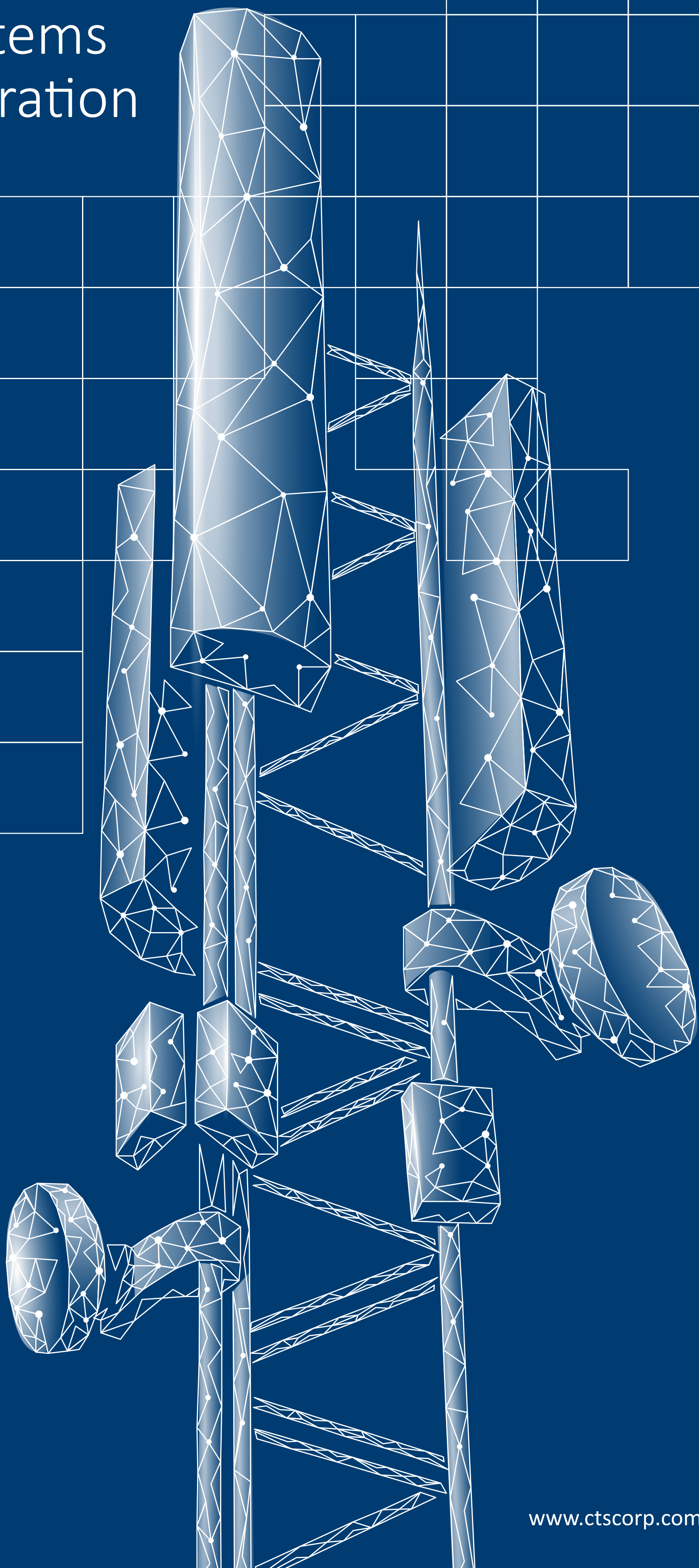
# Precision Timing – 5G mmWave (NR) Systems and Noise Consideration



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Whitepaper

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# Contents

## INTRODUCTION

As demand for video, voice and data increases, both at fixed and mobile networks, information “pipelines” must be broadened, and transmission speed must be enhanced.

5G communication networks offer service providers multiple choices to allow increased capacity and speed, such as applied higher speed modulation techniques, and multiple transmission channels at higher frequencies.

While modulation speed, added multiple channels, increased bandwidth and transmission frequencies offer advantages when it comes to capacity enhancement, they also introduce challenges when it comes to noise generation and noise tolerance. In this whitepaper, we will address noise in wireline systems (re: jitter) and in wireless systems (re: Error Vector Magnitude (EVM), major contributors for increased noise levels, and relationship to signal sources.

## HIGH FREQUENCY AND INCREASED SENSITIVITY TO NOISE

As transmission frequency and data modulation bandwidth increase, sensitivity to noise becomes a factor to address. In wireless systems, we analyze signal performance in the frequency domain; where phase noise and EVM figures are used as indicator values.

| The main contributors for high noise figures in wireless systems are: | In wireline systems we qualify system noise level using: |
|---|---|
| • D/A & A/D – conversion<br>• Crosstalk - Mismatch<br>• Frequency Multiplication (PRC &Synthesis)<br>• PA & LNA SNR<br>• Transmission Frequency<br>• Modulation BW | • A/D – conversion<br>• Crosstalk - Mismatch<br>• Frequency Multiplication (Synthesis)<br>• Transmission Frequency<br>• Modulation BW |

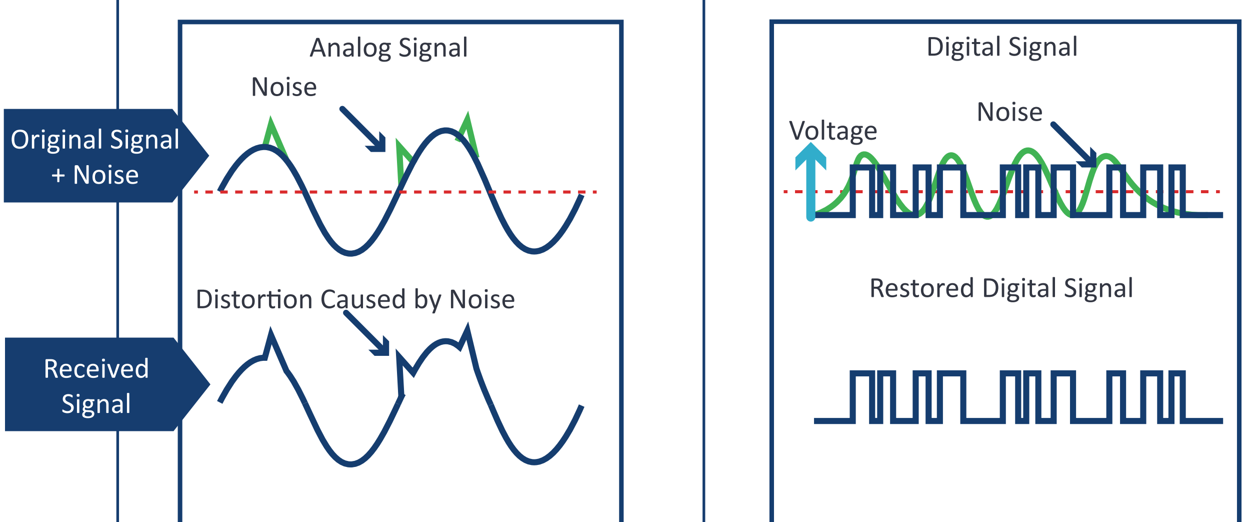


*Figure 1: Analog Signal and Digital Signal Correlation*

## NOISE CORRELATION BETWEEN FREQUENCY DOMAIN AND TIME DOMAIN

Signal measured/viewed in time domain vs. frequency domain could be interrelated mathematically through Fast Fourier Transform (FFT). Figure 2 displays noise mapped in the frequency domain and Figure 2a illustrates FFT and jitter calculations.

This correlation is very handy specifically when evaluating signal performance as well as noise in different applications. In digital applications such as fiber optics or ethernet transmission, Bit Error Rate (BER) and jitter (re. Time Domain Noise level) must be examined to avoid any loss of data packets. On the other hand, in wireless communication, frequency related noise is critical to guage proper functionality of the radio with high Signal to Noise Ratio (SNR) and low EVM.

Viewed in the frequency domain (Figure 2), we can see the carrier frequency while harmonics and spurious noise are observed as sidebands when measured with a spectrum analyzer. Figure 2a shows Fast Fourier Transform (FFT) and jitter calculations. See Figure 2a and Figure 2b.

When the 3D view is rotated by 90° into the time domain, note the blending of the carrier signal with harmonics and non-harmonic responses. See Figure 2c.

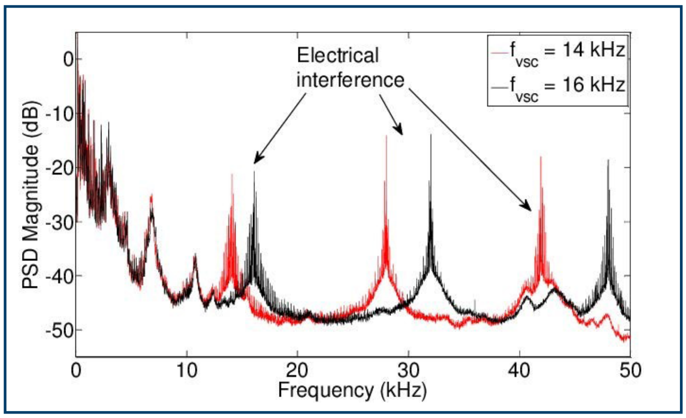


*Figure 2: Noise mapped in the frequency domain*
*Smith, Wade & Deshpande, Lav & Randall, R.B. & Li, Huaizhong. (2013). Bearing diagnostics in a planetary gearbox: a study using internal and external vibration signals.*

**Fast Fourier Transform (FFT)**
*Used for digitized waveforms where:*
F[k] = sample in frequency
f[n] = sample in time
n = time index
k = frequency index
N = number of samples
*N must be a power of 2 ( e.g. 256, 512, 1024)*

$$F[k] = \sum_{n=0}^{N-1} f[n] \cdot e^{-i2\pi k \frac{n}{N}}$$

*Figure 2a: FFT piecewise noise conversion to time domain*

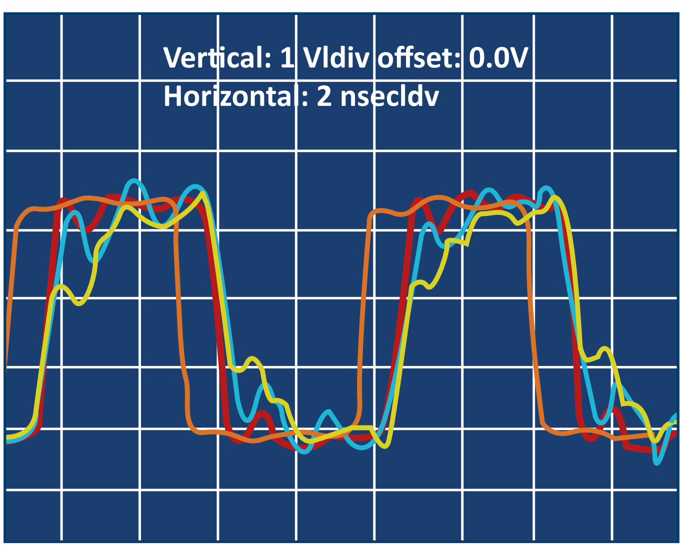


*Figure 2b: Noise mapped in the time domain*

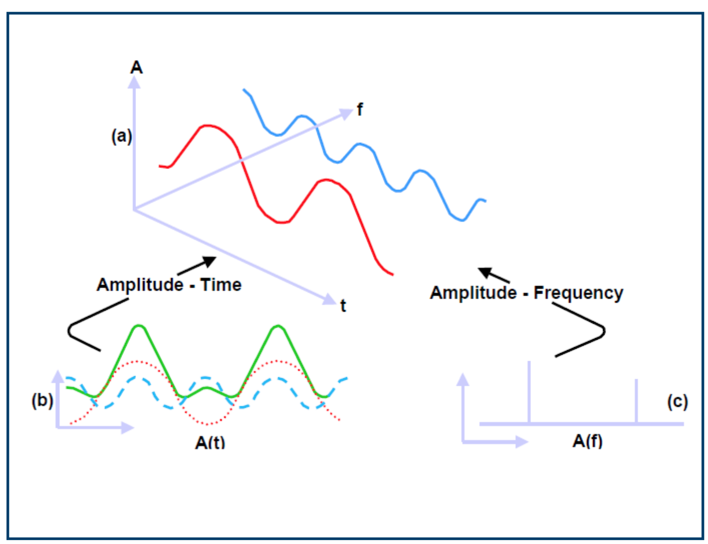


*Figure 2c: Frequency vs. time domains*

## HIGH FREQUENCY + HIGHER MODULATION RATE = HIGHER SENSITIVITY TO NOISE

Designing a system operating at a higher carrier frequency and higher modulation bandwidth requires an understanding of the challenges that come with it.  Generating high frequency transmission signal requires a high multiplication factor from the system's prime reference clock (PRC) unit. Whenever a multiplication of a local reference clock or system clock that run at low frequency is multiplied up to a carrier frequency, it results in a loss of 6dB/decade (20*log(n)).

Another subsequent challenge of multiplication is signal mixing of harmonic and non-harmonic sidebands. Mixing signals during multiplication means an increase of spurious content, and sub-harmonics/harmonics that translate to a higher noise floor of the multiplied signal compared to the phase noise of the PRC.

Next-generation networks, (re: 5G sub 6GHz and mmWave applications) require operation at higher modulation rates reaching up to QAM 1024, with future upgrade to QAM 2048, that are sensitive to noise tolerance and noise generation by reference clocks as well as the entire system as a whole (PAs, couplers, switches, modulators, PLL, etc.).

In wireless systems, system noise is quantified through multiple parameters: SNR, phase noise, BER and ultimately EVM. EVM signifies the modulation accuracy and the transmission performance between the measured signal and its corresponding ideal point in the signal constellation display.

In wireline applications, we examine jitter performance: system jitter, local clock jitter, and transmitter's jitter. System jitter affects data transmission and reception accuracy. As demonstrated earlier, jitter is directly proportional to frequency and phase noise while using mathematical FFT transformation, within a bandwidth of interest.

## PHASE NOISE

Phase noise is defined as single side band (SSB) frequency domain view of the spectral noise around an oscillator center frequency signal ($f_o$). It combines short-term random noise fluctuations and white noise.

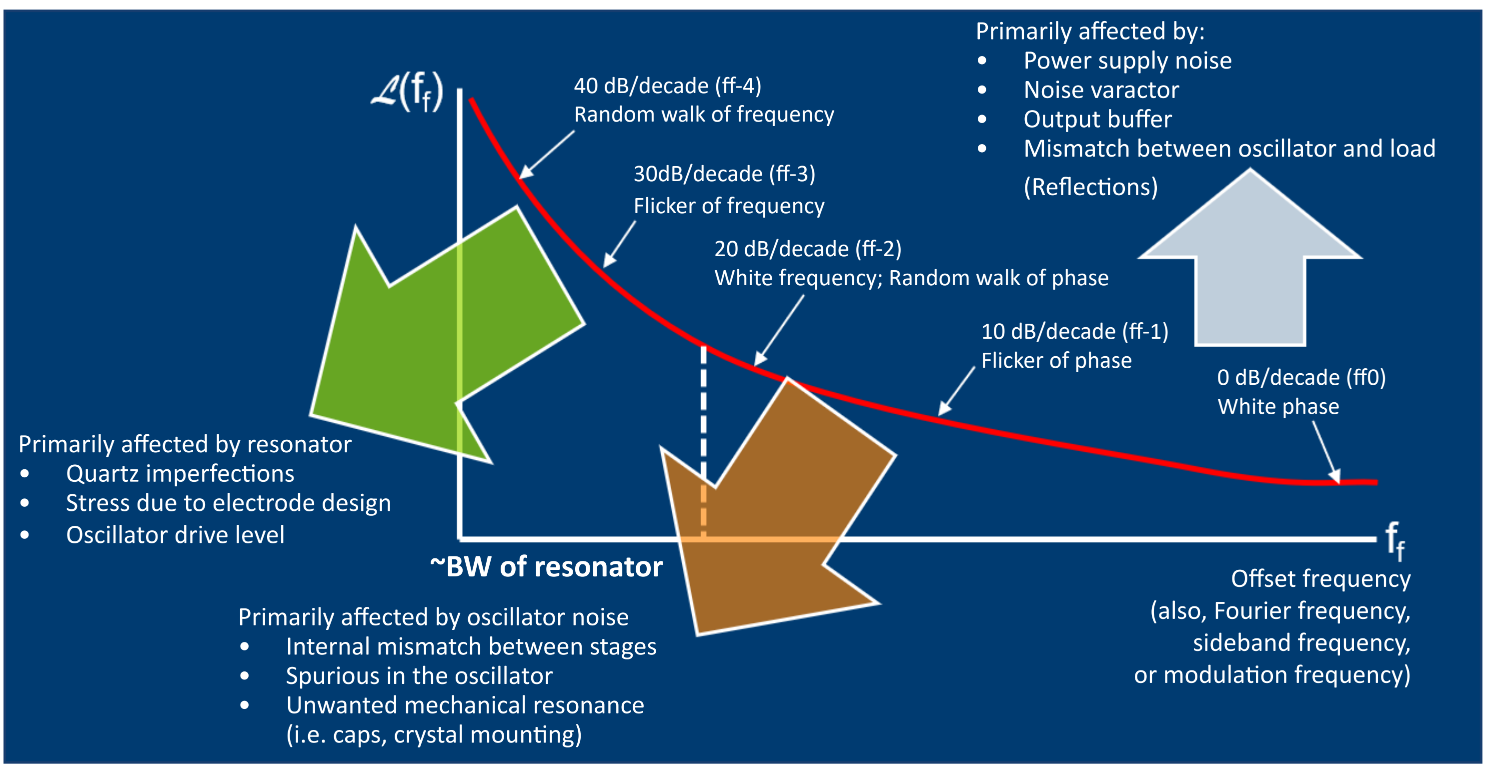


*Figure 3: Phase noise definition and interpretation*

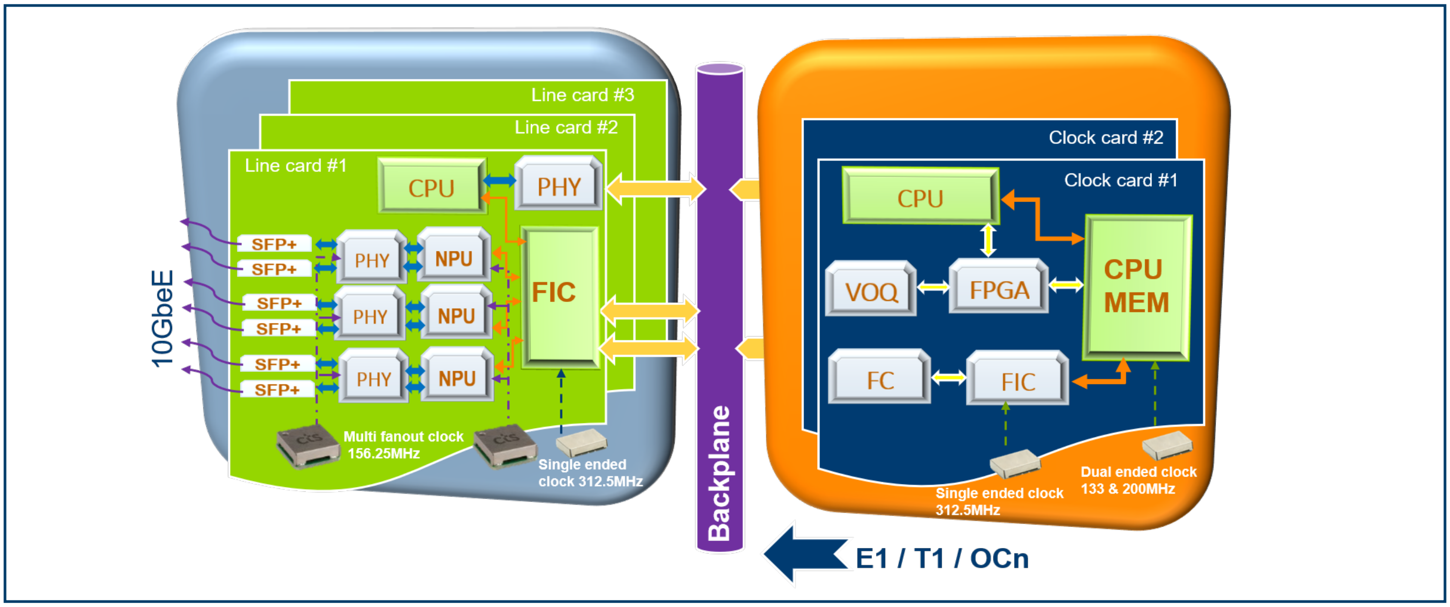


*Figure 4 - Wireline Switch Node - Timing*

## Example Application: Wireline Switching Node

A wireline switch with a gigabit ethernet backplane network reference includes a carrier frequency, as well as the data. As the reference signal is being extracted by the LIU, the LIU also contaminates the reference signal with noise. Frequency synthesizers are used to clean the jitter and perhaps multiply the base frequency up to a higher frequency and distribute the reference to subscriber line cards. In these cases, the main functionality of the synthesizers is to reduce system noise so that it does not corrupt the recovered data packets that could be generated by the node.

### *Time Domain "Noise" = Jitter*

ITU-T defines jitter as short-term variations of the significant instants of a digital signal from their ideal positions in time.

Rising and falling edges in a digital data stream never occur at exact desired timing; defining and measuring accurate timing of such edges concerns and affects performance of synchronous communication systems.

### *Jitter Content*

When testing a system's jitter noise in an oscilloscope, we see the total jitter. Essentially, this is the sum of the **deterministic jitter** and the **random jitter.**

**Deterministic Jitter (D):** The sub-components are measured in time domain and include crosstalk (leak of energy from one block to the other or through the traces that connect those blocks), EMI (noise that is coupled between AC line and RF signal sources), and reflection.

**Random Jitter (Rj):** Contains frequency domain components. These includes short term noise, flicker noise, and thermal noise .

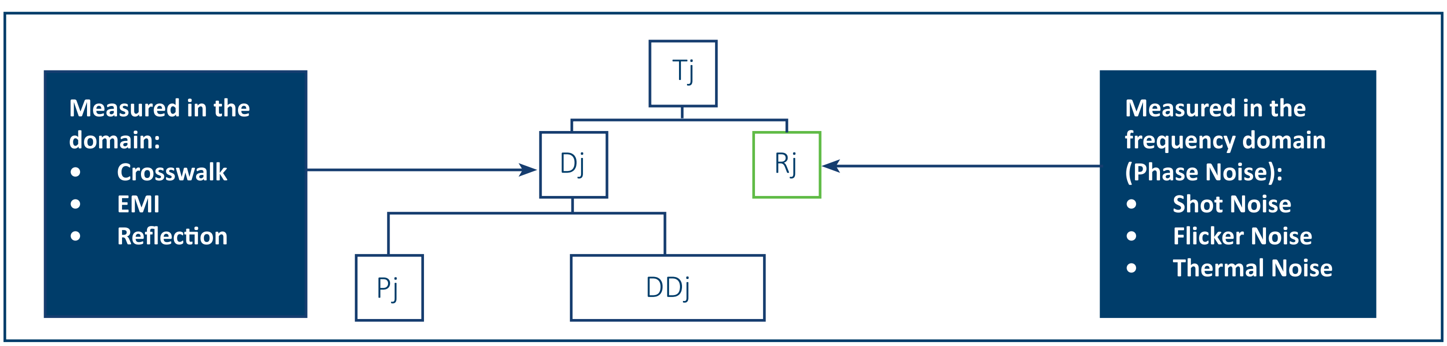


*Figure 5: Total jitter (TJ) and subcomponents*

## EVM – ERROR VECTOR MAGNITUDE AND LOCAL OSCILLATOR NOISE IN WIRELESS SYSTEMS

*Error Vector Magnitude:* a direct measurement of modulation accuracy and transmitter performance. It also helps to capture the error vector between a measured signal and its corresponding ideal point in the signal constellation display.

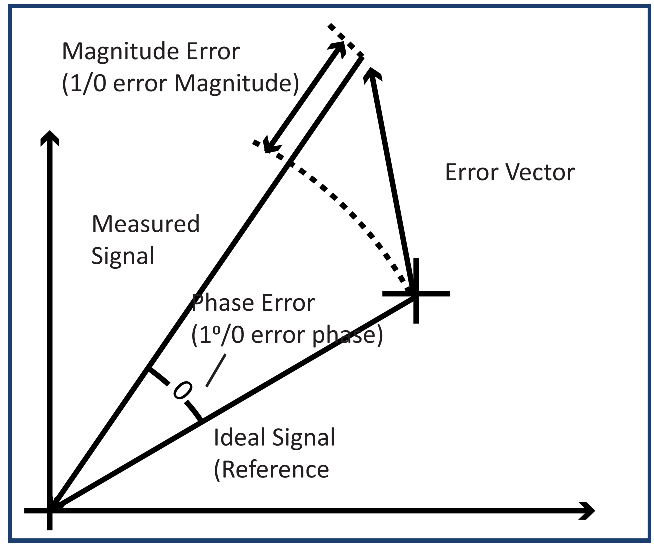


*Figure 6: Error Vector Magnitude*

*EVM helps to pinpoint transmission impairments such as:*

- Phase noise and frequency error
- IQ imbalance, such as gain and phase mismatch, which would result in local oscillator (LO) leakage and unwanted sideband components
- Signal compression and nonlinearities
- Spurious components.

EVM can be defined as the single sideband phase noise density, L(f), in dBc/Hz for a given frequency offset, f, or aggregately, in terms of root mean square (rms) phase noise, θrms, in radians, over the entire bandwidth. The phase noise affects modulation accuracy and impact is visually apparent as a circular distortion of the signal points around the center of the spectrum.

## PHASE NOISE TO EVM CALCULATION & REQUIREMENTS

Phase noise is a major contributor for EVM's magnitude and consequently is an indicator of the transmitter's performance.

*Typical design guidelines for budgeted EVM include:*

- Components' test: 10 dB better than the system as a whole
- System's test: 3 dB better than the source from the radio standard
- Oscillators shall be rated at < 50% of the entire system's figure

3GPP TS 38.101-1 EVM requirements for different 5G modulation schemes:

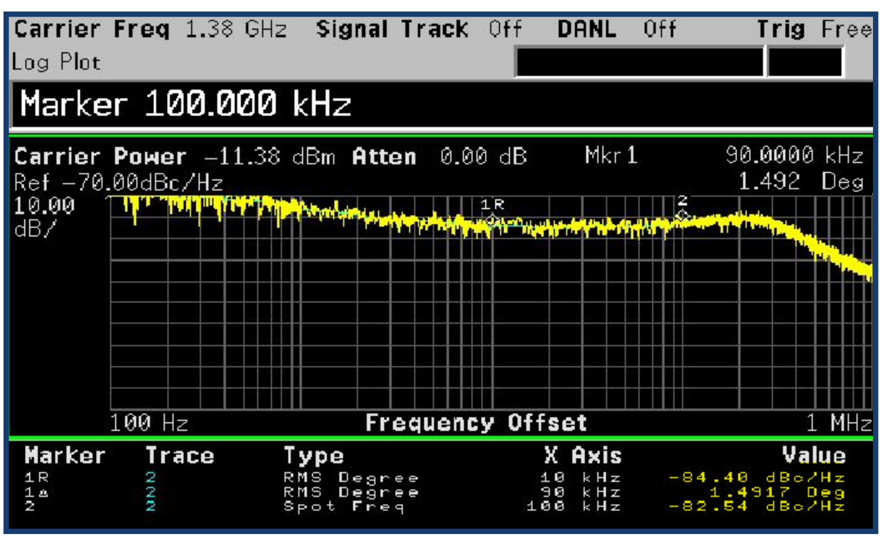


*Figure 7: σ2 = rms phase noise of the local oscillator in radians*

| Modulation for PDSCH | Requires EVM |
|---|---|
| QPSK | 17.5% |
| 16 QAM | 12.5% |
| 64 QAM | 8% |
| 256 QAM | 3.5% |

## EXAMPLE CASES: PHASE NOISE VS. EVM

### Example 1: CTS Low Noise High Frequency TCXO: at 100MHz

*Features*

- Output frequency Up to 1 GHz
- Ultra-Low Jitter and Phase Noise
- Meets Wander Generation MTIE/TDEV for ITU-T G.8262 Options 1 & 2
- Utilizes CTS Proprietary ASIC Technology (VFJA1412x)

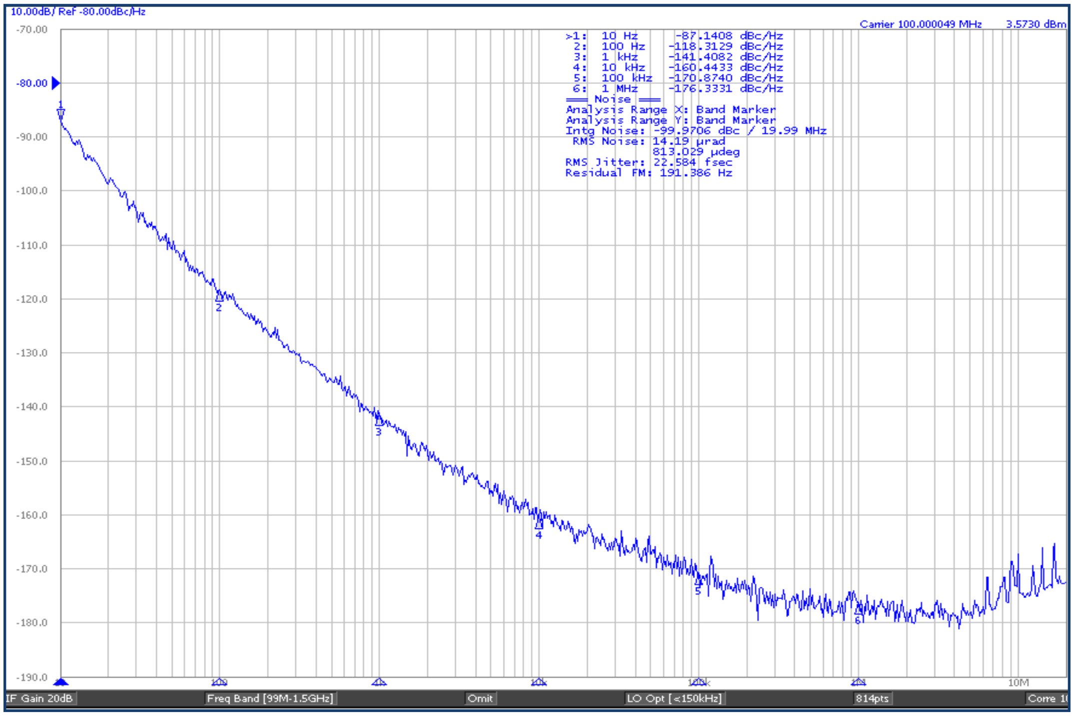


*Figure 8: 100MHz ultra low noise reference with -176 dBc/Hz at the floor.*

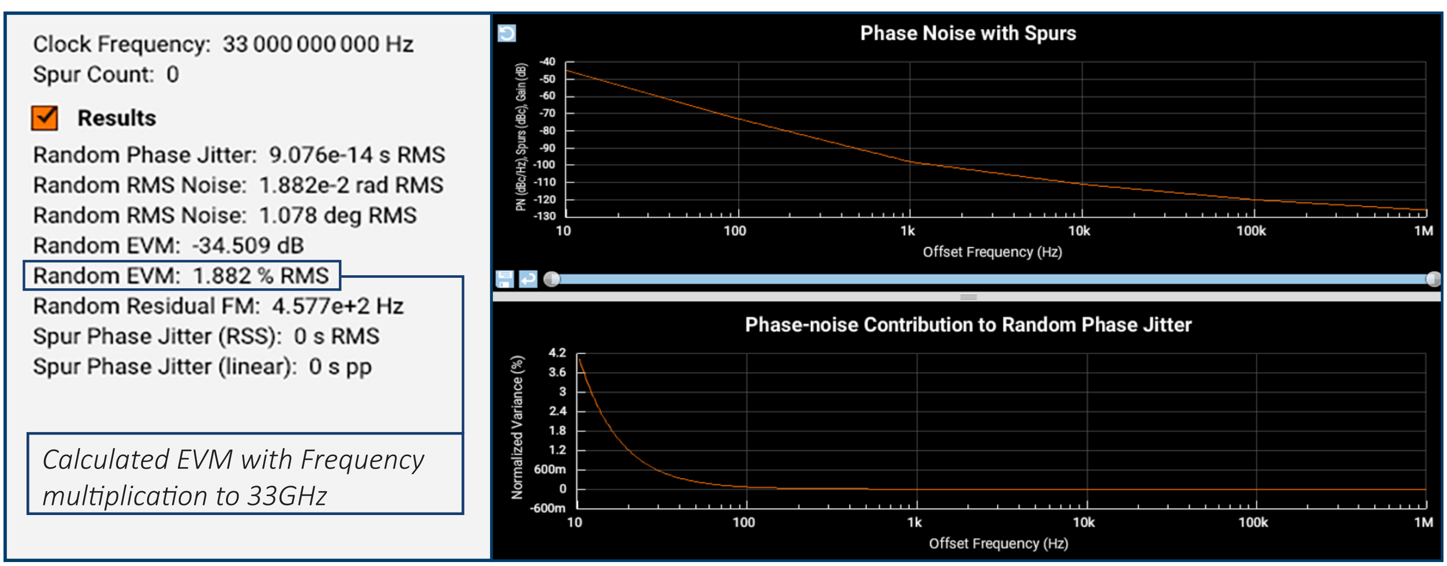


*Figure 9: EVM at 33GHz- Ultra low noise source.*

Applying a multiplication factor of 330 translates to a degradation of about 50.4 dBc on the noise floor. The EVM degradation increased from -77 dB all the way to -34.5 dB. The percentage of error increased from 0.014% RMS to 1.89%. Therefore, using this oscillator as the PRC comply with EVM required by 3GPP.

### Example 2: Generic TCXO + DPLL Multiplication at 100MHz

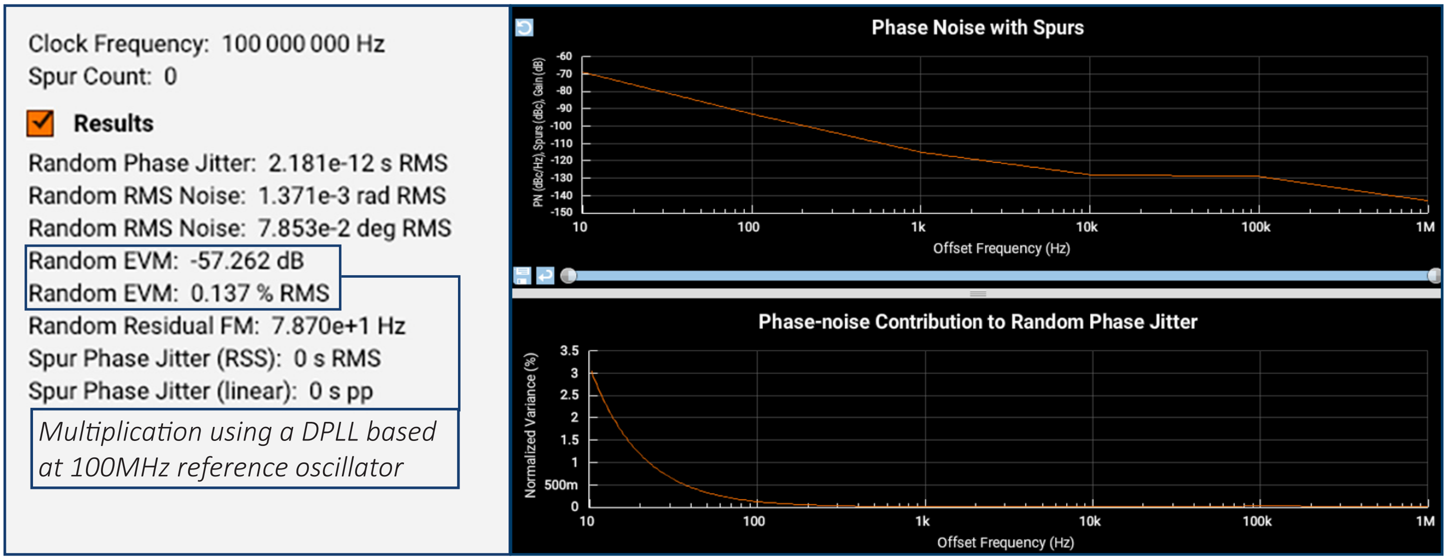


*Figure 10: A DPLL multiplier reference source with -143 dBc/Hz at the noise floor*

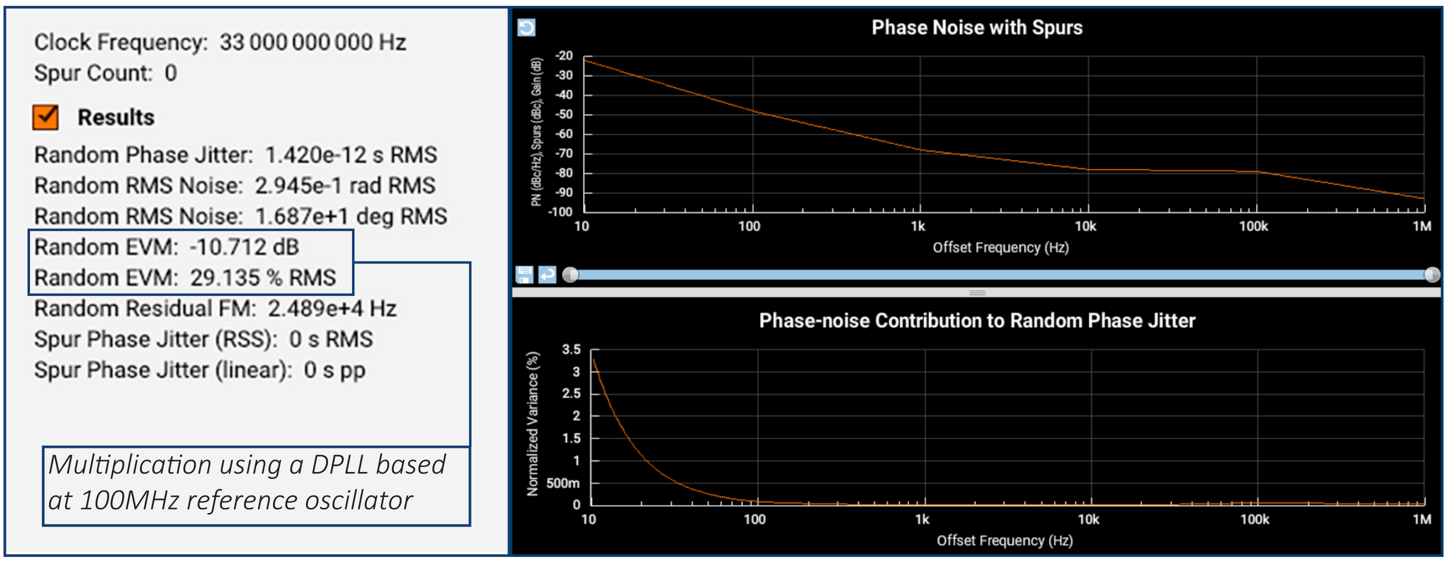


*Figure 11: EVM at 33GHz- PLL multiplied reference source.*

The EVM was degraded to almost -10 dB (from -57dB @100MHz). Percentage error exceeds 29%. According to 3GPP requirements, the entire system cannot be over 3.5%. In this case, the oscillator is already running in over 29%, exceeding the limit and failing to comply with 3GPP.

These last two examples demonstrate the contribution of reference clock noise level and the importance of proper selection of a quality PRC as a key contributor for the results of radio output.

## SOLUTIONS: LOW NOISE JITTER ATTENUATORS AND FREQUENCY SYNTHESIZERS

Elements within a given network are tied to a reference source through various options: a GPS, ethernet connection, or an optical transmission line. As the data is being decoded, the clock must be separated and extracted from that reference source.

In that reference extraction process, the reference clock gets contaminated, and additional signal filtering or signal regeneration of that clock must be applied.

*CTS' VFJA1419 Synthesizer Module, Jitter Cleaning Performance*

CTS offers a unique technology through an ASIC based solution in a single device, to regenerate and distribute that "clean" clock to the rest of the system.

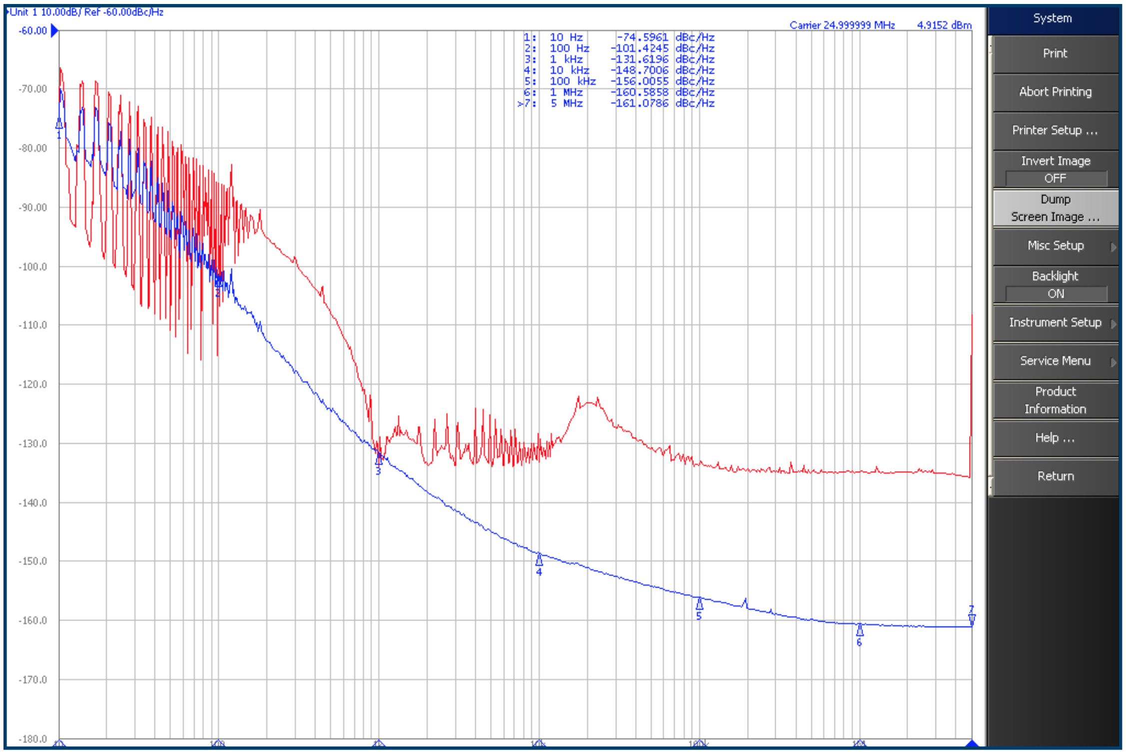


*Figure 12: Input (red) vs. Output (blue) of a regenerated noise signal*

### *CTS' VFJA0923 Synthesizer Module, Frequency Multiplying Performance*

In some cases, it may be necessary to multiply the reference clock to a higher frequency. The key objective is to do a very clean multiplication, which does not introduce any disruptive spurious or harmonics.

CTS has developed synthesizer technology through ASIC for this purpose.

## CONCLUSION

In this paper, we have addressed evolving new system noise requirements and challenges with 5G networks:

- Reference sources are becoming even more critical as transmission frequencies and modulation rates increase.
- EVM and phase noise help quantify system noise and local oscillator contribution.
- Minimizing multiplication factors helps reduce signal mixing and keeps SNR high with a low noise floor (higher PRC frequency).
- When multiplying frequency, a recommended low filter BW can help reduce the impact of sidebands.
- Solutions like CTS' family of synthesizers are necessary for clean, accurate multiplication and minimizing the number of multiplication stages.

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## ABOUT CTS

CTS (NYSE: CTS) is a leading designer and manufacturer of products that Sense, Connect, and Move. The company manufactures sensors, actuators, and electronic components in North America, Europe, and Asia. CTS provides solutions to OEMs in the aerospace, communications, defense, industrial, information technology, medical, and transportation markets.

## ENGINEERING CONSULTATION

***CTS provides complimentary consultations*** with one of our specialized design engineers to assist you in designing your embedded technology-based product or system.

***Picking the right frequency control component*** is critical for success. Comparing hundreds of available frequency control components is time consuming. Consult a CTS engineer to save time in evaluating the right component for your project.

***Leverage our engineering expertise.*** We encourage you to tap into our engineers' collective knowledge base to solve your most complex design issues and find the best solution to meet your needs, no matter the application.

***With a comprehensive portfolio*** of frequency control components, our engineers have a vast foundation of solutions to meet your requirements. However, if you need turnkey product development or a custom configuration to fit a specific application, our engineers are available to consult with you on how CTS can fulfill custom modifications to your meet your project specifications.

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## APPENDIX

**Deterministic jitter (Dj):** Specific causes, predictable and consistent. It has a non-Gaussian amplitude distribution that is always bounded, which can be characterized by its peak-to-peak value. It comes from system sources such as crosstalk, inter-symbol interference –ISI-(reflections) and power supply feed through (EMI).

**Periodic jitter (Pj):** Cyclical, resulting from a cross-coupling or EMI (AC power lines, RF signal sources, etc.) from a switching power supply. The latter is known as "uncorrelated periodic jitter," which couples into the data or system clock signal. A "correlated periodic jitter" is the coupling of an adjacent data signal from a clock of the same frequency. It is designated by a frequency and magnitude measured as a peak to peak number.

**Data Dependent jitter (DDj):** Divided into Duty Cycle Distortion (DCD) and Inter-Symbol Interference (ISI).

**Duty Cycle Distortion (DCD):** The deviation in propagation delay between high to low and low to high times.

**Inter-Symbol Interference (ISI):** Sometimes referred to as DDj; it is usually the result of bandwidth limitation in the transmitter or physical media, therefore creating varying amplitudes of data bits due to limited rise and fall times of the signal. It occurs when the frequency component of the data (symbol) is propagated at different rates by the transmission medium.

**Random jitter (Rj):** Considered not bounded and can be described by a Gaussian probability distribution. It affects long-term device stability characterized by its standard deviation (rms) value. It is generated from physical sources like thermal noise, white noise and scattering in optical media.

**Total jitter (Tj)** = The sum of Deterministic jitter (Dj) and Random jitter (Rj)

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