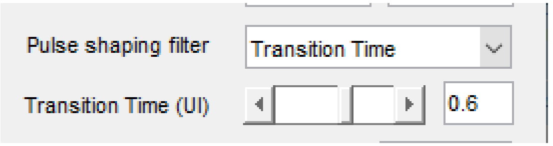
0 1 0 1 1 0



- In an AWG, you typically have more than one sample per symbol and the ratio (sample rate / symbol rate) is no necessarily an integer

0 1 0 1 1 0





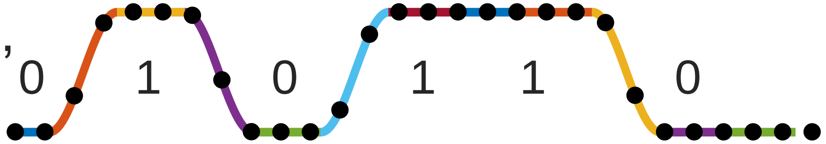
Pulse shaping filter: Transition Time

Transition Time (UI): 0.6

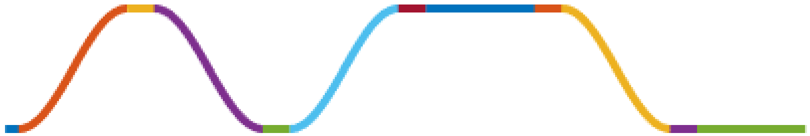
Algorithm #1 – Variable Transition Time

How to get from symbols to samples

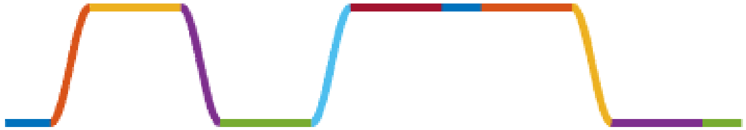
- Combine “straight line” and “cosine” waveform segments, then place sampling points on the calculated shapes



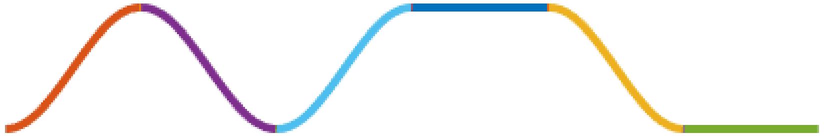
- Depending on the desired rise and fall time, the cosine segments are „squeezed“ or „expanded“
  - Slow transition time:



  - Fast transition time:



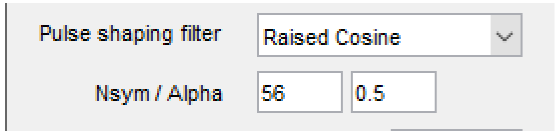
- With transition time = 1 UI, the pulse shape is very close to a Raised Cosine with alpha = 1 (i.e. sinusoidal)



- **This algorithm works well with large oversampling ratios (i.e. low baudrates)**

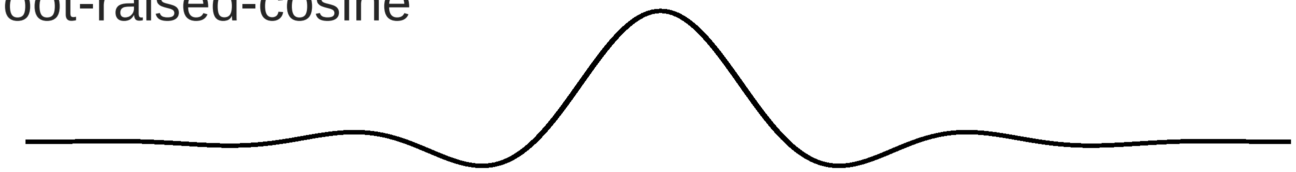
KEYSIGHT

Algorithm #2 – Using a Pulse Shape Filter


Pulse shaping filter: Raised Cosine
Nsym / Alpha: 56 0.5

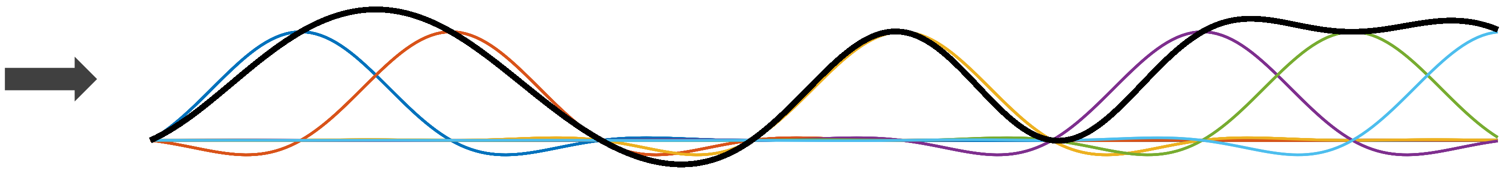
How to get from symbols to samples

- For RF signals, a **pulse-shape filter** is usually applied in order to reduce the occupied bandwidth. The same approach can be used for NRZ or PAM-n signals to reduce their bandwidth
- Each symbol is treated as a dirac pulse, convoluted with impulse response of the pulse shape filter, typically a raised cosine or root-raised-cosine
- Example: impulse response of
  a raised cosine filter with alpha = 0.3



- The final waveform is **the sum of the impulse responses of all symbols**

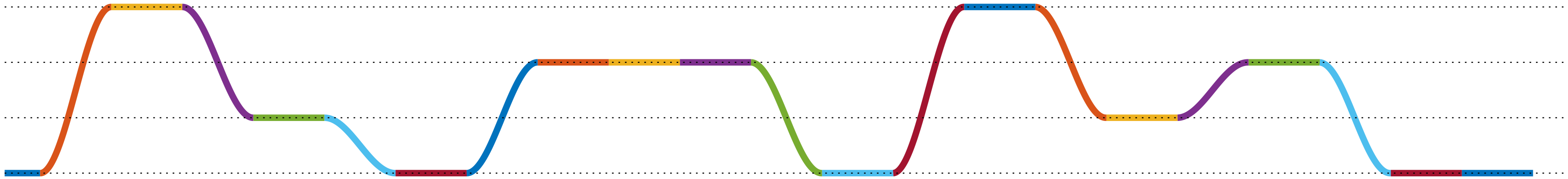
1 1 0 0 1 0 1 1 1



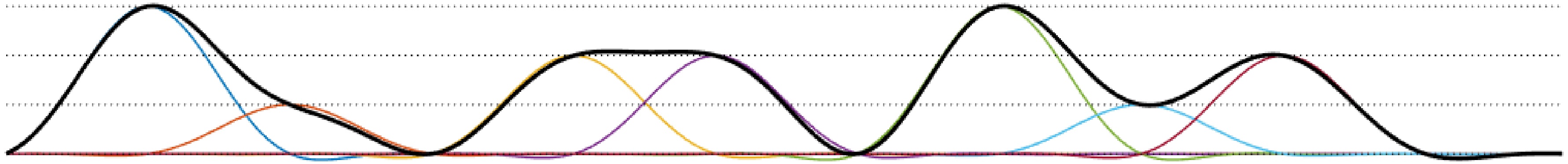
Multi-Level signals (PAM-n)

How to get from symbols to samples

- Both previously mentioned algorithms work with multi-level (PAM-n) signals equally well. Here is an example with PAM-4:
- Transition time algorithm



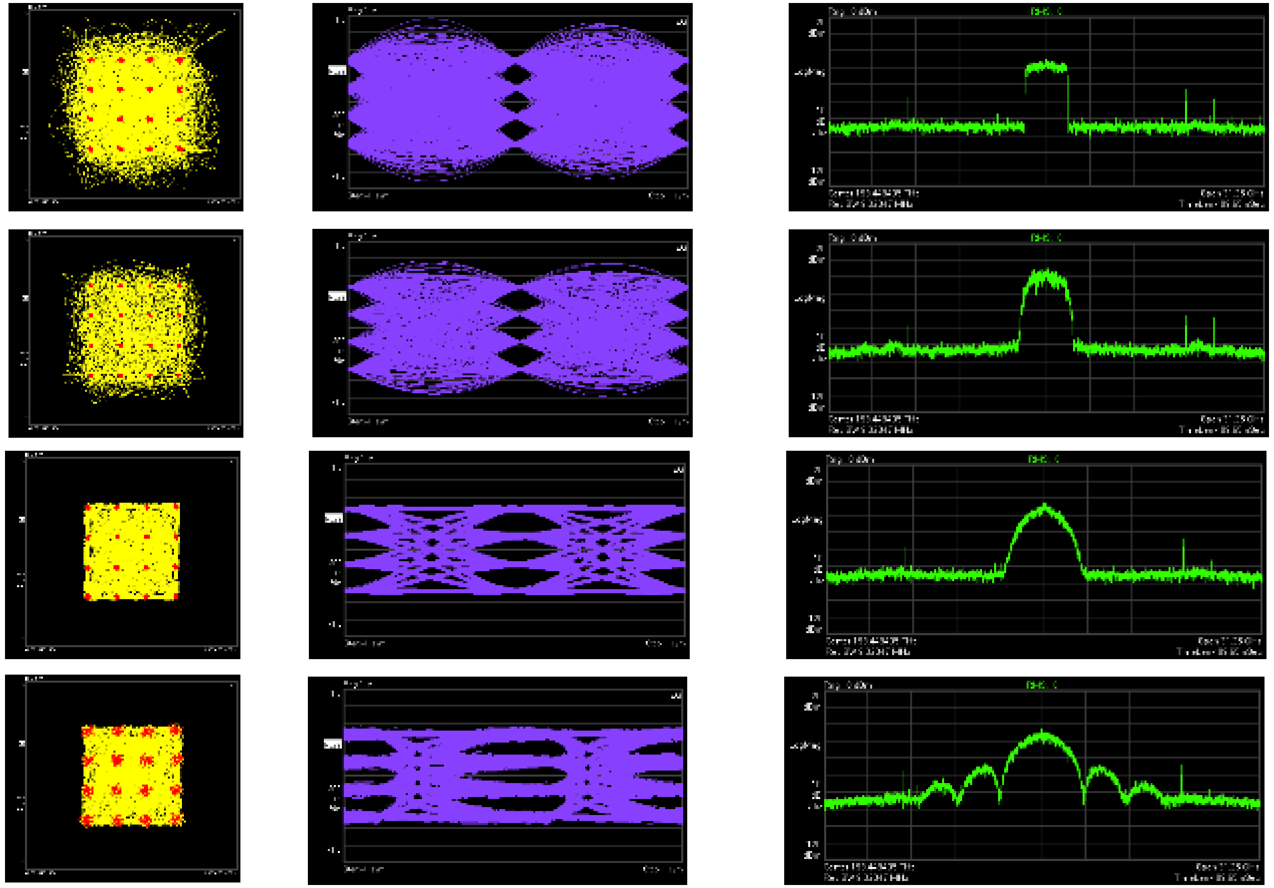
- Pulse-Shape algorithm



KEYSIGHT

Spectral Effects of Pulse Shaping

Pulse Shape affects Signal Waveform



Narrowest spectrum — Raised cosine $\alpha = 0.05$

Best EVM — Raised cosine $\alpha = 0.35$

Best Q-Factor — Raised cosine $\alpha = 1.0$

Lowest Jitter — Transition time = 0

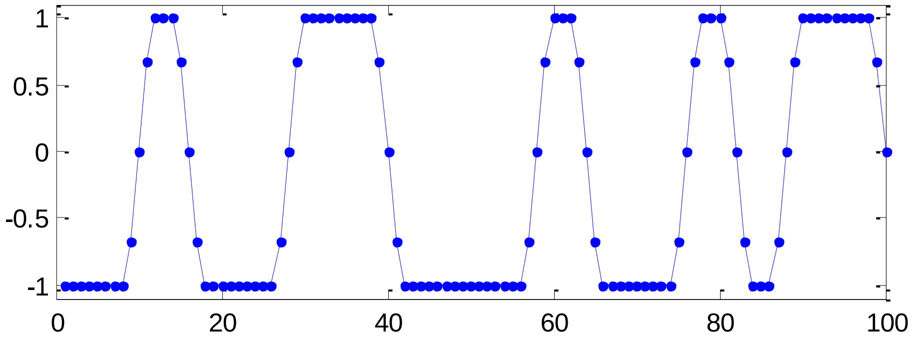
It’s time for a demo…

Pattern Definitions

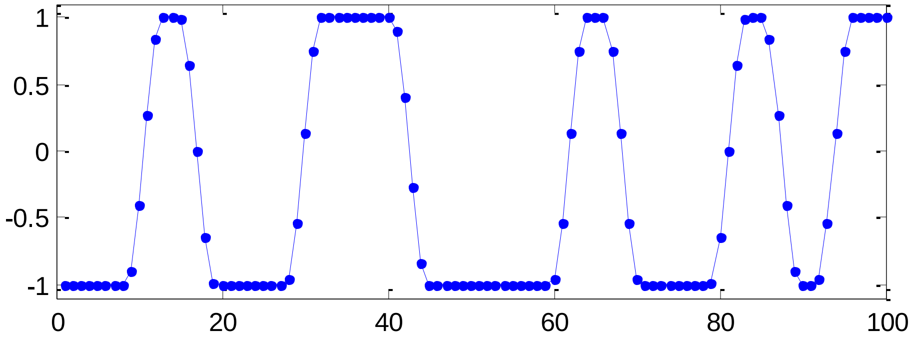
- **Random**
  - uses the MATLAB “rand()” function to generate random bits/symbols
  - Works also for “odd” PAMs (e.g. PAM-3, PAM-5, PAM-6, etc.) where there is no 2^n mapping from bits
  - is not limited to a certain number of symbols and hence works well for demo purposes ;-)
- **PRBS 2^n-1**
  - Standard PRBS patterns, can be used with NRZ or PAM4
  - Be aware that the correct pattern length will likely require the sample rate to be adjusted
- **SSPRQ, QPRBS-13, etc.**
  - Special patterns for PAM-4 testing. Same restrictions as with PRBS patterns
- **User defined**
  - Allows an arbitrary MATLAB expression to be specified as a pattern
  - E.g. **[randi([0 3],1,128]** will generate 128 random PAM-4 symbols. You can use variable names and functions from the MATLAB workspace, e.g. **csvread()**
- **Pattern from file**
  - Reads symbol values from a file. Values can be either 0 and 1 for NRZ or 0,1,2,3 for PAM4 or even decimal values for slight offsets from nominal signal levels (e.g. 0 1 0 1 0 **0.9** 0 1 0 1)

It’s time for a demo…

Integer vs. Fractional Re-sampling



Integer Re-sampling

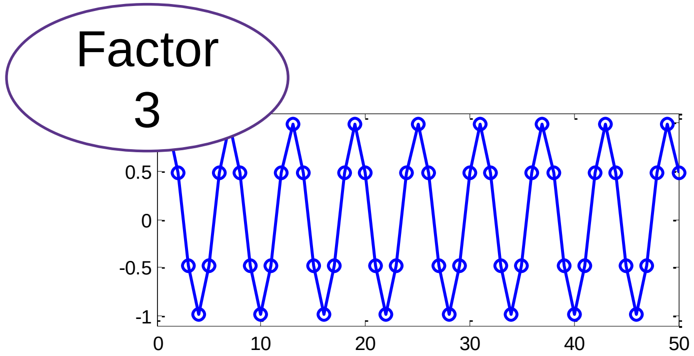


Fractional Re-sampling

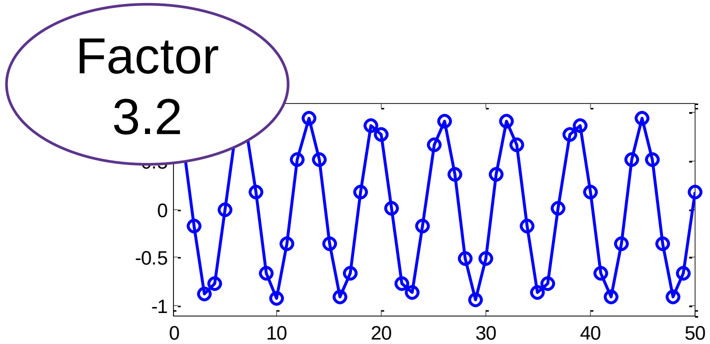
Integer vs. Fractional Re-sampling

32 Gbaud Signals and Beyond

Example: Symbol rate: **20 GSa/s, QPSK, raised cosine,** α**=1**


Factor
3

Integer re-sampling


Factor
3.2

Fractional re-sampling

slightly lower jitter for clean signals, but cannot add infinitesimally small amount of timing distortions

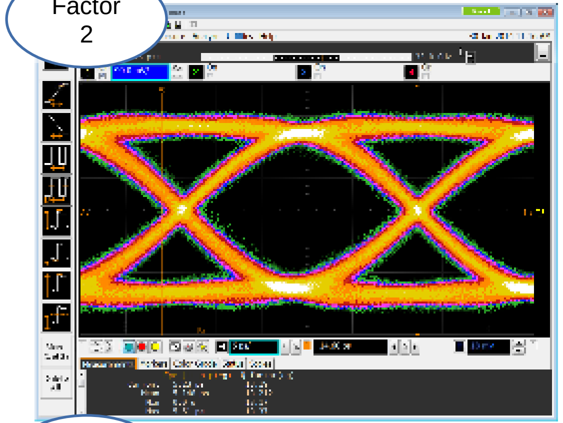
intrinsic jitter slightly higher, but distortions can be added smoothly

Integer vs. Fractional Re-sampling

M8195A Different Sample Factors

Integer Re-sampling

Factor
2

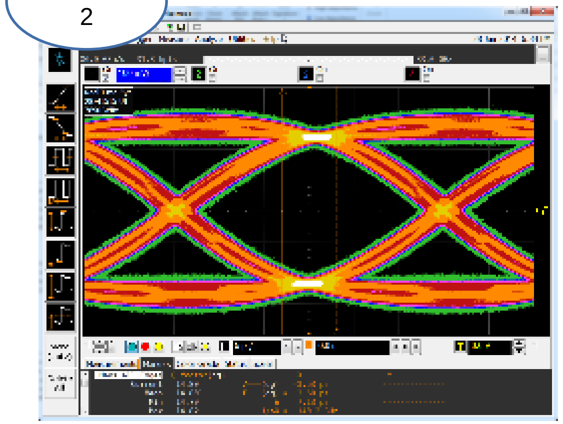


32 Gb/s,
PRBS 11

Pulse shaping:
raised cosine,
alpha = 1.0

Q-Factor: **13.2**,
Jitter: **5.2 ps** (pp)

Factor
2

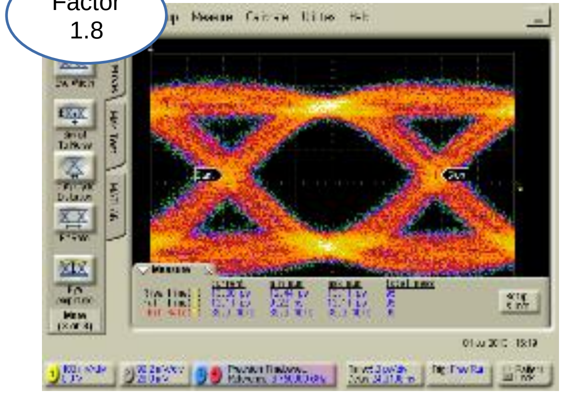


28 Gbit/s,
PRBS 11,
Pulse shaping:
raised cosine,
alpha = 0.7

Q-Factor: **14.8**

Fractional Re-sampling

Factor
1.8

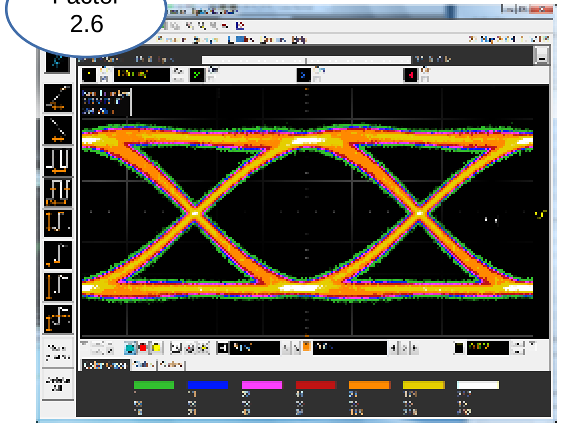


35 Gb/s
PRBS15

Pulse shaping:
raised cosine
rolloff 1.0

Rise time: 13 ps
Fall time: 13 ps
Equivalent BW: 27 GHz

Factor
2.6

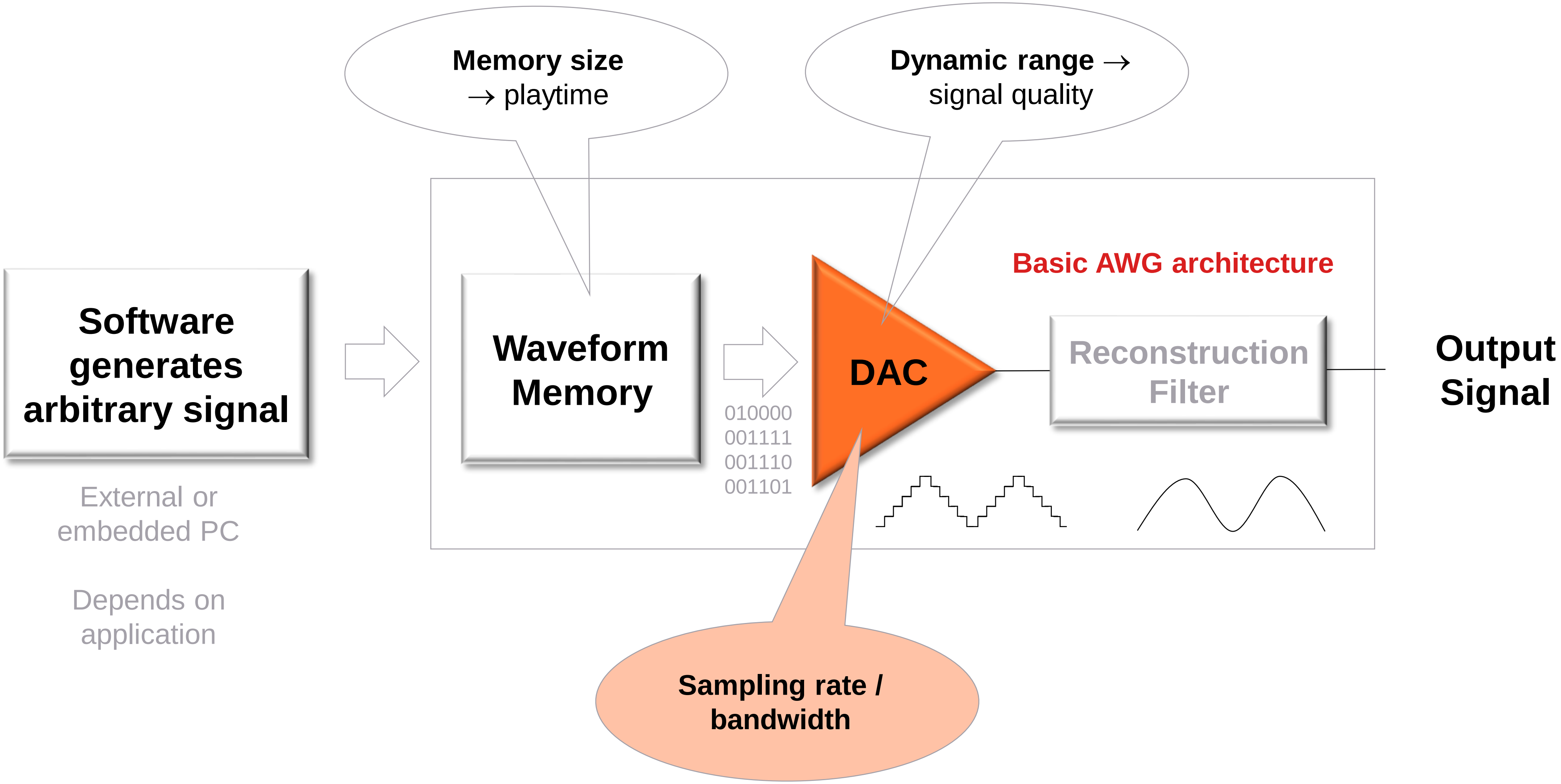


25 Gb/s

It’s time for a demo…

Theory of AWG Operation

Key Blocks and Specifications: Bandwidth



Memory size → playtime

Dynamic range → signal quality

Basic AWG architecture

Software generates arbitrary signal

External or embedded PC

Depends on application

Waveform Memory

DAC

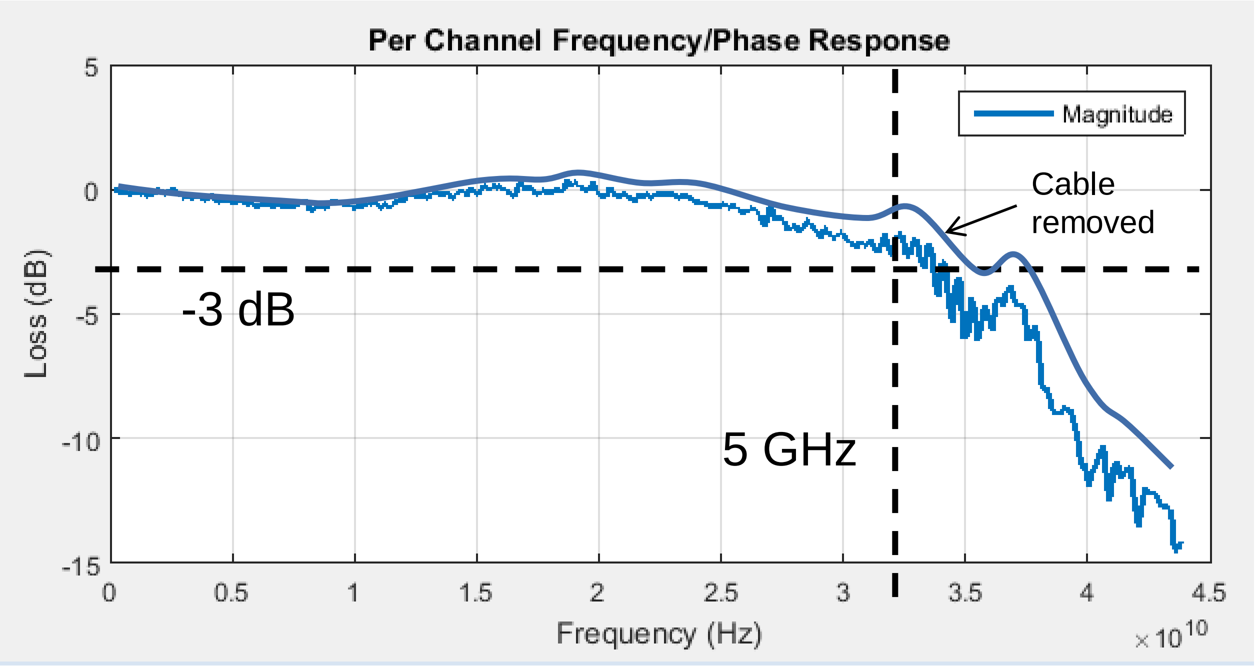
Reconstruction Filter

Output Signal

Sampling rate / bandwidth

AWG Basics: Analog Bandwidth

Frequency Response

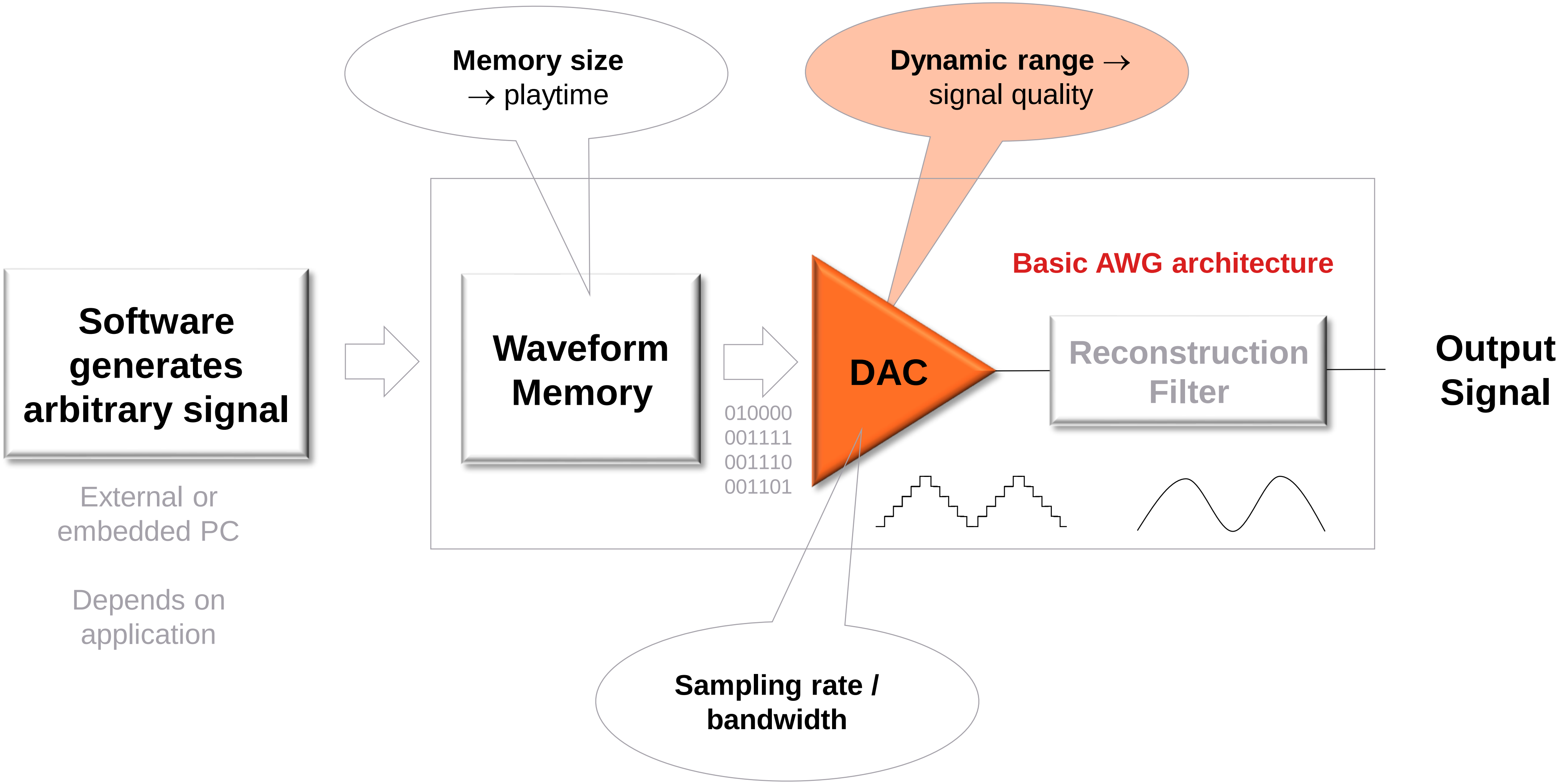


3 dB point

The 3 dB point defines the analog bandwidth

Theory of AWG Operation

Key Blocks and Specifications: Dynamic Range/signal quality



Memory size
→ playtime

Dynamic range →
signal quality

Basic AWG architecture

Software generates arbitrary signal

Waveform Memory

DAC

Reconstruction Filter

Output Signal

010000
001111
001110
001101

External or embedded PC

Depends on application

Sampling rate / bandwidth

AWG Basics: Dynamic Range and Resolution

Quantisation and Quantisation Error

- A N-bit ADC has quantisation steps of $n = 2^N$.
- The Quantisation Error q of a signal with an Amplitude A is calculated using $q = \frac{A}{2^N - 1}$.

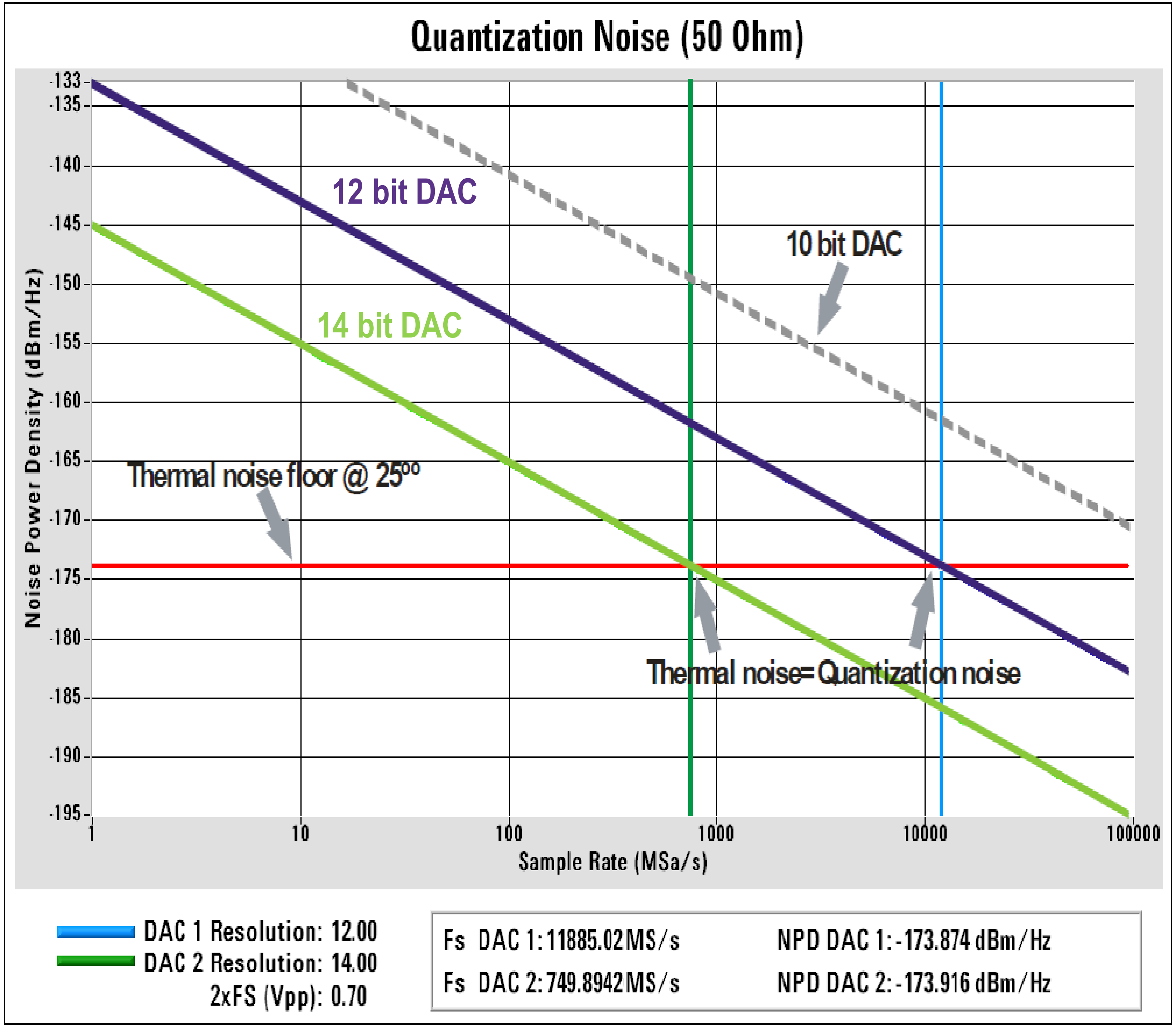
Example for a signal with an amplitude of 1V at full scale:

- ✓ Vertical resolution for an 8-bit DAC is $n = 2^8 = 256$ steps.
- ✓ The quantisation Error is then calculated to $q = \frac{1V}{2^8 - 1} = 3.9\ mV$

- ✓ Vertical resolution for an 10-bit DAC is $n = 2^{10} = 1024$ steps.
- ✓ The quantisation Error is then calculated to $q = \frac{1V}{2^{10} - 1} = 0.98\ mV$
- ✓ Often q is also called „quantisation noise“ which can be analyzed easily within the frequency domain.

Quantization Noise Power Density vs. Sample Rate

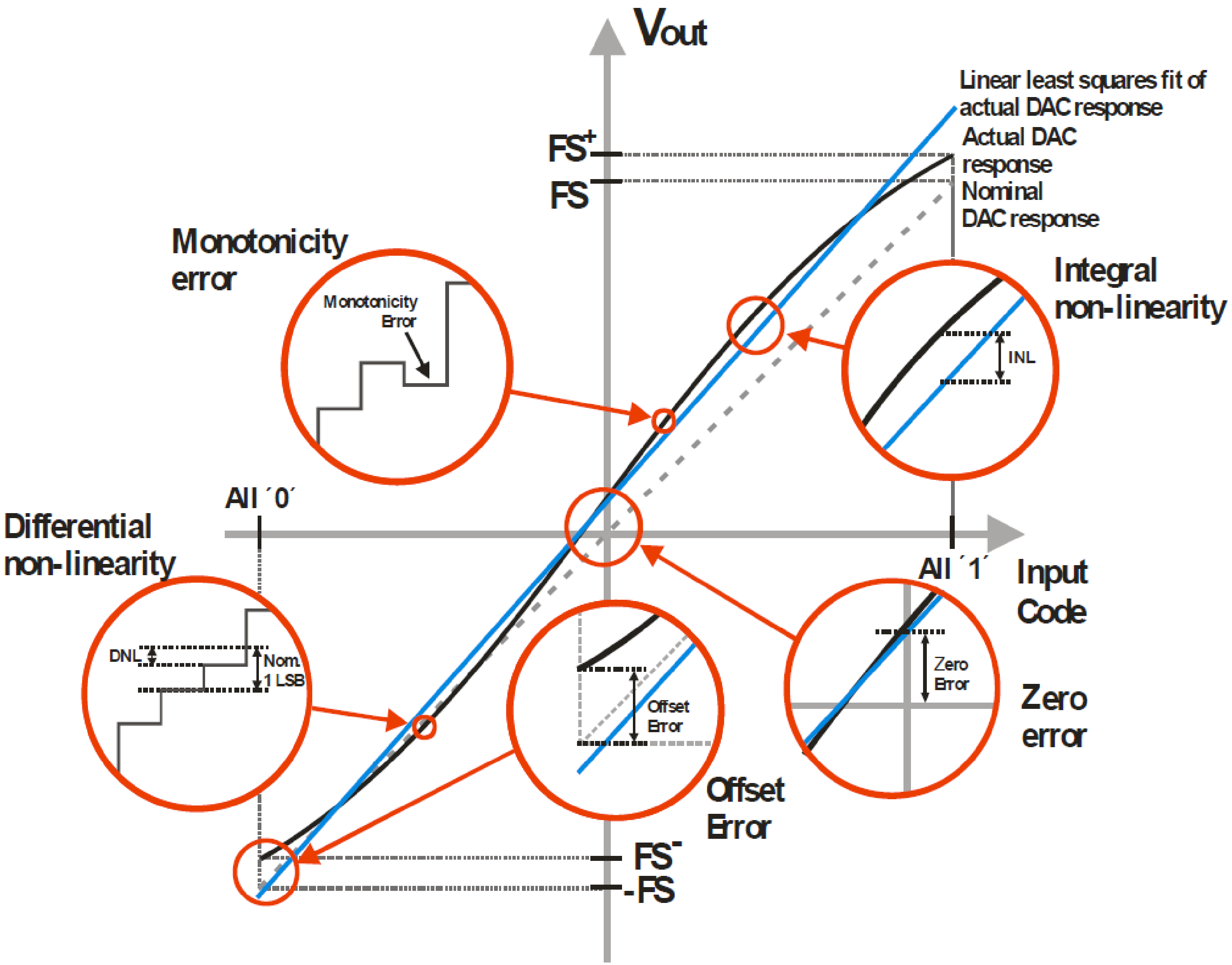
- In the Keysight M8190A AWG, with 14 bits resolution at 8GSa/s and 12 bits at 12 GSa/s, **quantization noise is negligible** in front of other noise sources, however, it may not stand true for a 10 bit instrument running at the same speed.



AWG Basics: Non-Linearities

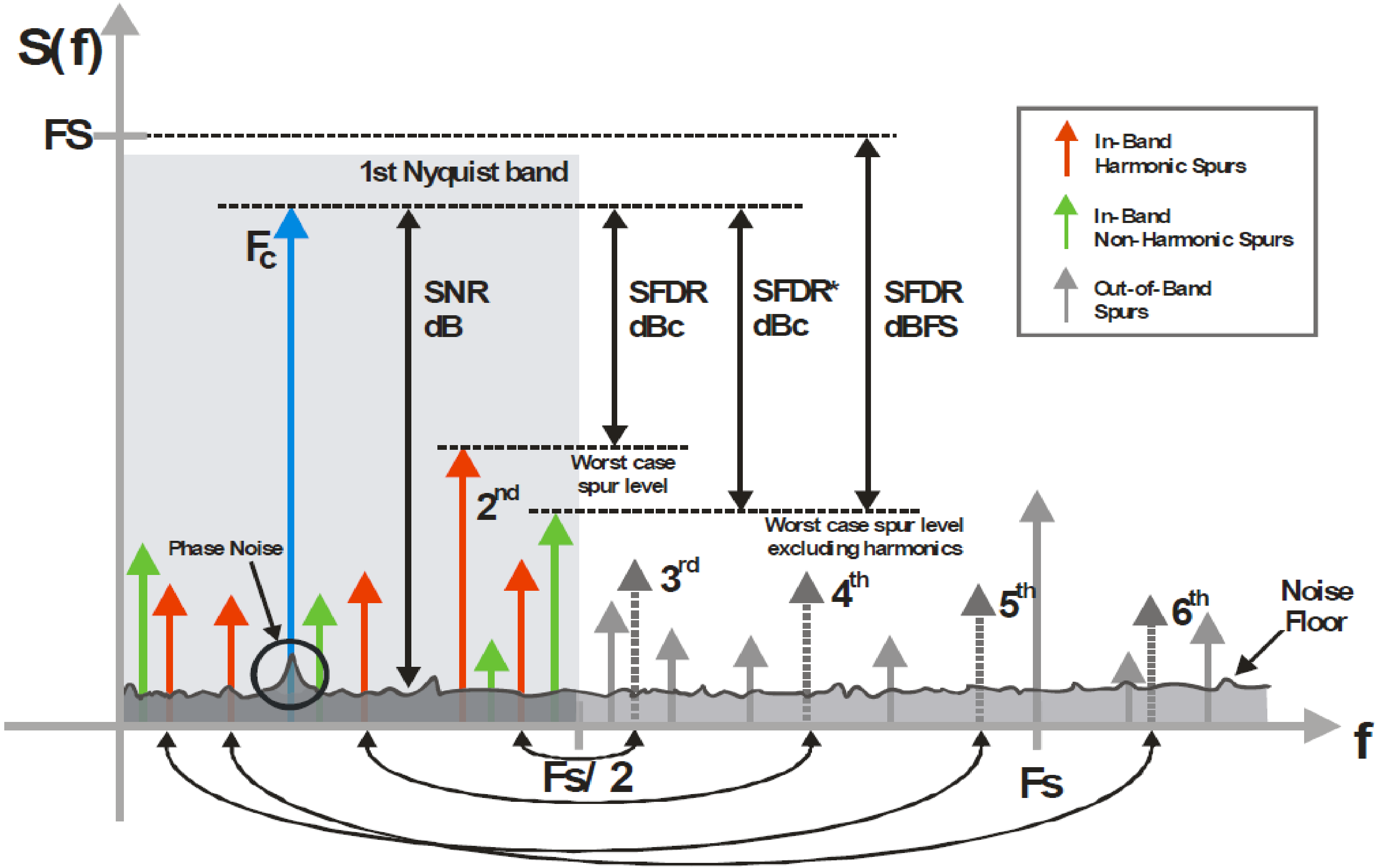
Theory of AWG Operation

- Real world DACs are not perfect and transfer function deviates from the ideal response.
- Linear component will not result in harmonic or inter-modulation distortion in the output waveform as opposed to the non-linear components.



AWG Basics: Non-Linearities

Frequency Domain



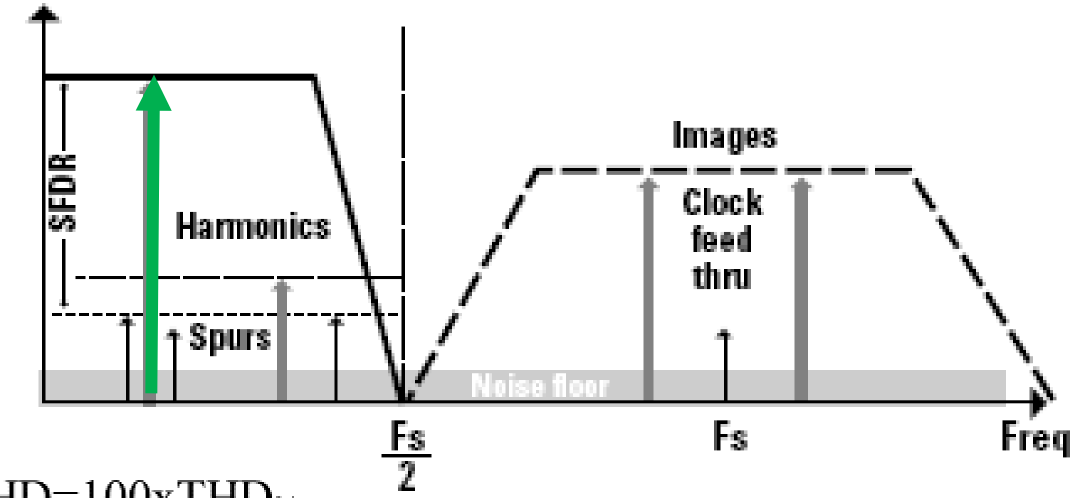
$$THD_{\%}=(\Sigma H_n^2)^{1/2}/S \times 100\%,\ n=2\ldots N,\ H_n \text{ and } S \text{ are rms values}$$

Effective Number of Bits *or* ENOB

Impairments limit AWG Dynamic Range !

SFDR = Spurious Free Dynamic Range
SINAD = ratio of the total signal power level (Signal + Noise + Distortion) to unwanted signal power (Noise + Distortion)

Images
Sample Clock Feedthru
Harmonics
Spurious
Noise Floor



$$\mathrm{SINAD}_{\mathrm{dBc}} = 10\log_{10}(10^{-\mathrm{SNR}/10} + 10^{-\mathrm{THD}/10}),\ \mathrm{THD} = 100\mathrm{x}\mathrm{THD}_{\%}$$

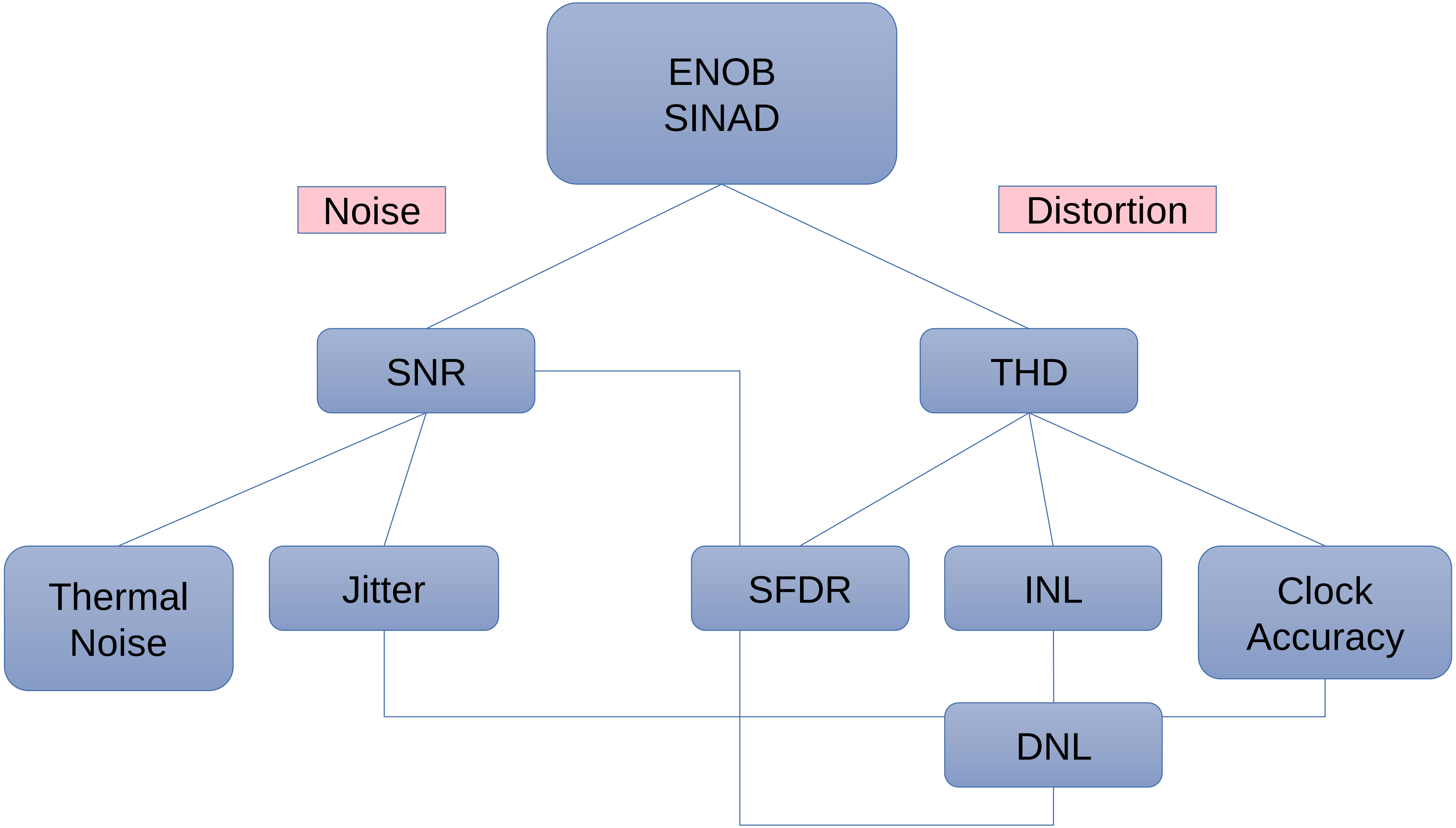
$$\mathrm{ENOB} = \left(\frac{SINAD - 10log(3|2)}{20log2}\right) = \frac{SINAD - 1.76}{6.02}$$

determines dynamic range
Every Bit in DAC doubles the voltage resolution
~ 6 dB per bit

$$\mathrm{SNR}_{\mathrm{dBc}} = 6.02\mathrm{N} + 1.76\mathrm{dB}, \qquad \mathrm{DC} < f < \mathrm{FS}/2$$

Effective Number of Bits *or* ENOB

What Sources are Included in the Calculation?



Effective Number of Bits *or* ENOB

What does ENOB ignore?

- ☐ Testing is done with a sine wave
  (which has no harmonics)
- ☐ Effective bits ***neglect*** these sources of error:
  - ☐ Amplitude Flatness
  - ☐ Phase Linearity
  - ☐ Gain Accuracy
  - ☐ Offset Accuracy

High-Precision AWG Example

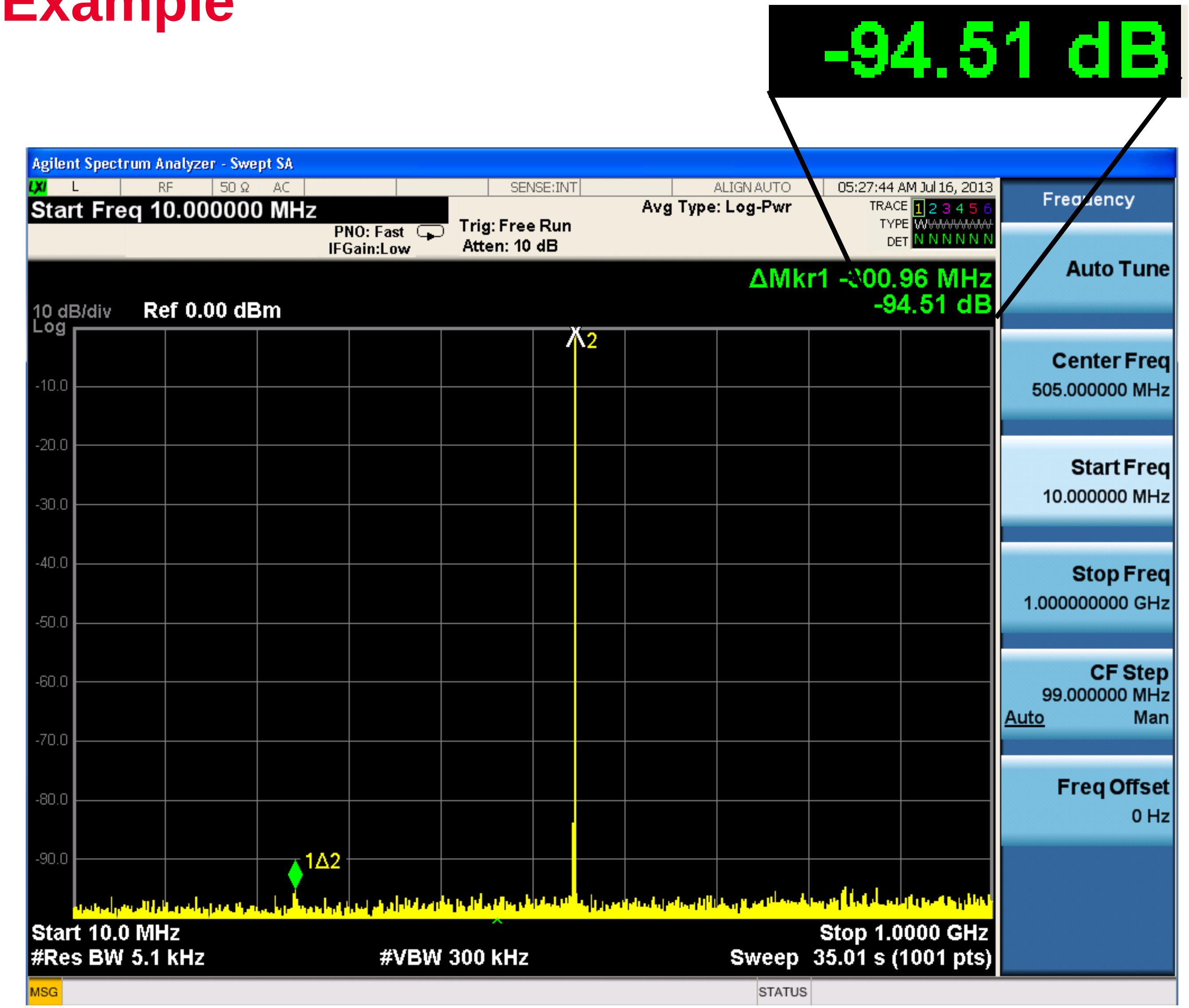
CW Signal

Single tone
555 MHz

Fs = 7.2 GHz

Spurs: < -90 dBc

(in the range
0 to 1 GHz)



-94.51 dB

Agilent Spectrum Analyzer - Swept SA

L RF 50 Ω AC SENSE:INT ALIGN AUTO 05:27:44 AM Jul 16, 2013

Start Freq 10.000000 MHz

PNO: Fast
IFGain:Low

Trig: Free Run
Atten: 10 dB

Avg Type: Log-Pwr

TRACE 1 2 3 4 5 6
TYPE WWWWWW
DET N N N N N N

ΔMkr1 -300.96 MHz
-94.51 dB

10 dB/div Ref 0.00 dBm
Log

Start 10.0 MHz
#Res BW 5.1 kHz

#VBW 300 kHz

Stop 1.0000 GHz
Sweep 35.01 s (1001 pts)

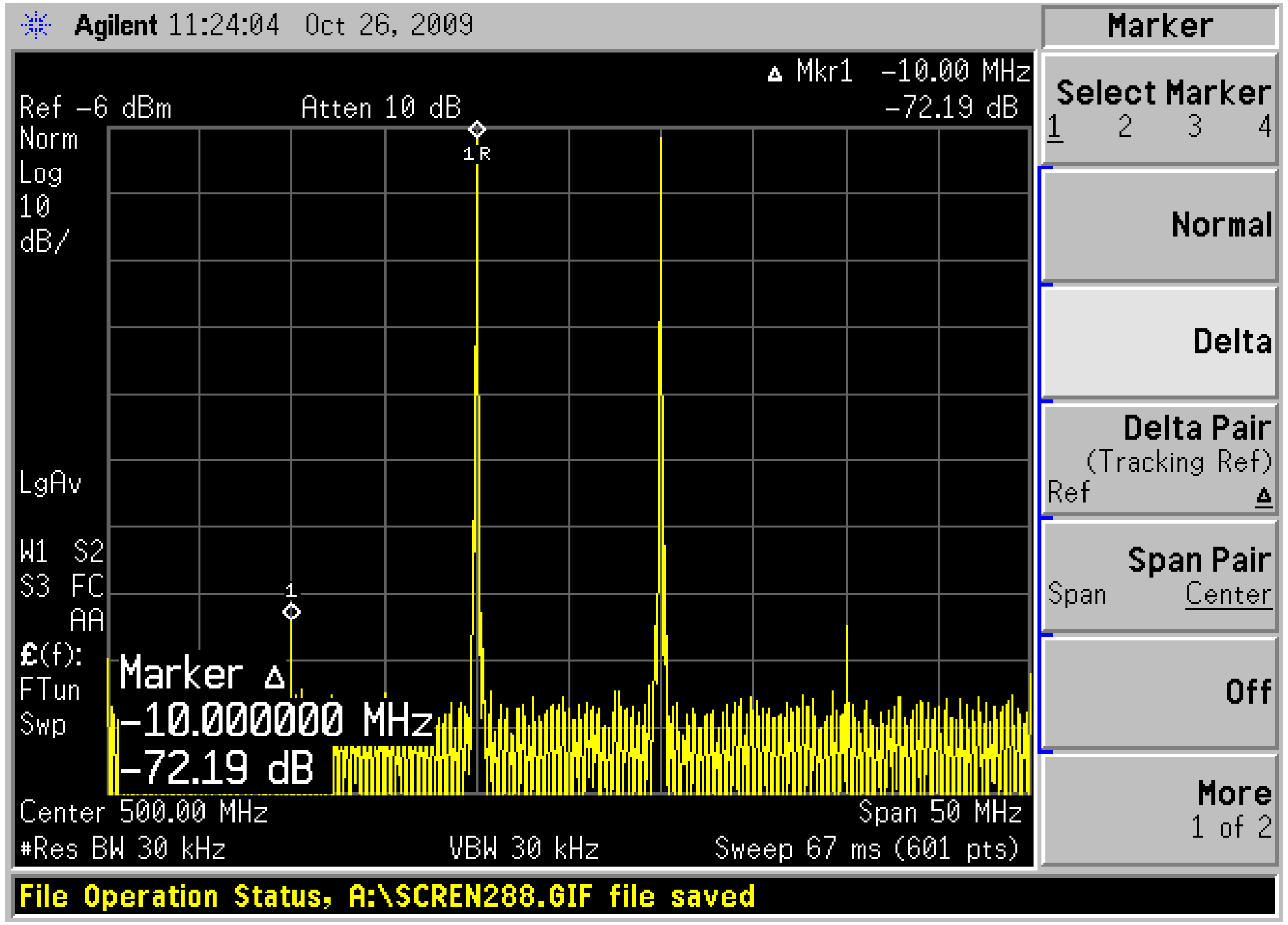
High-Precision AWG Example:

Two-Tone Signal

Two-tone signal
Center 500 MHz
Distance 10 MHz

Fs = 7.2 GHz

IMD: -72 dBc



Agilent 11:24:04 Oct 26, 2009

Δ Mkr1 -10.00 MHz
-72.19 dB

Ref -6 dBm Atten 10 dB
Norm
Log
10
dB/

LgAv

W1 S2
S3 FC
AA
£(f):
FTun
Swp

Marker Δ
-10.000000 MHz
-72.19 dB

Center 500.00 MHz Span 50 MHz
#Res BW 30 kHz VBW 30 kHz Sweep 67 ms (601 pts)

File Operation Status, A:\SCREN288.GIF file saved

It’s time for a demo…

Agenda

AWG Workshop

Arbitrary Waveform Generation Fundamentals

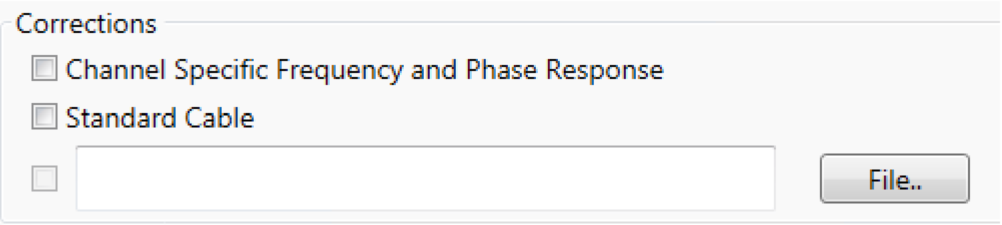
Frequency Response Correction

In-System Calibration

Conclusion & Summary

Corrections (1)

Types



Corrections

☐ Channel Specific Frequency and Phase Response

☐ Standard Cable

☐

- Channel-specific frequency and phase response
  - Frequency and phase response has been characterized individually per channel and for different output amplitudes. Range is 32 GHz in 10 MHz steps.
  - Reference is the output connector.
  - Stored in the calibration flash.
- Standard cable corrections based on a typical high-quality, high-bandwidth 0.85m microwave cable (Huber+Suhner type M8041-61616)
- File with correction factors. Format is compatible with adaptive equalizer files exported in CSV format from the Keysight 89600 VSA.

Corrections (2)

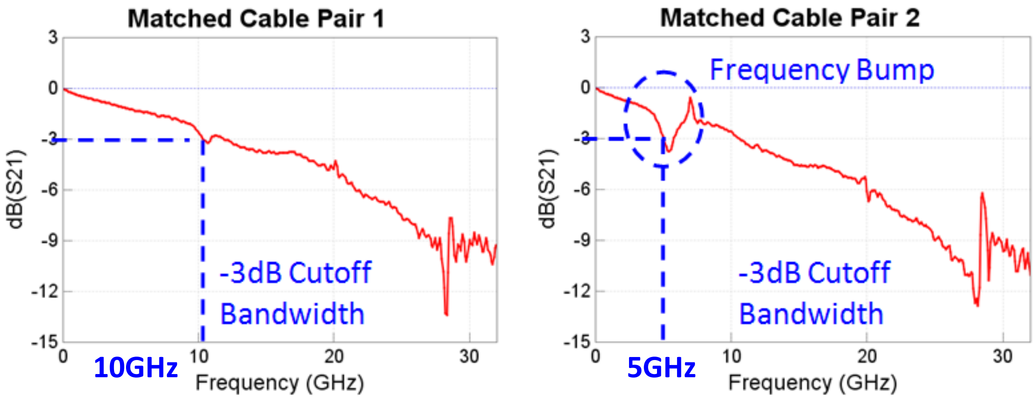
File Format

```
// MyCorrectionFile
InputBlockSize, 1024 // number of correction factors
XStart, 1.0E+09         // first factor is at 1 GHz
XDelta, 1.0E+06         // step size is 1 MHz
YUnit, lin              // lin: linear relative amplitude, dB: logarithmic relative amplitude
Y
0.987, -0.2343          // amplitude, phase in radians
0.995, 0.5674
…
…
1.269, -0.765
```

RF Cables Performance Matters!

Element Models affect correction Results

- Good element models (S-parameter) are critical to accurate de-embedding/correction results.
- One of the biggest pitfall of de-embedding is using questionable element models.
  - Always confirm the S-parameter represents your circuit components.
  - Don’t assume model stays the same for similar parts. Performance can vary even they are the same component and circuit.
  - Verify the performance with Network Analyzer whenever possible.



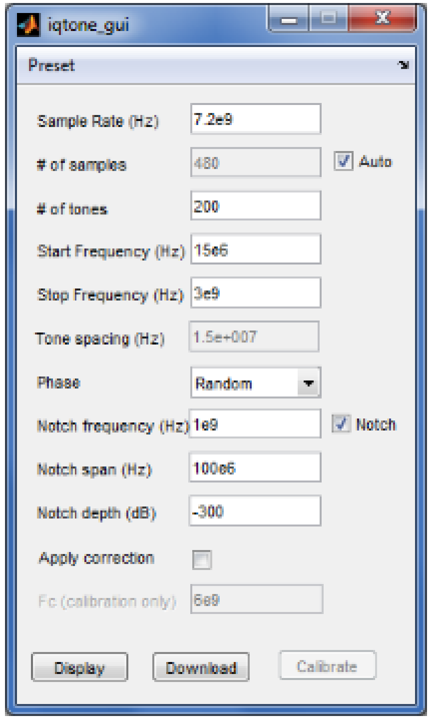
Responses of a matched cable pair. They are not exactly matched!

Amplitude Correction

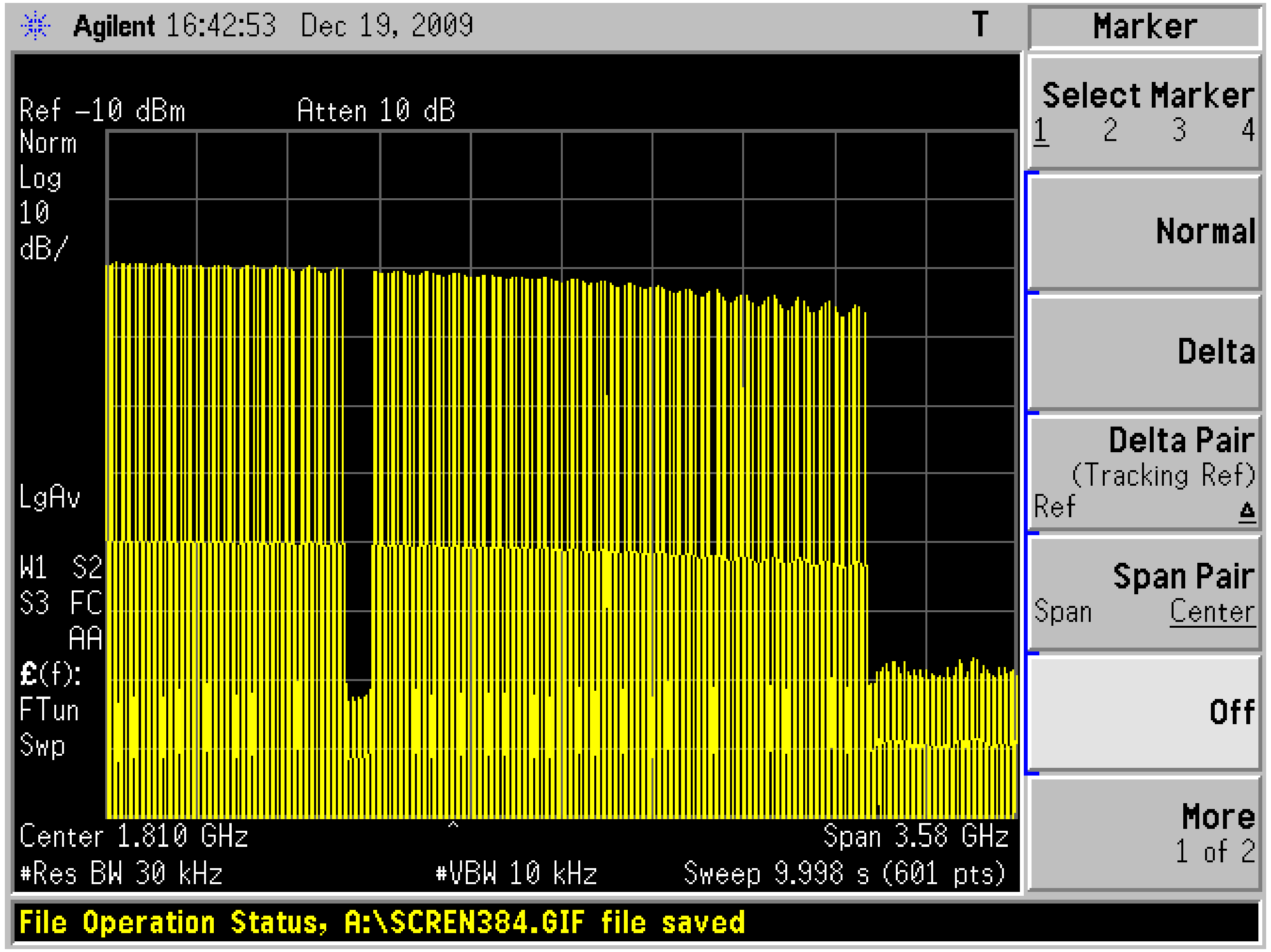
Multi-Tone Signal

Multi-tone signal with 200 tones,
3 GHz bandwidth

Fs = 7.2 GHz
without amplitude correction



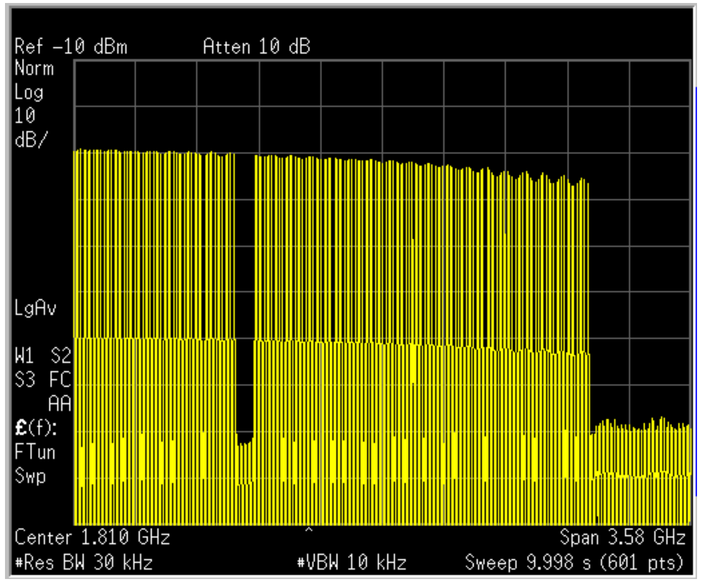
Sample Rate (Hz): 7.2e9
# of samples: 480 ☑ Auto
# of tones: 200
Start Frequency (Hz): 15e6
Stop Frequency (Hz): 3e9
Tone spacing (Hz): 1.5e+007
Phase: Random
Notch frequency (Hz): 1e9 ☑ Notch
Notch span (Hz): 100e6
Notch depth (dB): -300
Apply correction ☐
Fc (calibration only): 6e9



Agilent 16:42:53 Dec 19, 2009
Ref -10 dBm Atten 10 dB
Norm
Log
10
dB/
LgAv
W1 S2
S3 FC
AA
£(f):
FTun
Swp
Center 1.810 GHz Span 3.58 GHz
#Res BW 30 kHz #VBW 10 kHz Sweep 9.998 s (601 pts)
File Operation Status, A:\SCREN384.GIF file saved

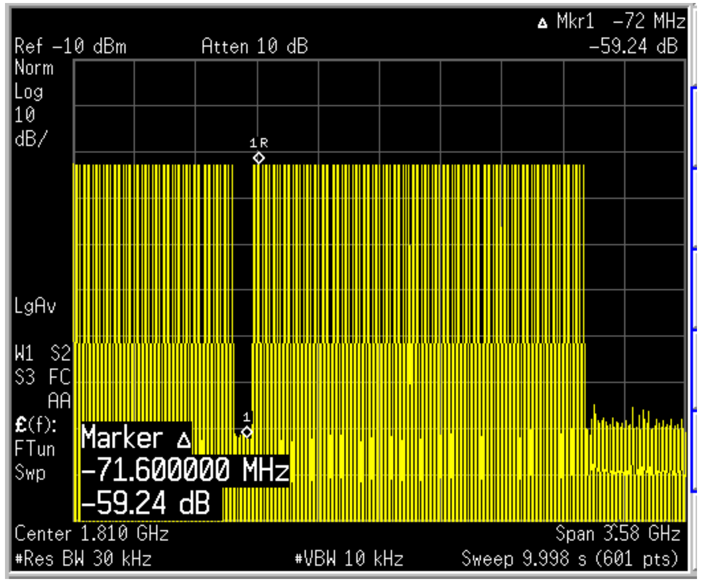
Amplitude Correction

Frequency and phase response correction



Ref -10 dBm
Atten 10 dB
Norm
Log
10
dB/
LgAv
W1 S2
S3 FC
AA
£(f):
FTun
Swp
Center 1.810 GHz
Span 3.58 GHz
#Res BW 30 kHz
#VBW 10 kHz
Sweep 9.998 s (601 pts)

Original Signal



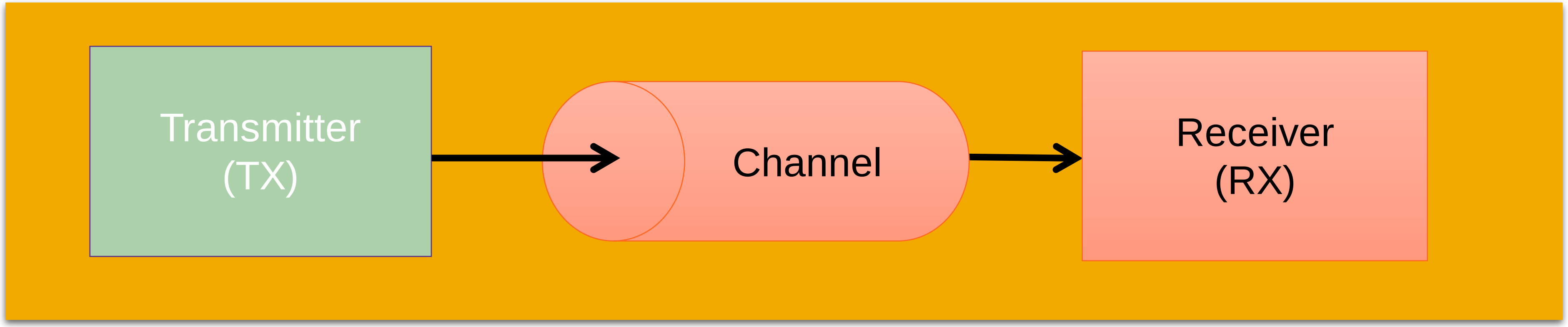
Δ Mkr1 -72 MHz
-59.24 dB
Ref -10 dBm
Atten 10 dB
Norm
Log
10
dB/
LgAv
W1 S2
S3 FC
AA
£(f):
FTun
Swp
Marker Δ
-71.600000 MHz
-59.24 dB
Center 1.810 GHz
Span 3.58 GHz
#Res BW 30 kHz
#VBW 10 kHz
Sweep 9.998 s (601 pts)

With digital pre-distortion

Depending on the bandwidth and carrier frequency, the flatness can be calibrated to around 0.1 dB flatness

Channel De-embedding

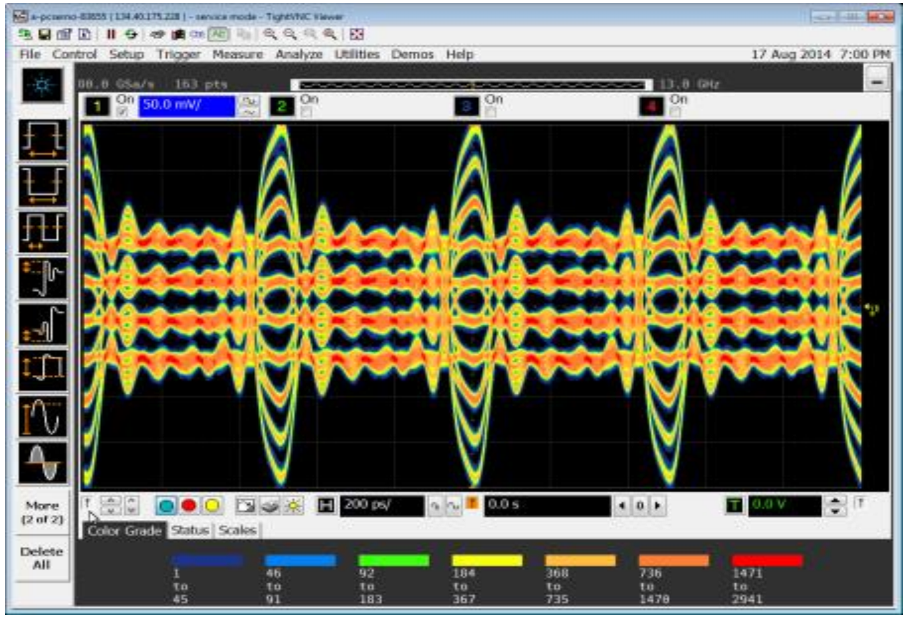
Using S-Parameters or measured in-system

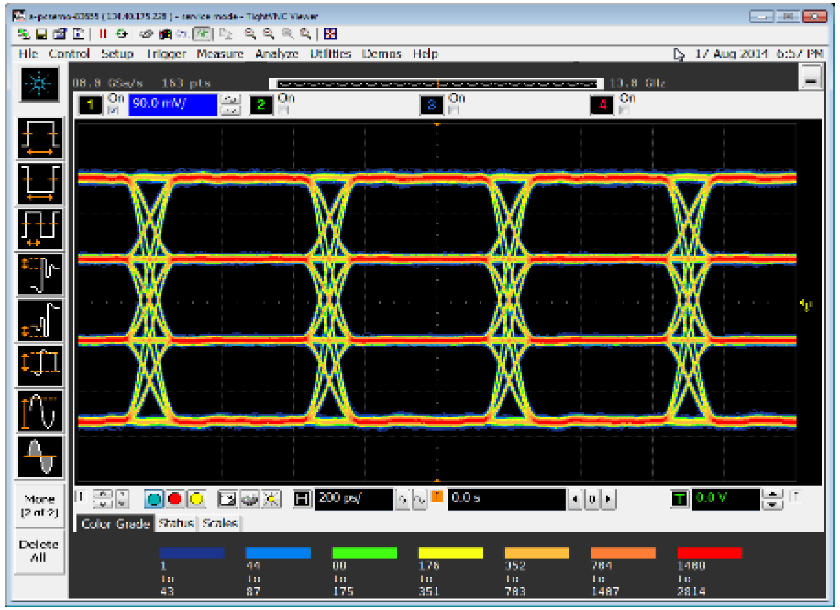


Transmitter (TX)

Channel

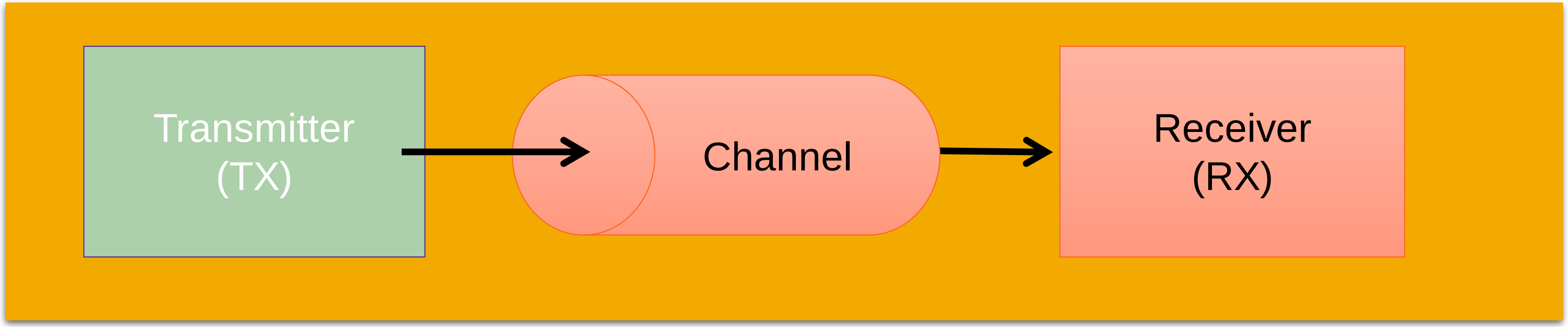
Receiver (RX)





Channel Embedding

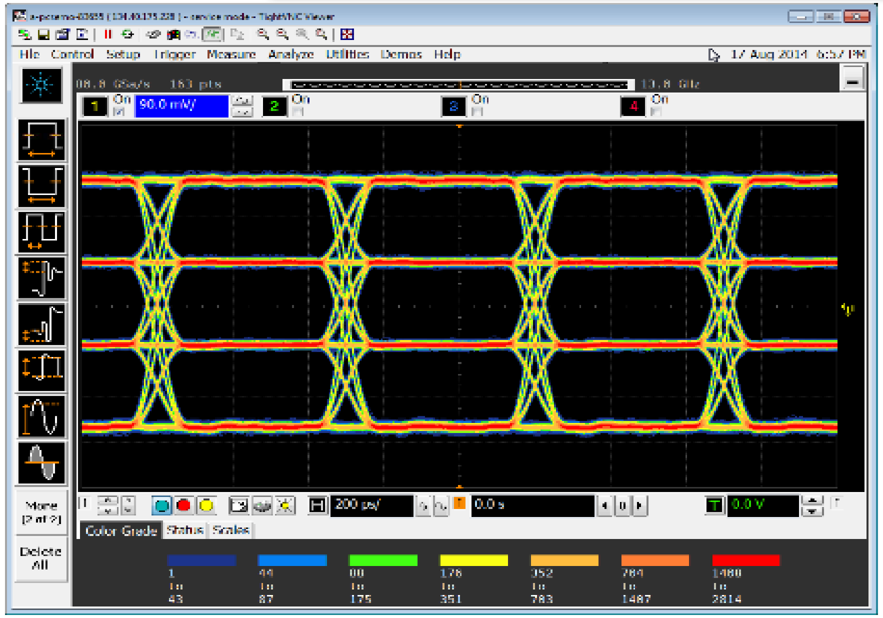
Using S-Parameters or measured in-system

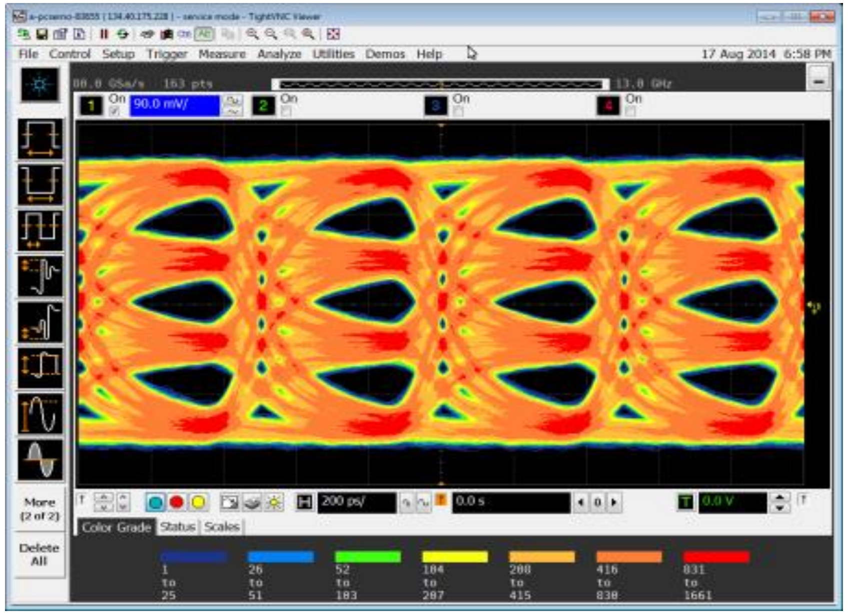


Transmitter (TX)

Channel

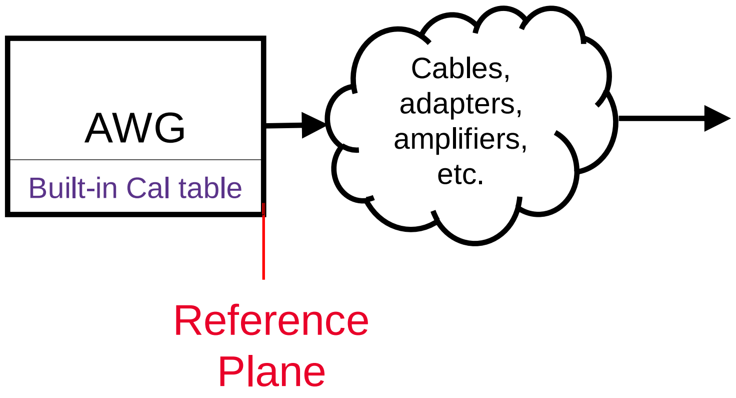
Receiver (RX)





Where is the Reference Plane?

AWG factory calibration



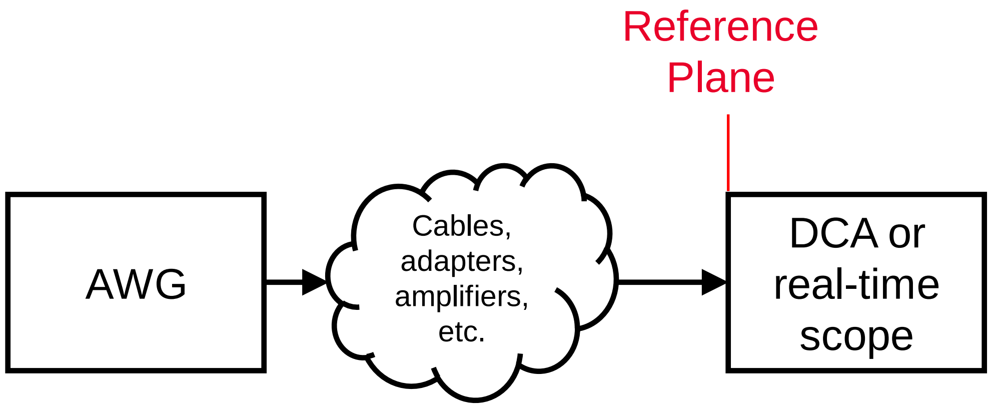
AWG

Built-in Cal table

Cables, adapters, amplifiers, etc.

Reference Plane

The desired reference plane location



Reference Plane

AWG

Cables, adapters, amplifiers, etc.

DCA or real-time scope

(required for calibration measurement)

It’s time for a demo…

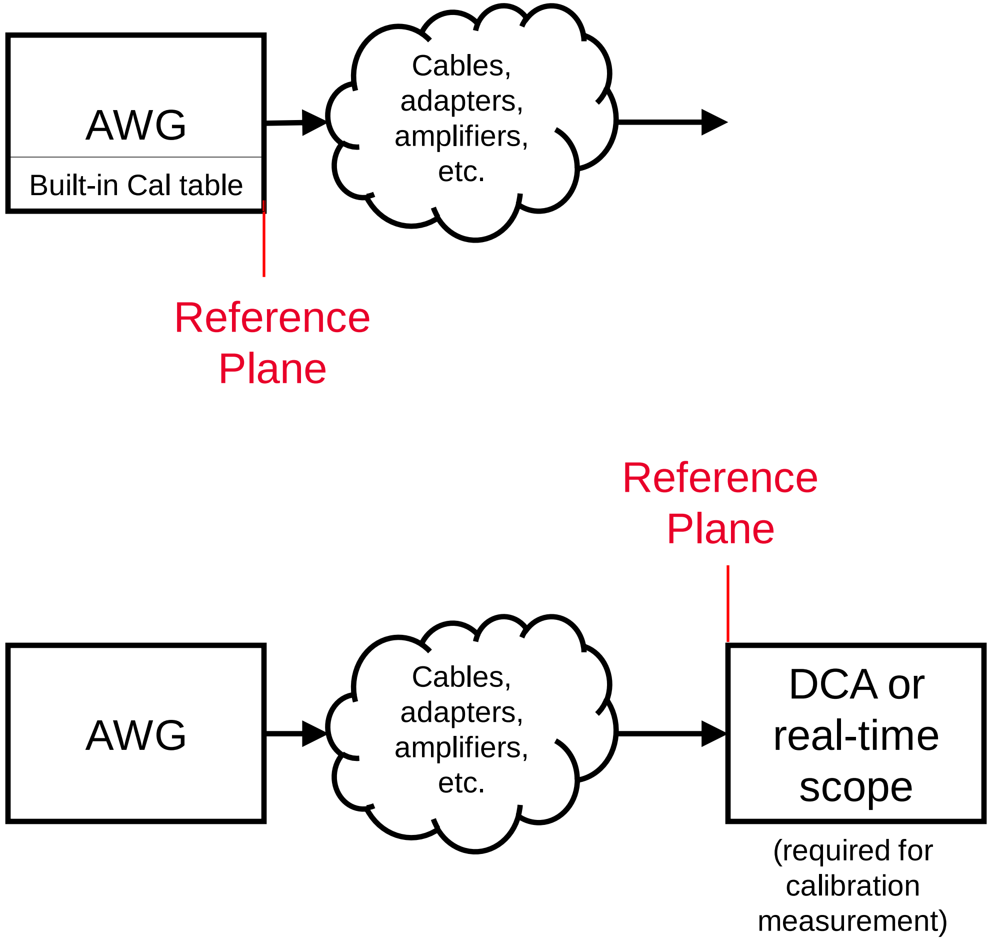
Agenda

AWG Workshop

- Arbitrary Waveform Generation Fundamentals
- Frequency Response Correction
- In-System Calibration
- Conclusion & Summary

Built-in Vs. In-system Frequency/Phase Response Calibration

- **Built-in correction**
  - No calibration measurement required
  - Additional circuits can be deembedded using S-parameters
- **In-system calibration**
  - More accurate
  - One-time calibration measurement required
  - Takes external circuitry into account
  - Setup does not need to be modified



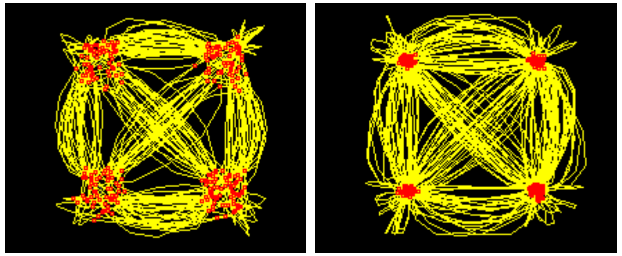
Accurate and Repeatable Test Results

Out-of-the-box calibration to ensure clean signal at the front connector

In-situ calibration – extend clean signal to the receiver test point

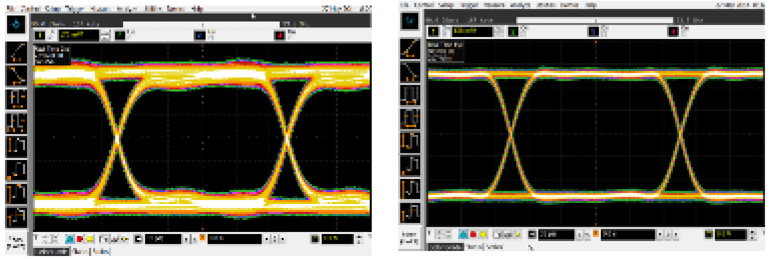
- S-Parameters of channel are embedded or de-embedded
- Frequency/phase response is measured in-system and then de-embedded

QPSK, 32 Gbaud



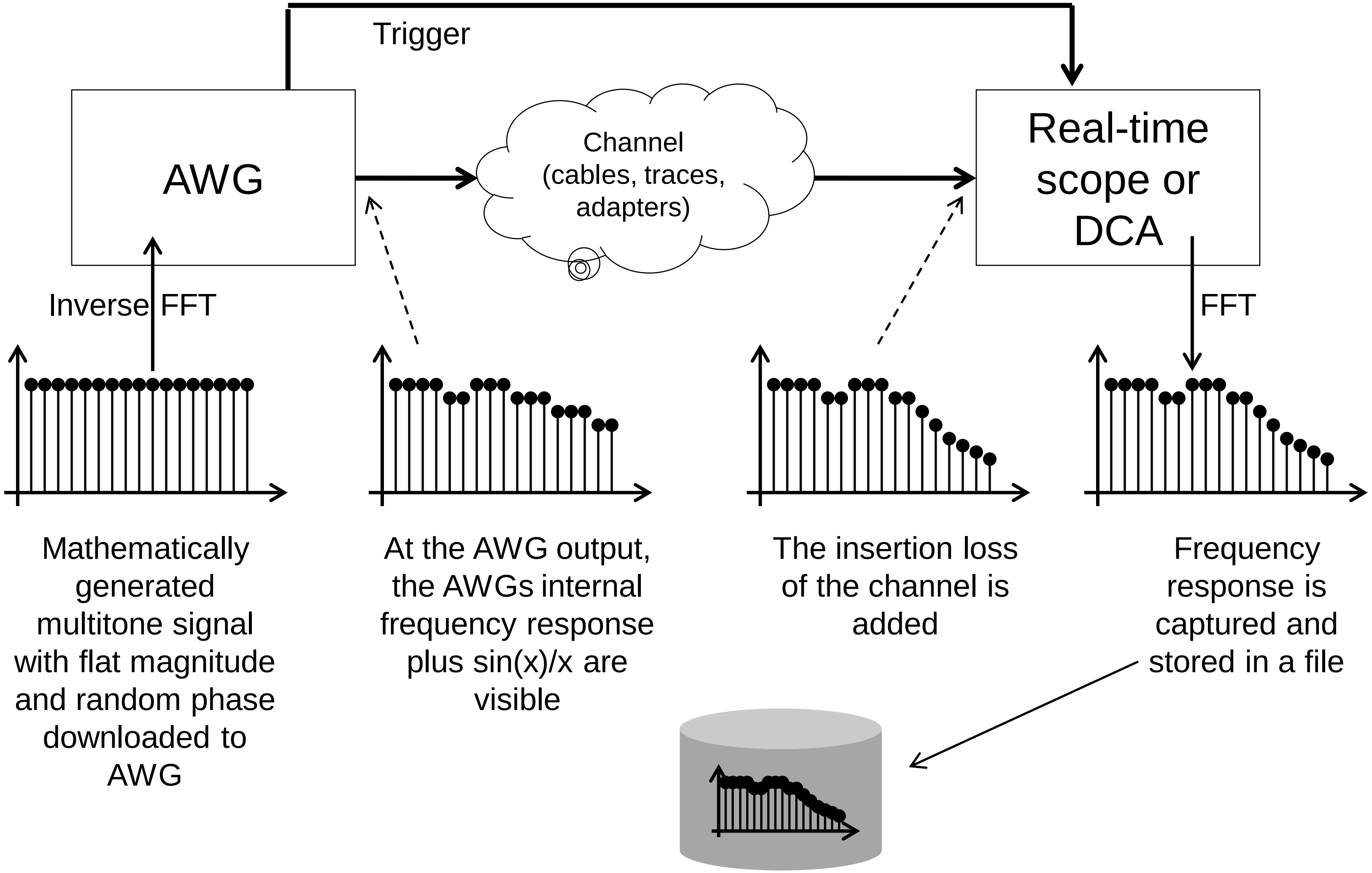
Without correction With correction

PRBS 6 Gbit/s



Without correction With correction

How Does In-system Calibration Work?



Trigger

AWG

Channel (cables, traces, adapters)

Real-time scope or DCA

Inverse FFT

FFT

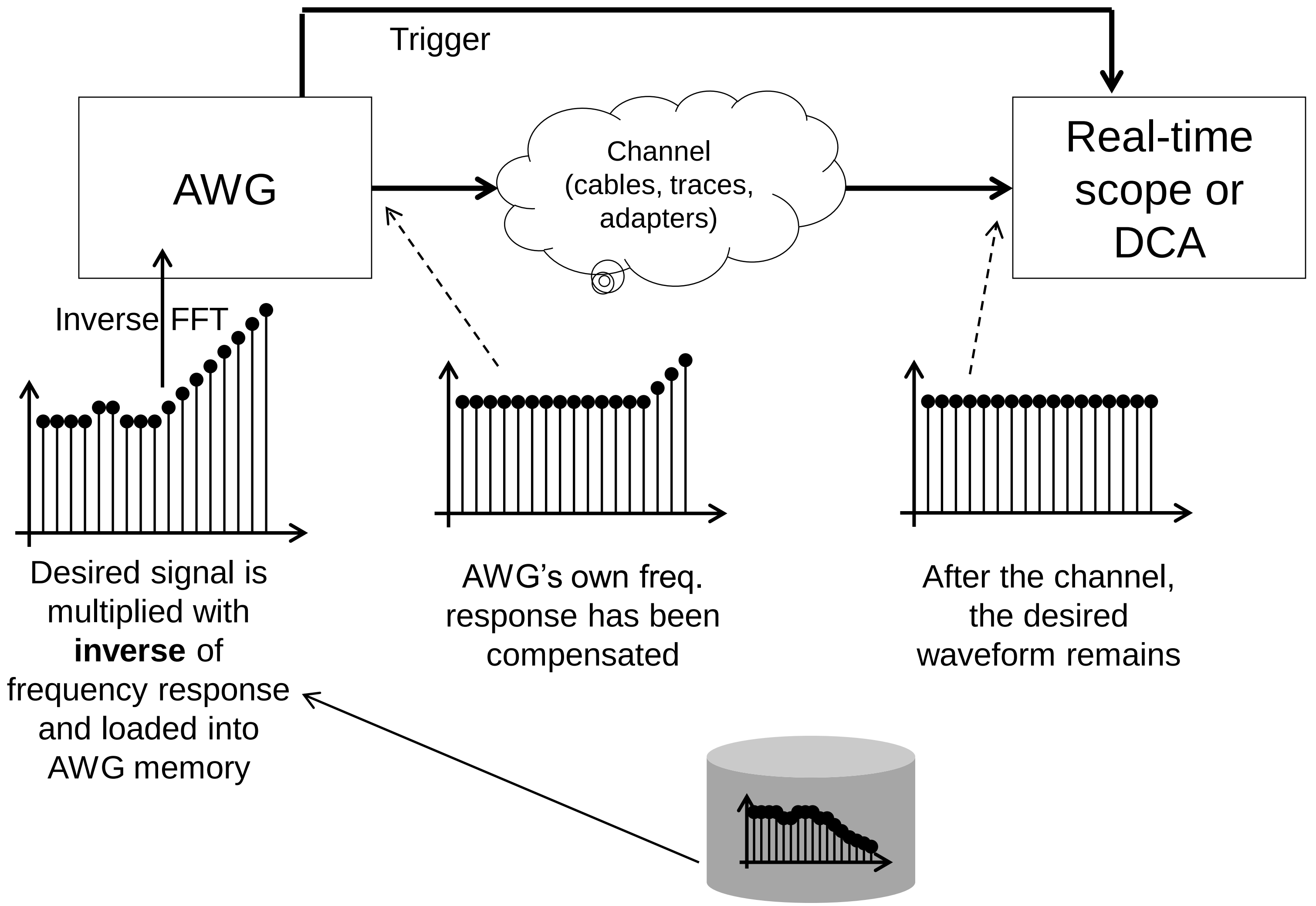
Mathematically generated multitone signal with flat magnitude and random phase downloaded to AWG

At the AWG output, the AWGs internal frequency response plus sin(x)/x are visible

The insertion loss of the channel is added

Frequency response is captured and stored in a file

How Is In-system Calibration Applied?



Desired signal is multiplied with **inverse** of frequency response and loaded into AWG memory

AWG's own freq. response has been compensated

After the channel, the desired waveform remains

It’s time for a demo…

Agenda

AWG Workshop

- Arbitrary Waveform Generation Fundamentals
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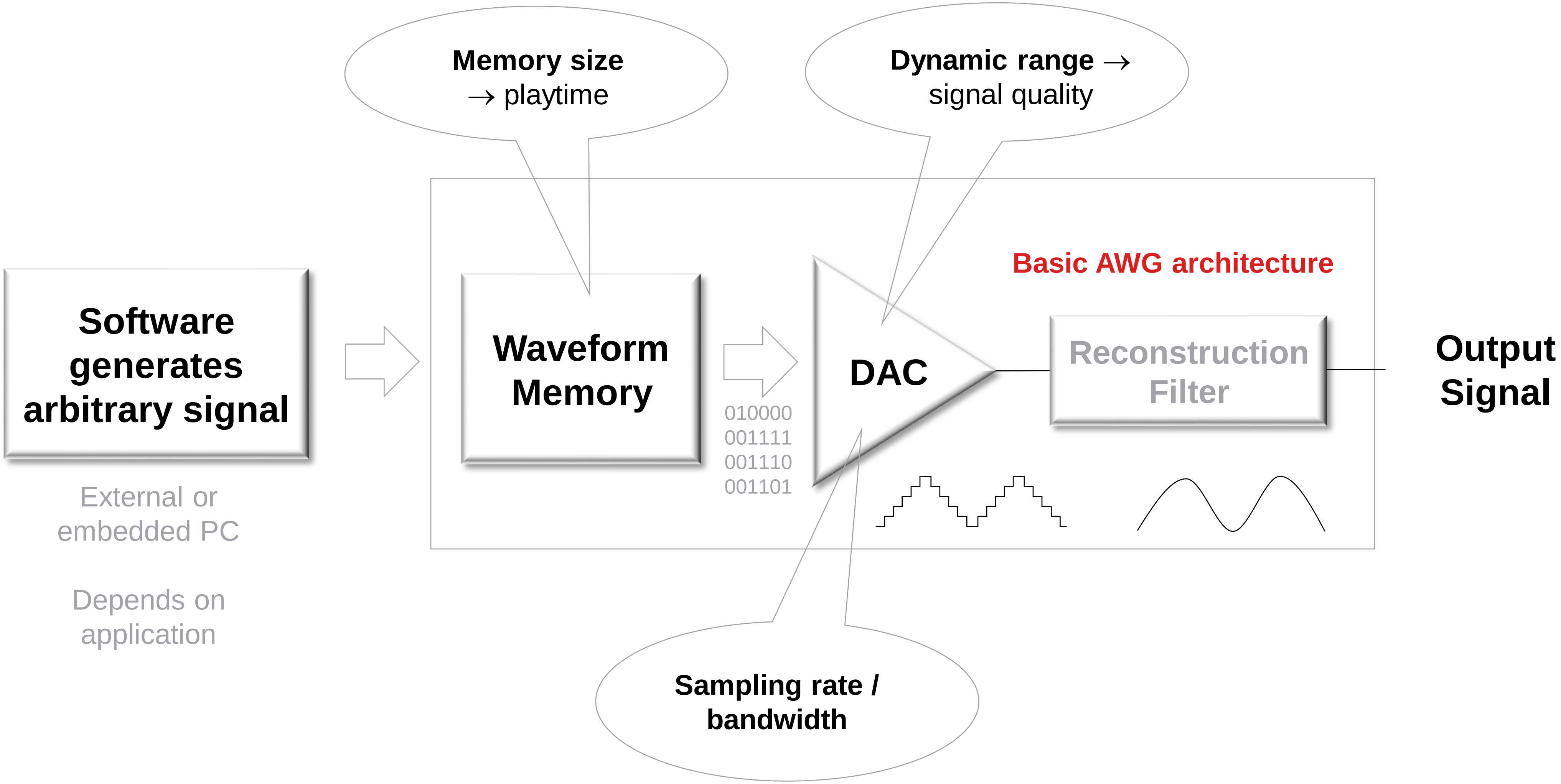
Review of the Previous

Key Blocks and Specifications



Memory size → playtime

Dynamic range → signal quality

Basic AWG architecture

Software generates arbitrary signal

External or embedded PC

Depends on application

Waveform Memory

DAC

Reconstruction Filter

Output Signal

Sampling rate / bandwidth

Short Quiz

Question 1

Which of the following is not true about AWGs?

a) AWGs provide more flexibility in generating pulse shapes and pre-distortion than pulse generators typically do

b) AWGs typically can’t generate multiple carriers

c) AWGs typically have wider modulation bandwidth vs signal generators

d) AWGs typically have less dynamic range than signal generators

Short Quiz

Question 1

Which of the following is not true about AWGs?

a) AWGs provide more flexibility in generating pulse shapes and pre-distortion than pulse generators typically do

b) AWGs typically can't generate multiple carriers

c) AWGs typically have wider modulation bandwidth vs signal generators

d) AWGs typically have less dynamic range than signal generators

Short Quiz

Question 2

The sampling frequency for an AWG should be at least twice the highest frequency contained in the signal.

a) True

b) False

c) Other…

Short Quiz

Question 2

The sampling frequency for an AWG should be at least twice the highest frequency contained in the signal.

a) True

b) False

c) Other…

Short Quiz

Question 3

Using s-parameters to simulate the effects of running a signal through additional channels is called

a) De-embedding

b) Embedding

Short Quiz

Question 3

Using s-parameters to simulate the effects of running a signal through additional channels is called

a) De-embedding

b) Embedding

Short Quiz

Question 4

An AWG’s playback time can be improved by

a) Decreasing its sample rate

b) Using other techniques such as sequencing

c) Both of these could improve an AWG’s playback time

Short Quiz

Question 4

An AWG’s playback time can be improved by

a) Decreasing its sample rate

b) Using other techniques such as sequencing

c) Both of these could improve an AWG’s playback time

Short Quiz

Question 5

An AWG's reconstruction filter limits the bandwidth and "smooths out" the waveform.

a) True

b) False

Short Quiz

Question 5

An AWG’s reconstruction filter limits the bandwidth and “smooths out” the waveform.

a) True

b) False

KEYSIGHT

Thank you

KEYSIGHT