Hideo Okawara's
Mixed Signal Lecture Series

DSP-Based Testing – Fundamentals 47
Coherent Waveform Reconstruction

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Preface to the Series

ADC and DAC are the most typical mixed signal devices. In mixed signal testing, analog stimulus signal is generated by an arbitrary waveform generator (AWG) which employs a D/A converter inside, and analog signal is measured by a digitizer or a sampler which employs an A/D converter inside. The stimulus signal is created with mathematical method, and the measured signal is processed with mathematical method, extracting various parameters. It is based on digital signal processing (DSP) so that our test methodologies are often called DSP-based testing.

Test/application engineers in the mixed signal field should have thorough knowledge about DSP-based testing. FFT (Fast Fourier Transform) is the most powerful tool here. This corner will deliver a series of fundamental knowledge of DSP-based testing, especially FFT and its related topics. It will help test/application engineers comprehend what the DSP-based testing is and assorted techniques.

Editor's Note

For other articles in this series, please visit:
http://www1.verigy.com/ate/support/ttrc/tstmthds/index.htm

Preface

"Coherent Waveform Reconstruction" is already discussed several times in the previous issues. In the V93000 SOC Tester there is actually a handy API "DSP_SHUFFLE()" available for performing this task. It is so useful processing that it is utilized in various situations. In this article, let's look at how data is processed inside and check what kind of applications it is practically applied to for refreshing your memory.

Basic Theory

A sinusoidal waveform can be drawn as the projection of a rotating vector. Figure 1 illustrates a vector rotating in the left-hand side. When the vector rotates 5 times, its projection forms 5 cycles of sinusoidal waveform as shown in the right-hand side.

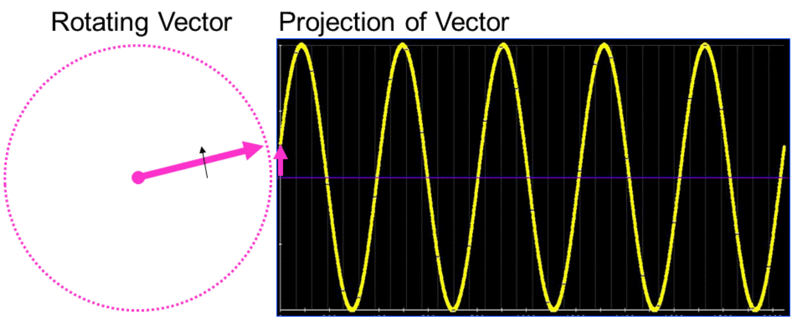

Figure 1: Rotating Vector and Its Projection

Figure 2 illustrates the 5 (=M) cycles of sinusoidal waveform is sampled at 32 (=N) sampling strobes. The sampled points are marked with colored dots on the trace. The different coloring distinguishes each cycle or rotation. There are 5 vector plains illustrated in the lower half of Figure 2. They show where the rotating vector is located at each time of sampling. The key is that each one of the sampled points resides different primary phase of the sinusoid.

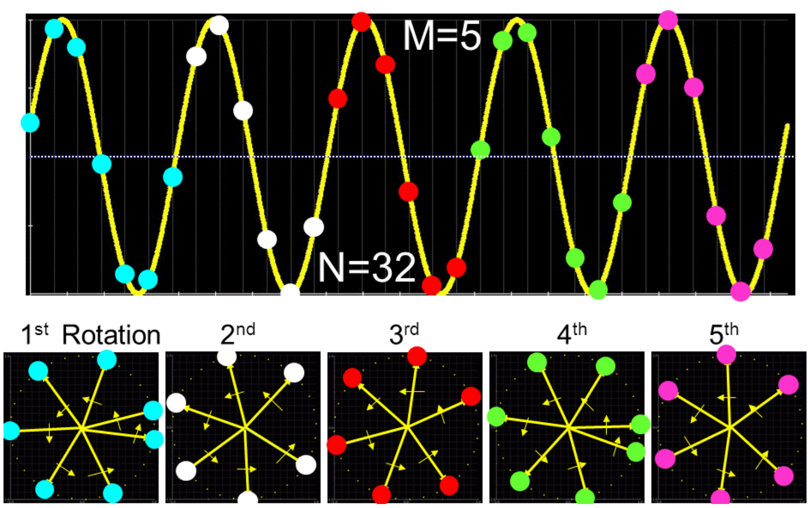

Figure 2: 5-Cycle Sampled at 32 Strobes

Therefore, when the 5 vector plains in Figure 2 are overlaid in one plain, each one of the sampled points can be aligned in a circle depicted as Figure 3. The key in the figure is that each colored point does not take any duplicate seat so that they are very well aligned on a single circle.

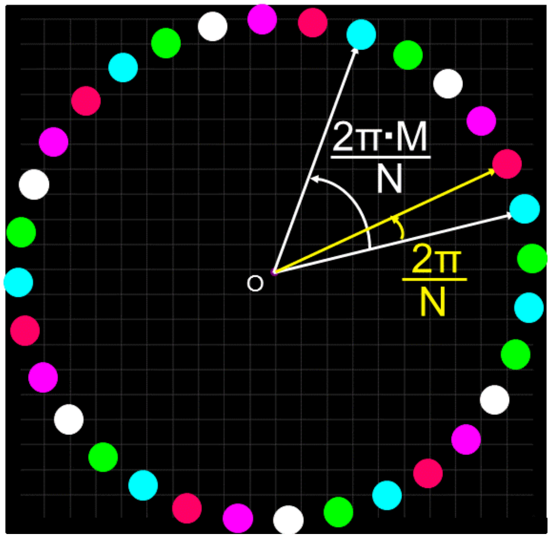

Figure 3: 5 Rotation Plains Overlaid

This is because M (=5) and N (=32) do not have any common divisors at all. This is called a coherent condition. When looking at Figure 3, the same colored dots rotate $2\pi M/N$ [rad] every time. The whole 32 dots are aligned in a single circle so that the phase rotation of each one of the dots is $2\pi/N$ [rad].

The circle or rotating vector shown in Figure 3 would project a single cycle sinusoidal waveform. This fact implies that if the relationship of M and N is coherent, M cycles of sinusoidal waveform can always be reshuffled into a single cycle of sinusoid. Figure 4 illustrates how it is reshuffled. The single cycle sinusoid in Figure 4 corresponds to the projection of the circle in Figure 3.

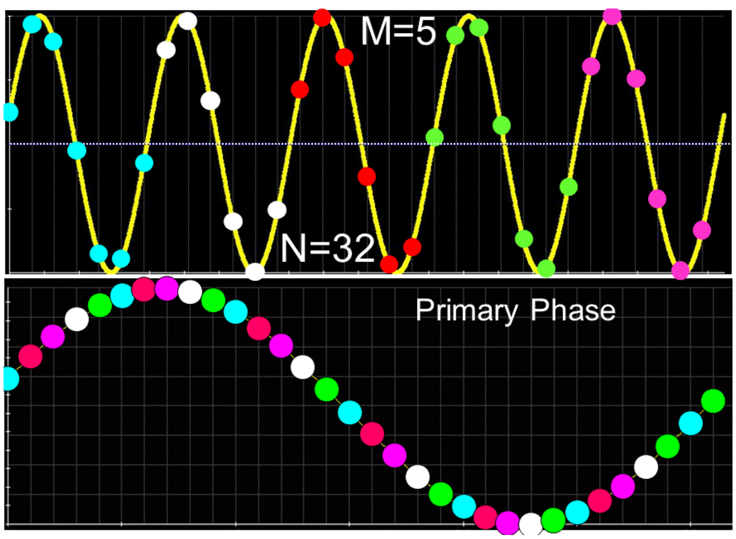

Figure 4: 5-Cycle Reshuffled into 1-Cycle

In a mixed signal test, when you capture M cycles of sinusoidal waveform in N points of data, if M and N are coherent with each other, you can reshuffle the captured data and reconstruct it as a single cycle of sinusoid without duplication. In general, this reshuffling is called a coherent waveform reconstruction. This is a handy technique in the practical testing venues. Therefore, a specific API is provided in the V93000 SOC Tester as follows;

```
DSP_SHUFFLE(M_Cycle_Sinusoid_Array, One_Cycle_Sinusoid_Array, M);
```

This API works fine for a waveform conforming with the coherent condition. In reality you may not always make up your test condition as coherent for various restrictions and reasons. Then the API might hit an exception error. Even for non-coherent situation, you may want to perform reshuffling. If it is not coherent, duplication occurs so that multiple points would fall in each of the limited number of seats. Therefore, if you perform the reconstruction processing by your own program code, you could work around the error. List 1 shows an example coding based on Figure 3.

```
10:   int    i,k,M,N;
11:   double d2PI,dP,dQ,dR;
12:   ARRAY_D dVorg; // Input Waveform
13:   ARRAY_D dWave; // Reshuffled Waveform
14:
15:// “dVorg” holds the input waveform.
16:// It assumes containing 5 cycles of signal.
17:
18:   M=5;              // # of signal cycles
19:   N=dVorg.size();   // # of data
20:   dWave.resize(N); // Create Output Container
21:   dWave.init(0.0); // Initialize Container
22:
23:   d2PI=2.0*M_PI;
24:   dP=d2PI*M/N;
25:   dQ=d2PI/N;
26:
27:   dR=0.0;
28:   k=0;
29:   for (i=0;i<N;i++) {
30:      dWave[k]=dVorg[i];
31:      dR=dR+dP;
32:      dR=dR-(int)(dR/d2PI)*d2PI;
33:      k=(int)(dR/dQ+0.5);
34:   }
35:
```

List 1: Example Code for Reshuffling

The array dVorg[] is the container of the input data containing multiple cycles of waveform, and the array dWave[] is the output container which will be filled with reshuffled data – a single cycle of waveform at the end. If the condition is coherent, each one of the output array component is completely filled up with one of the input data points. If the input waveform does not conform with the coherent condition, duplication occurs and some of the output array component cannot be filled up with any data. It is not good that variables are empty from the programming point of view. Therefore, dWave[] should be initialized as Line 21 so that it would not cause an error even if the condition is not coherent.

Practical Applications

As mentioned, coherent waveform reconstruction is very useful and applied in many situations. Let's look at some practical examples.

Simple Sinusoidal Test

A sinusoidal waveform is the most typical test signal in testing venues. A single tone, dual tones and multi-tones are employed in various situations. The first example is a single tone sinusoid test. Figure 5 illustrates the configuration. A DAC generates a 3762.5 Hz tone which is measured by a digitizer at the sampling rate of 102.4 ksps. When you develop a test program and start an online debug, the first thing you should do is a quick check to verify if the test condition is correctly programmed.

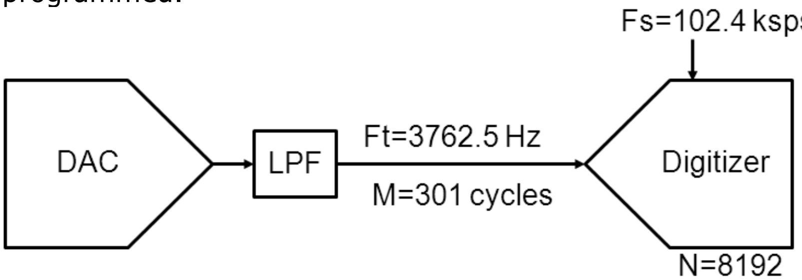

Figure 5: Simple Sinusoidal Waveform Test; Configuration and Condition

Figure 6 shows the measured waveform. The digitizer captures 8192 points of data containing 301 cycles of sinusoid. The raw waveform shown in Figure 6 (a) is too dense to see if a correct waveform is programmed and captured or not. Just perform the coherent waveform reconstruction, then the reshuffled waveform looks as (b) so that you can understand it is a good sinusoid at a glance. There is neither saturation nor collapsed pattern found in (b). So you can confidently move forward to analyze the waveform and pick up performance parameters by using the FFT, etc.

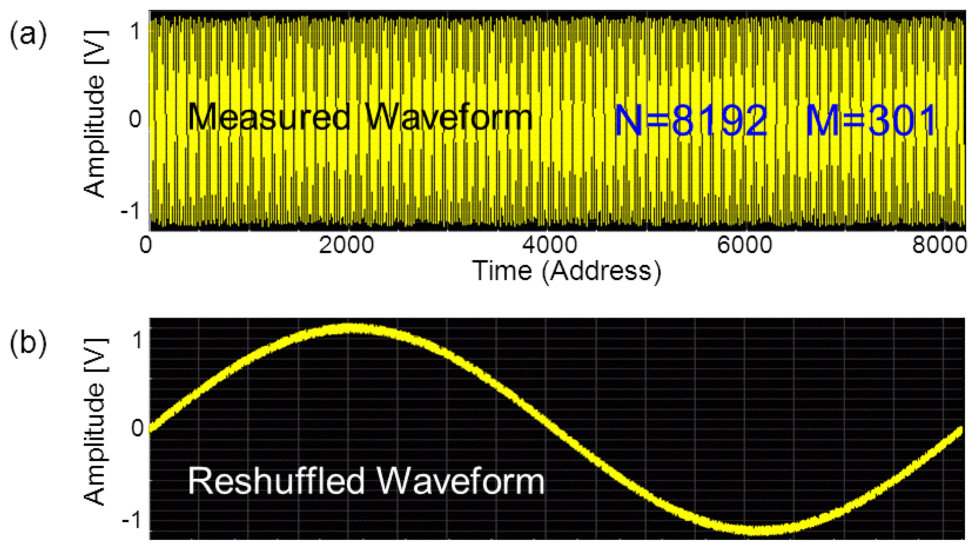

Figure 6: Simple Sinusoidal Waveform Test Result

Eye Diagram Test

This is a digital functional test. Figure 7 illustrates the test configuration. A PS9G driver generates 127-bit PRBS bit stream at the bit rate of 2 Gbps, which is captured by another PS9G receiver comparator. The sampling speed is set 8.06299212598 Gbps and the 1024-bit expected data is set all "H". This condition means that the unit-test-period of the 1024-bit functional test exactly matches the duration of 2 times 127-bit PRBS that is total 254 unit intervals (UI). This functional test is repeated while modifying the threshold voltage from -0.5 V to +0.5 V by 10 mV step, total 100 steps.

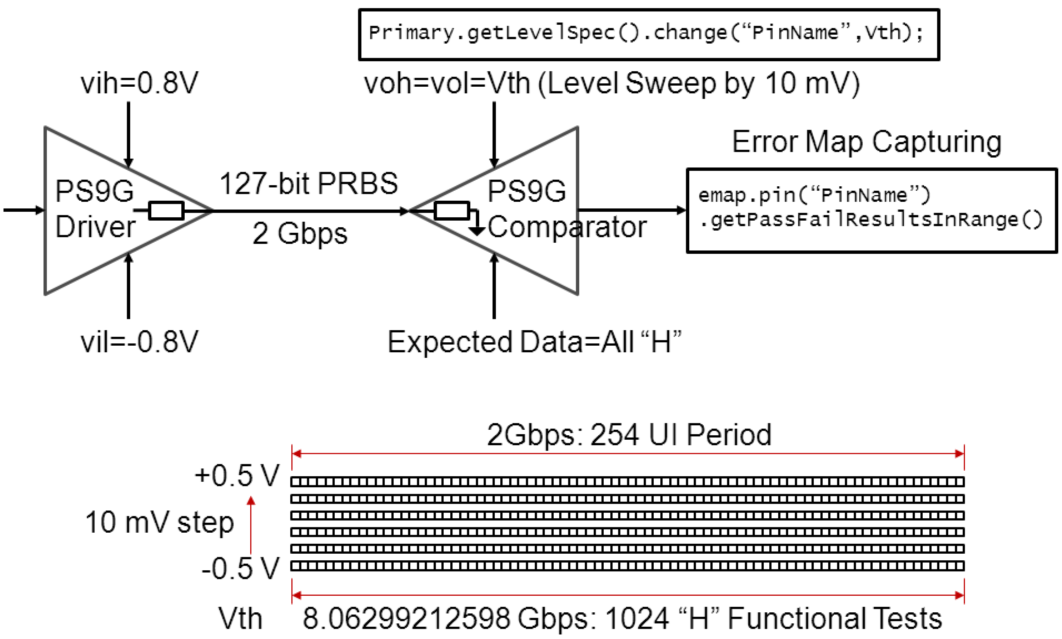

Figure 7: Digital Functional Test; Configuration and Condition

A pin comparator can be considers as a 1-bit waveform sampler. Each one of the error map patterns of the multiple functional tests means that the signal existing possibility at each threshold level. When completing the entire functional test sweeps, if you count the numbers of PASS and FAIL at each sampling strobe and plot the ratio of PASS and FAIL, you can reveal the PRBS waveform as shown in Figure 8. This is much faster than the method of DIGITAL_WAVEFORM() that sweeps the strobe timing by a small step and the threshold levels by a small step respectively.

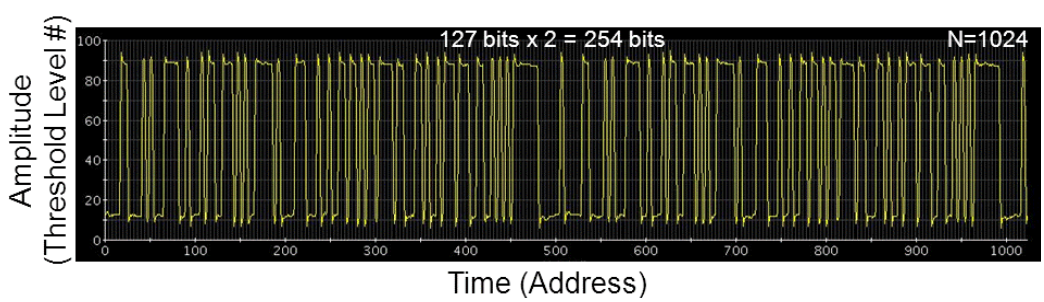

Figure 8: DNA Measurement: 2 Loops of 127-bit PRBS Capturing

There are total 254 bits of the bit stream captured in 1024 points in Figure 8. When you perform the coherent waveform reconstruction to the whole waveform by the factor of 127, the PRBS waveform is automatically converted into en eye diagram shown in Figure 9. In this case, the combination of

M=127 and N=1024 is coherent so that reshuffling works fine. This method is known as “DNA (Data aNAlysis).[1]” The reason that total 254 bits of data are captured here is that the final eye diagram is planned to make an eye of 2-UI time.

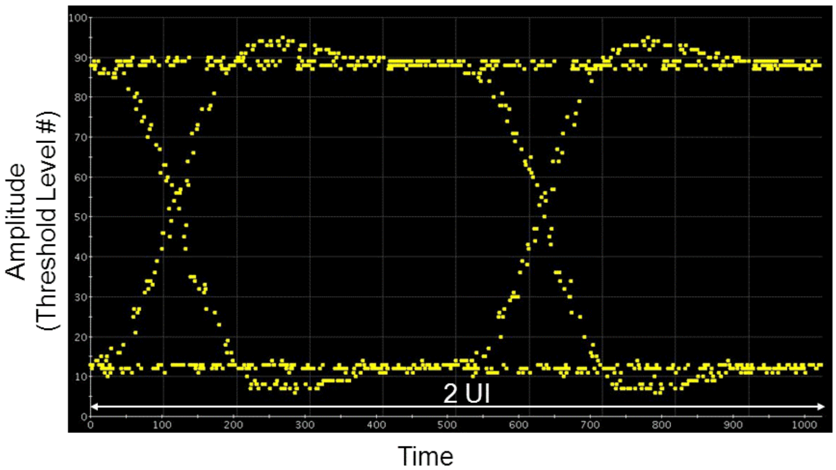

Figure 9: Eye Diagram

Wideband Signal Spectrum Test

Figure 10 illustrates the simplified test configuration. MCC is the module ID of 6GQS that is the 6GHz bandwidth waveform sampler whose analog bandwidth reaches up to 10GHz actually. The test signal is a wideband signal, which is generated by using digital pins here. The signal contains 8192 bits of data running at the speed of 8.96 Gbps. The purpose of the measurement is to capture the signal spectrum up to 10GHz by using the waveform sampler.

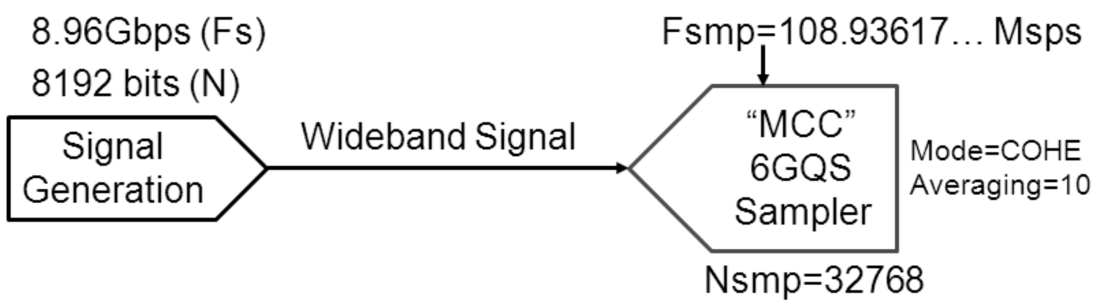

Figure 10: Wideband Signal Test; Configuration and Condition

The MCC can run at the speed of maximum 110 Msps so that its Nyquist bandwidth is 55 MHz. Therefore, you are apt to think that a single measurement can capture a <55 MHz bandwidth signal so that you need to do multiple measurements for the target larger than 55 MHz bandwidth. However, this is not true. It can take DC to 10 GHz span with a single measurement.

Look at Figure 11 showing the page concept of under-sampling. Extremely wideband could be folded and degenerated into a single baseband page[2]. The 55 MHz band in the discussion above is the baseband. You can force lots of spectral lines in the baseband so that you can measure extremely wideband signal at a single measurement. This is really a thrill of under-sampling.

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[1] Jinlei Liu, “Data Analysis on PinScale3600”, VOICE (User Group Meeting) Presentation, Agilent Technology 2006

[2] Hideo Okawara, “DSP-Based Testing Fundamental 27; Multi-tone Under-sampling Conditioning”, go/semi 2010

According to Figure 10, let's see the decision making process of the test condition as follows;

1. Signal Domain
   - Fs=8.96 GHz, N=8912, then the signal spectrum resolution ΔF=Fs/N
   - In order to see up to 10 GHz, the number of spectrum L~10000
2. Sampler Domain
   - Fsmp~110 Msps, Nsmp>2L=20000 so that let's make Nsmp=32768
   - The sampler spectrum resolution Fres=Fsmp/Nsmp
3. Fres x Nx = ΔF   and   Nx = Odd Integer
   - Nx=(Fs/N)(Nsmp/Fsmp)=329   (decision)
   - Fsmp=(Fs/N)(Nsmp/Nx)=108.93617021.. Msps

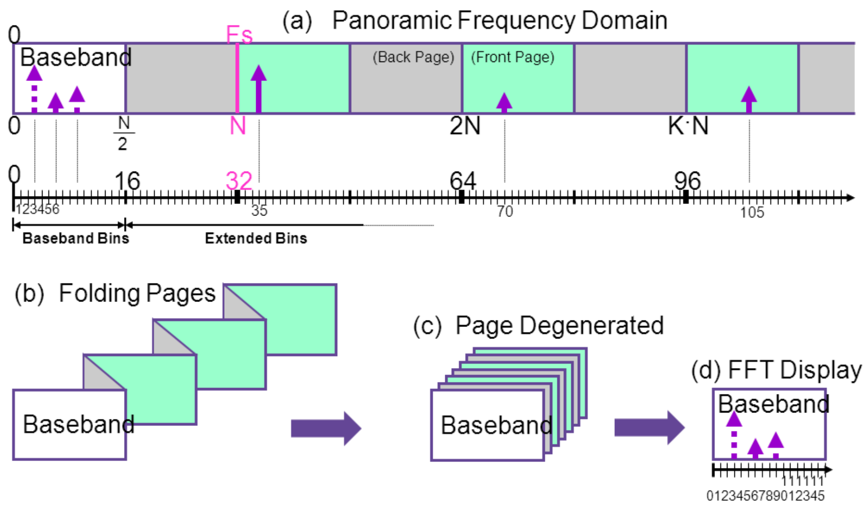

Figure 11: Page Concept of Under-sampling

This is the way the MCC sampling rate is precisely decided. Using these conditions, the MCC captures the waveform as shown in Figure 12 (upper graph). Its FFT spectrum is shown in the lower graph, which does not show any meaningful result, because the original waveform is scrambled.

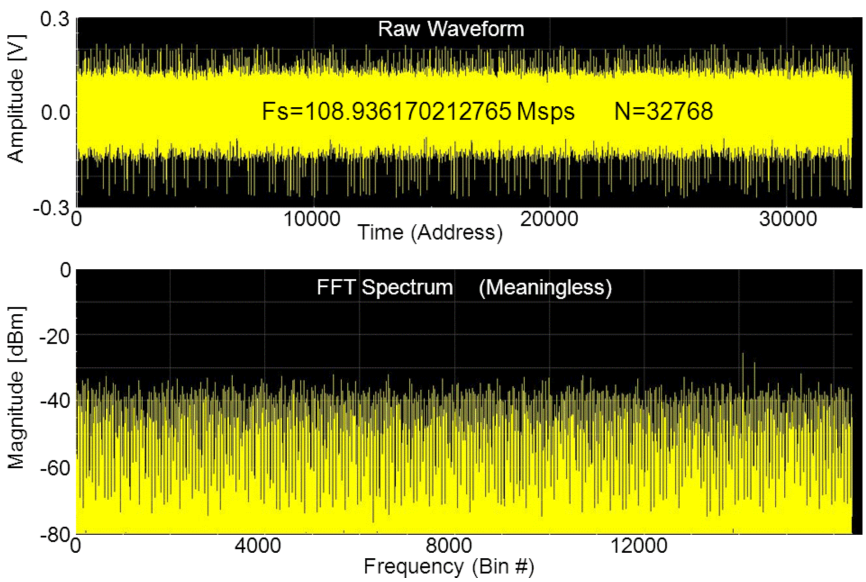

Figure 12: Measured Waveform and Spectrum (Raw)

The first procedure is to reshuffle the raw waveform to reconstruct an expected waveform by the factor of Nx (=329). Figure 13 shows the reshuffled waveform and its FFT spectrum. Now the spectrum shows an expected appearance.

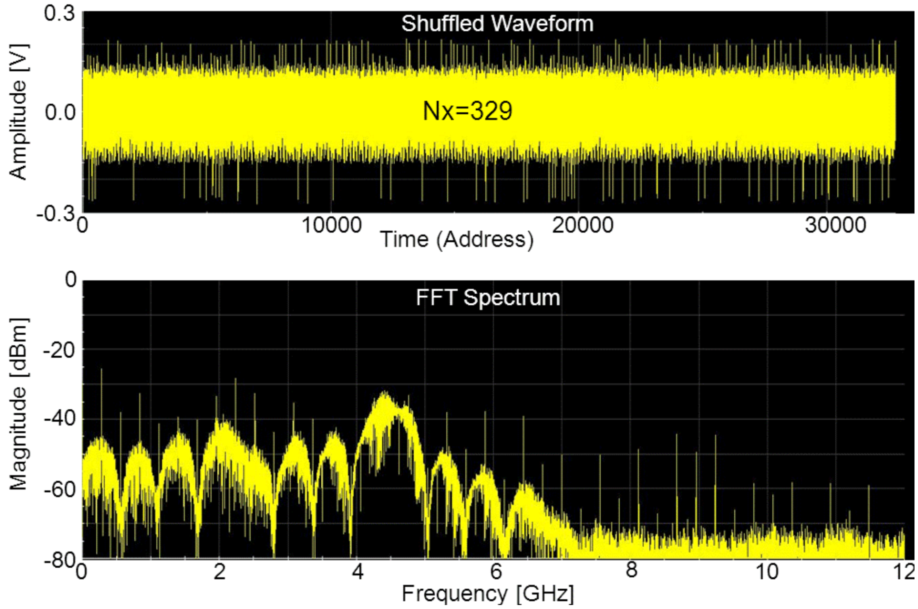

Figure 13: Reshuffled Waveform and Spectrum

In order to validate this particular spectrum, the test signal in Figure 10 is measured by the Agilent E4440A spectrum analyzer. Its display dump is shown in Figure 14 (right). Two spectrum displays are really correlated so that you are convinced that the under-sampling is as successfully performed by the MCC as planned.

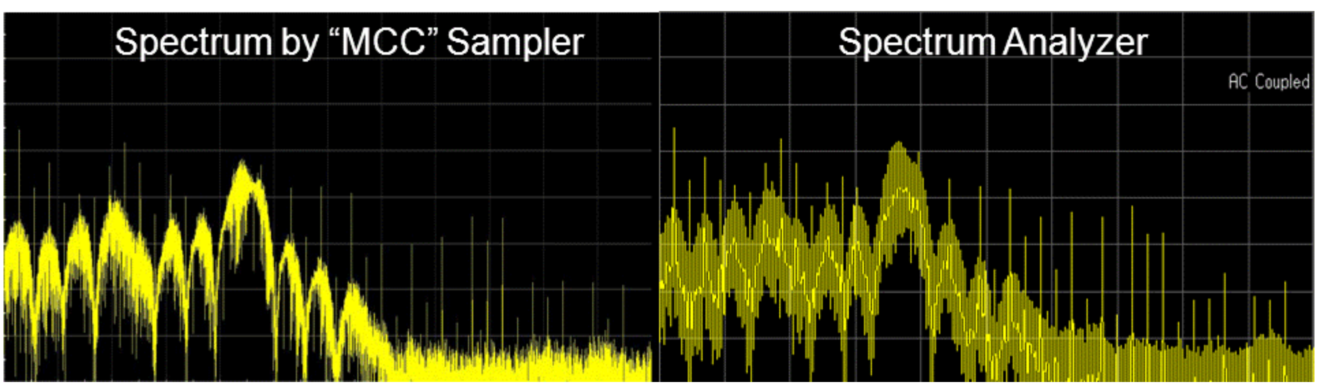

Figure 14: Spectrum Comparison by Waveform Sampler vs. Spectrum Analyzer

There are three typical applications of coherent waveform reconstruction demonstrated. Author hopes that readers are impressed how it is effective and useful.