Shaking Up 5G

Phase Noise vs EVM in OFDM Systems

A Leading Provider of Smart, Connected and Secure Embedded Control Solutions

Presented by

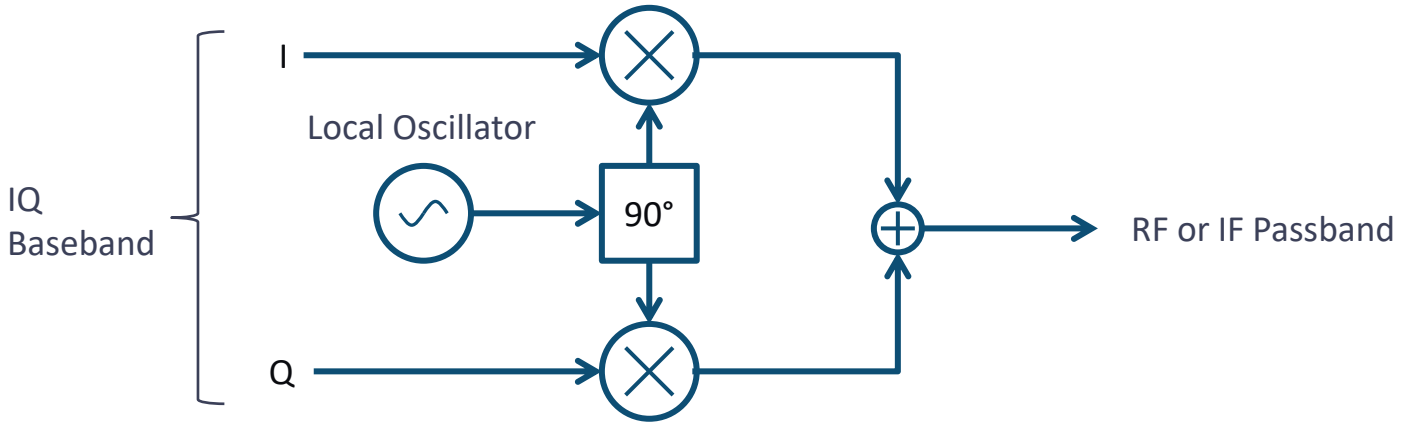
Dan Boschen and David Chandler

September 6, 2025

Agenda

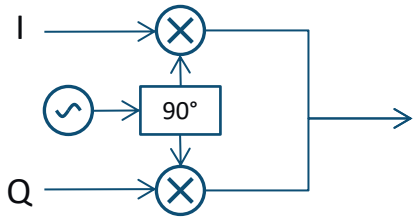
- Quadrature Amplitude Modulation (QAM)
- Orthogonal Frequency Division Multiplexing (OFDM)
- g-Sensitivity: vibration effects
- Practical implementation of 5G NR signal at 6.05 GHz
- Phase carrier tracking
- Phase Noise impact on Error Vector Magnitude (EVM)

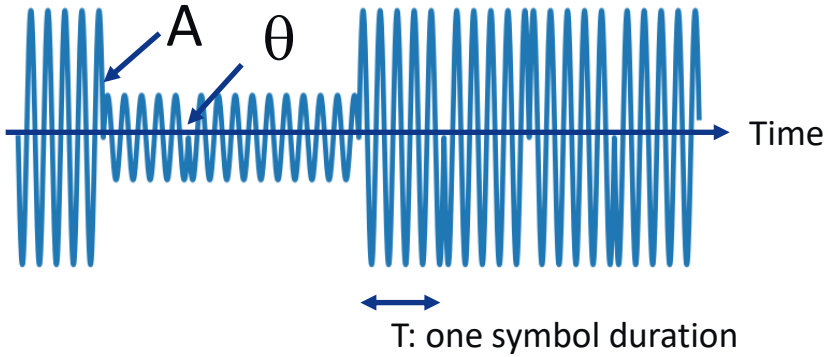
Quadrature Amplitude Modulation (QAM)

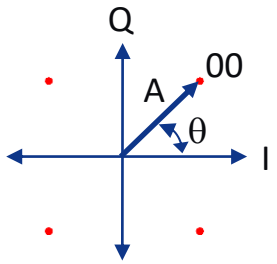


Quadrature Amplitude Modulation (QAM)

The levels of "**I**" and "**Q**" at **baseband** set the **magnitude** and **phase** of an RF carrier for each of the possible **M symbols** to be transmitted at any given time

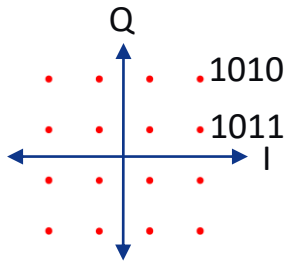






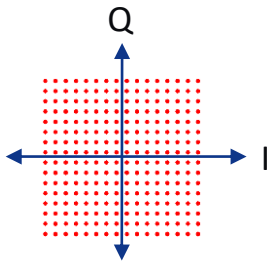
QPSK
(M=4)

2 bits/symbol



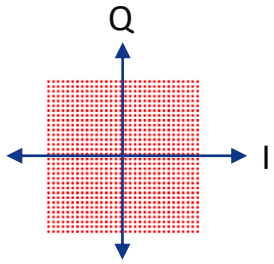
16-QAM
(M=16)

4 bits/symbol



256-QAM
(M=256)

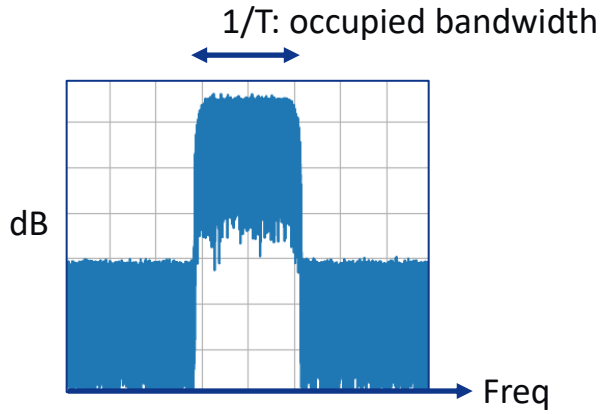
8 bits/symbol



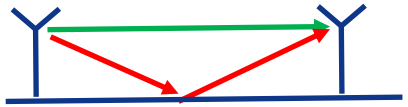
1024-QAM
(M=1024)

10 bits/symbol

The **Symbol Rate** 1/T sets the **RF Bandwidth**:



Orthogonal Frequency Division Multiplexing (OFDM)



Challenge with a single wideband QAM carrier:

Multipath fading

Delay spread > symbol duration T => frequency selective fading (hard!)

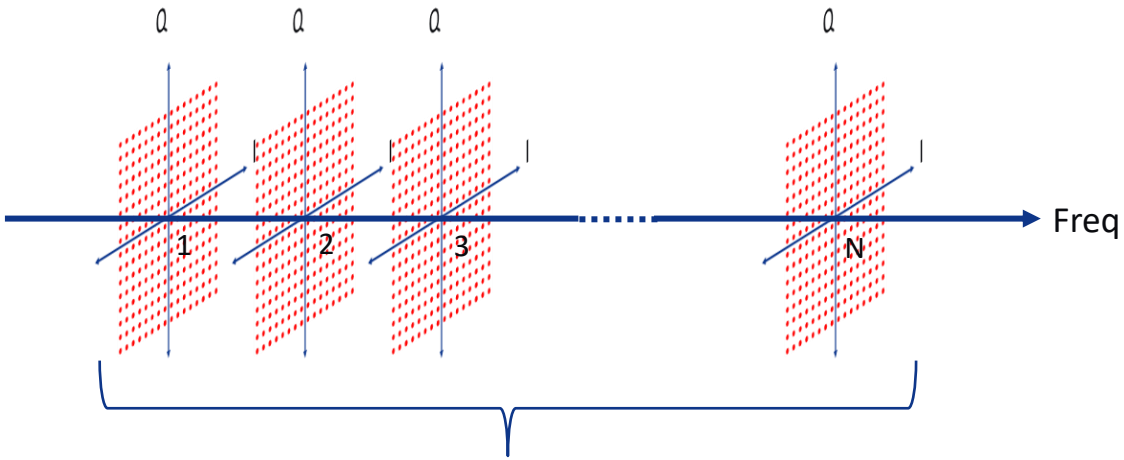
Solution:

Send **multiple narrow band QAM carriers** in parallel

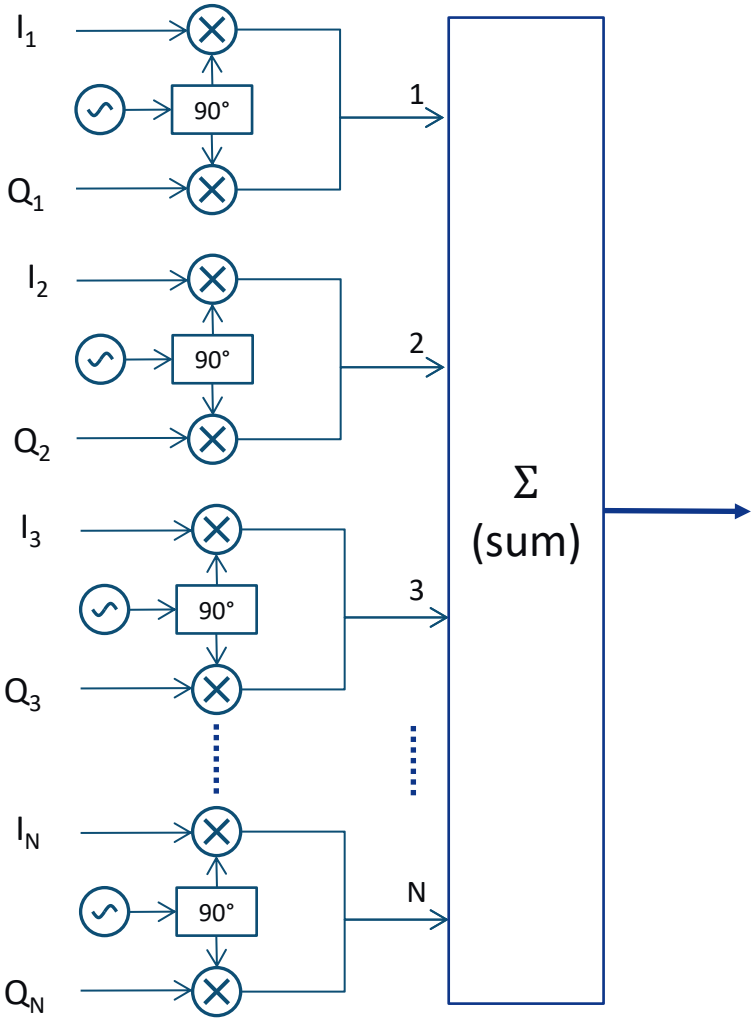
OFDM

Delay spread < symbol duration T => flat fading (easy!)

Challenge with OFDM: Phase noise

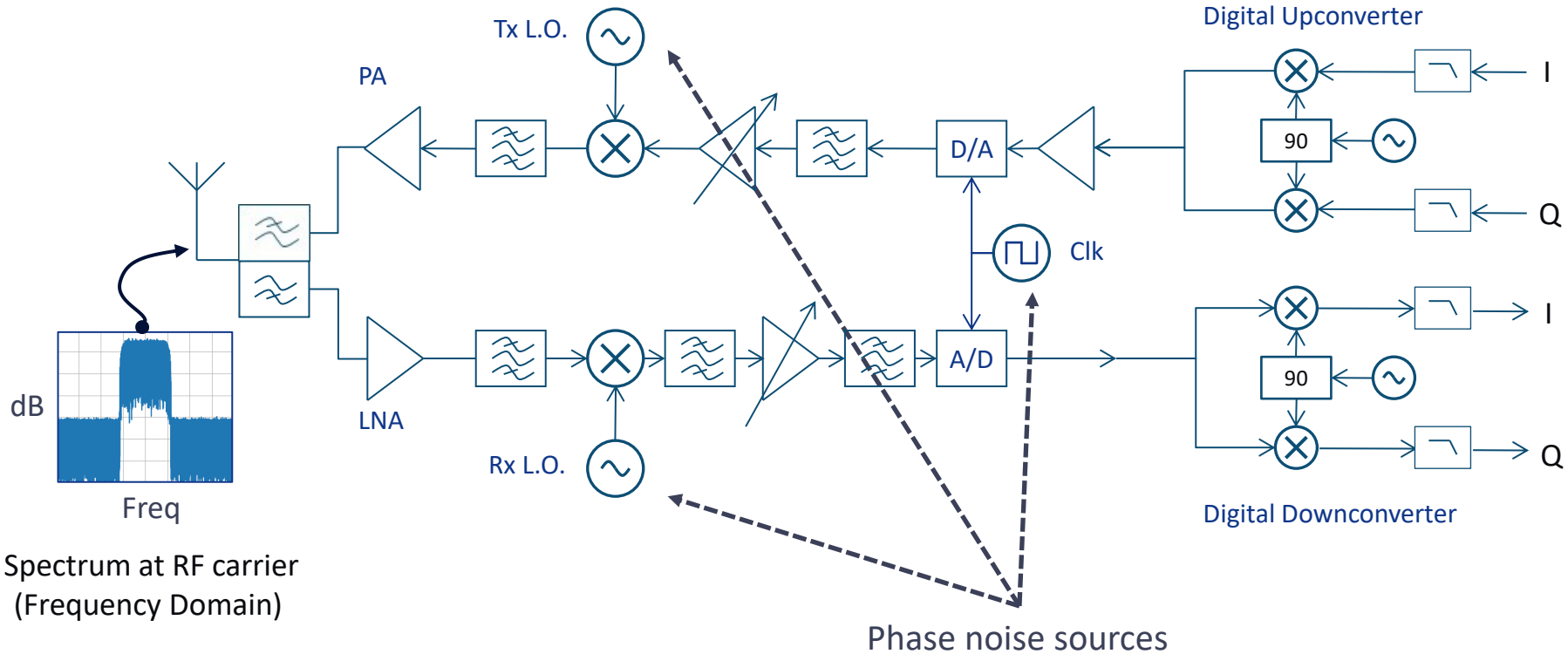


N Sub-carriers as bins of an FFT is the resulting sum in the frequency domain

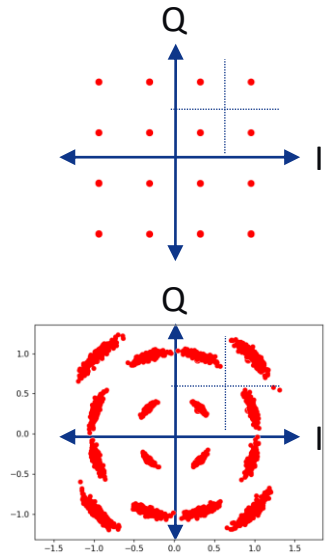


Radio Transceiver Block Diagram

(I,Q) Can be samples of Single Carrier QAM or the time domain OFDM waveform



Spectrum at RF carrier
(Frequency Domain)



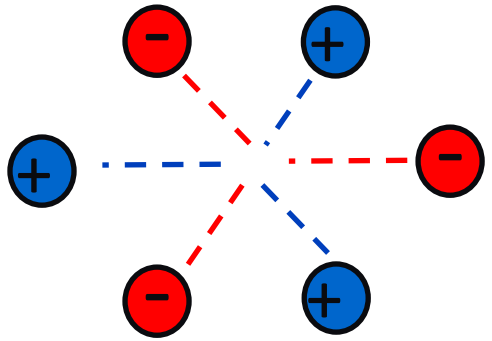
IQ Constellations at baseband
(Time Domain)

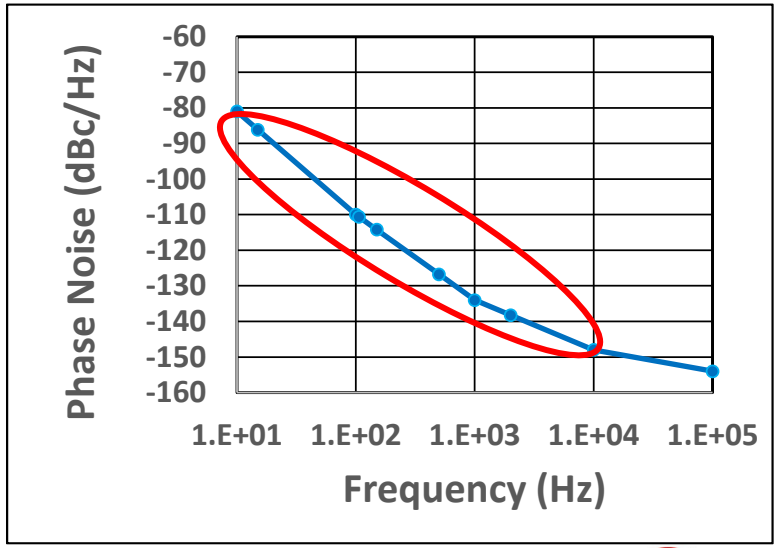
EVM ⇨ Bit error rate

From “DSP for Software Radio” Dan Boschen https://dsp-coach.com

Frequency Sources

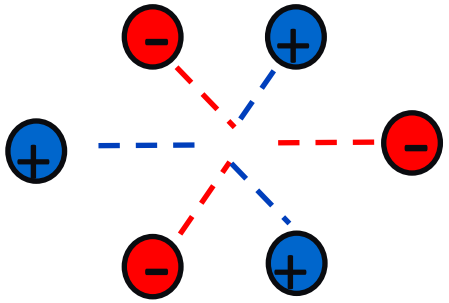
- The local oscillator (LO) is a combination of a low frequency oscillator and a synthesizer
- The oscillator is typically some form of piezoelectric or electrostatic resonator (quartz or mems)
- In either case there is a mechanical vibration of the resonator
- Close in phase noise is dominated by the Q of that resonator

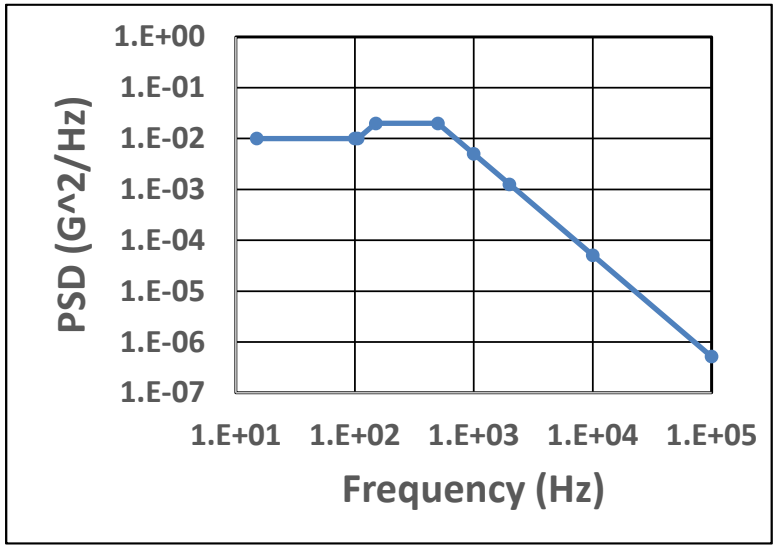




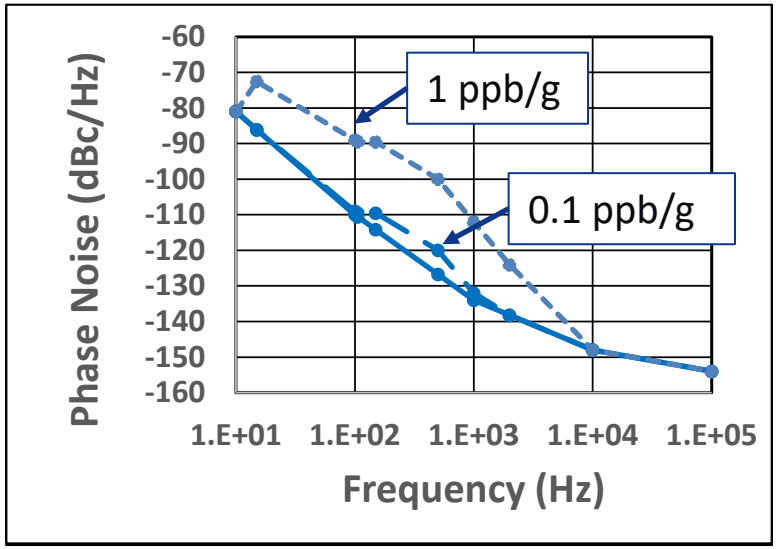
Vibration Effects on LO

- Additional vibration modulate the resonance
- Net effect is increase in phase noise at vibration frequencies
- Different oscillators have different coupling sensitivities
- γ - g-sensitivity
- Units measured ppb/g
- Often not listed in specifications





$$\mathcal{L}(f) = 20 \log\left(\frac{\bar{\gamma} \bullet \bar{A} f_0}{2f}\right), \quad where\ |\bar{A}| = [(2)(PSD)]^{1/2}$$



Random Vibration Profiles for Moving Vehicles

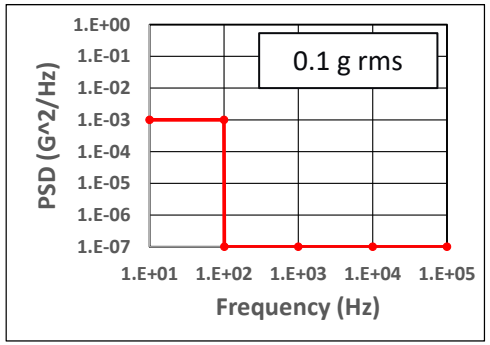
Naval Surface Vessel

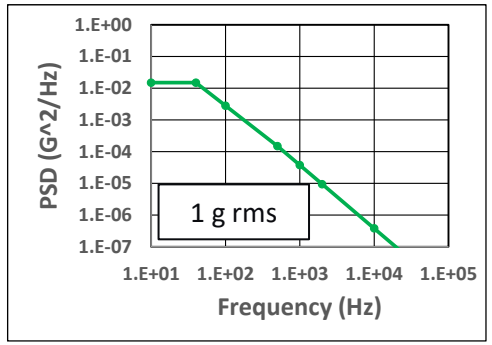
Road Vehicle

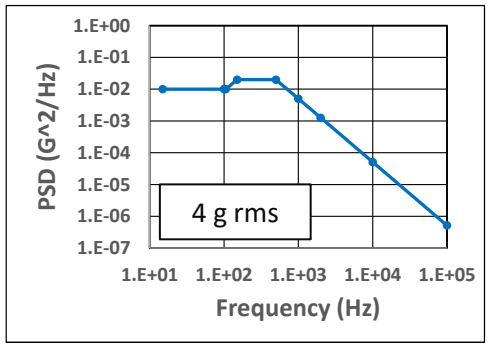
Commercial Airliner

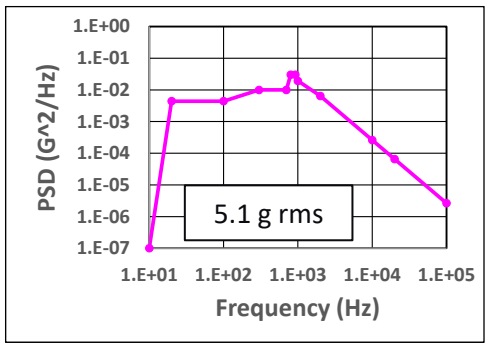
Rocket Payload

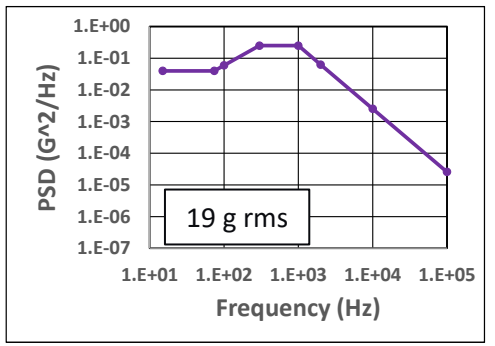
F15 (not cockpit)











- Vibration profiles from Mil-Std-883, Falcon 9 user guide, and NASA/TM-2002-210719
- Most profiles only list vibrations out 2 kHz due to transmissibility and measurability
- Limited energy > 2 kHz, but any energy in phase noise integration region can have large effect
- Extrapolated slopes from 2 kHz out to 100 kHz
- Simulated phase noise for these profiles with a 50 MHz TCXO at 1 ppb/g and 0.1 ppb/g
- Does not include any isolation, resonance, or higher-level modes

MICROCHIP

Phase Noise of TCXO at 1 ppb/g and 0.1 ppb/g

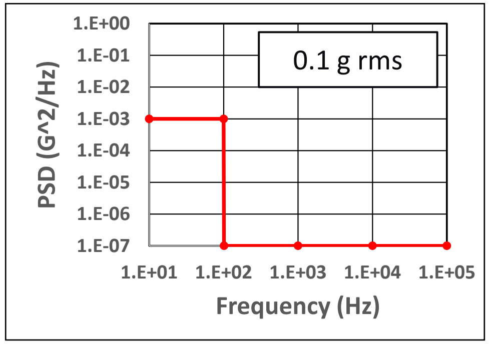
Naval Surface Vessel

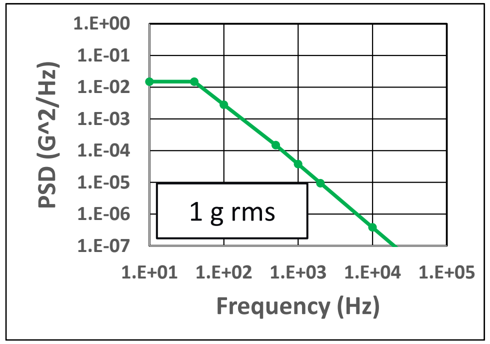
Road Vehicle

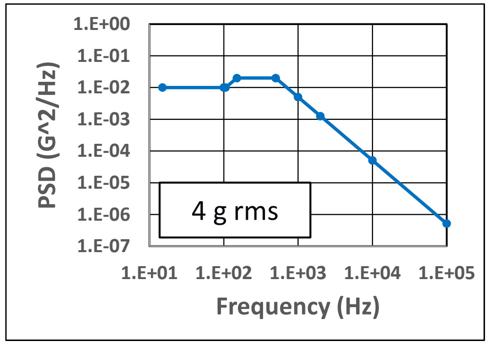
Commercial airliner

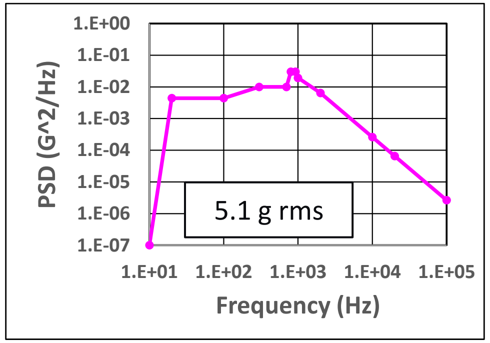
Rocket Payload

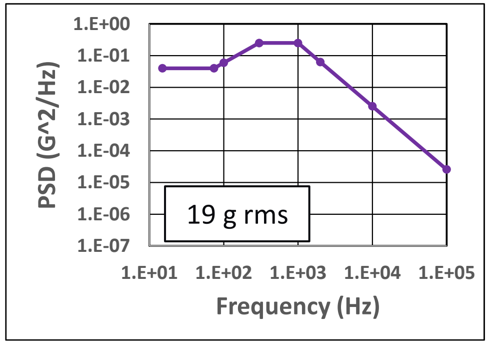
F15 (not cockpit)

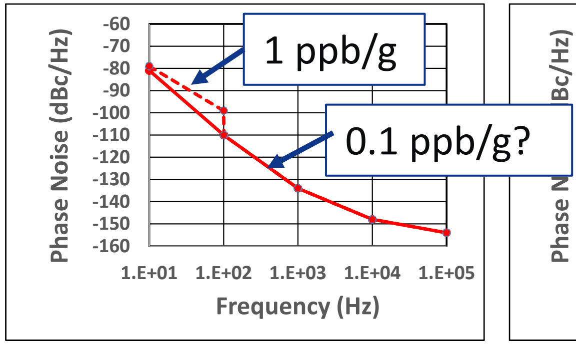


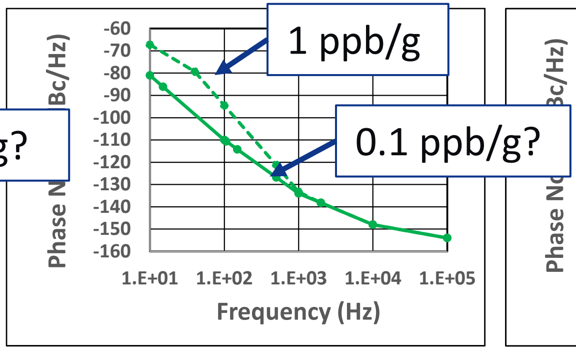


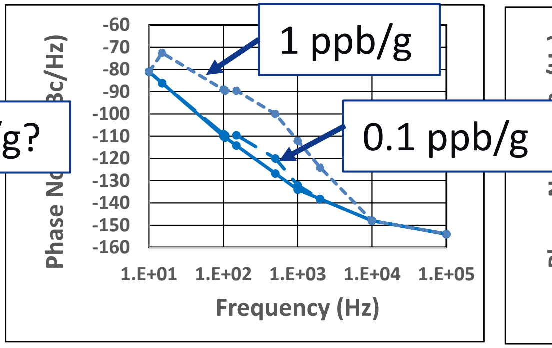


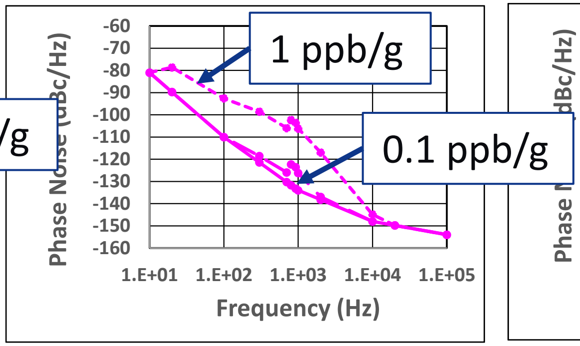


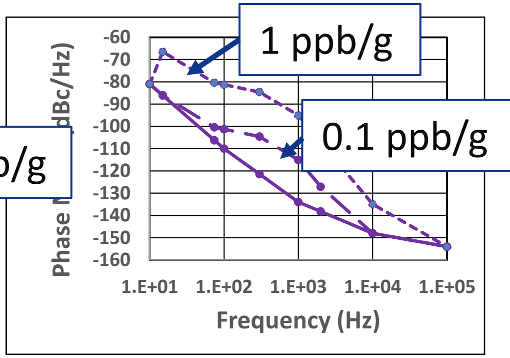












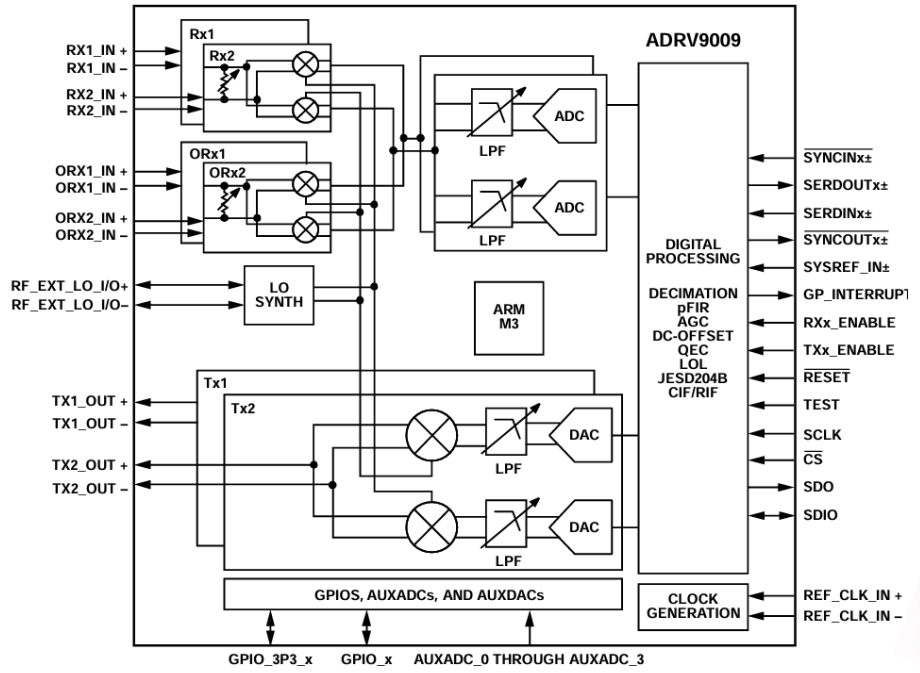
LO phase noise degradation at 50 MHz due to profiles out to 100 kHz

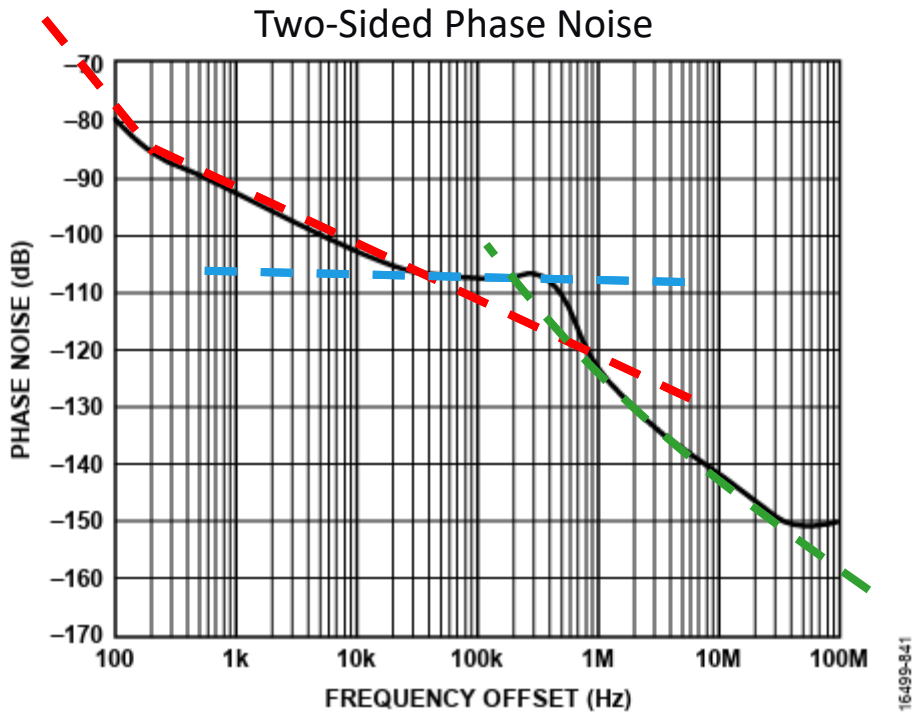
MICROCHIP

Impact at 6 GHz - Transceiver Chip Used for Simulations

- XO ref + 20Log(N) < 200 Hz and PLL 1/f noise > 200 Hz
- PLL flat noise: PN1Hz+10Log(F_{PFD})+20Log(N)
- uW VCO Phase Noise

FUNCTIONAL BLOCK DIAGRAM





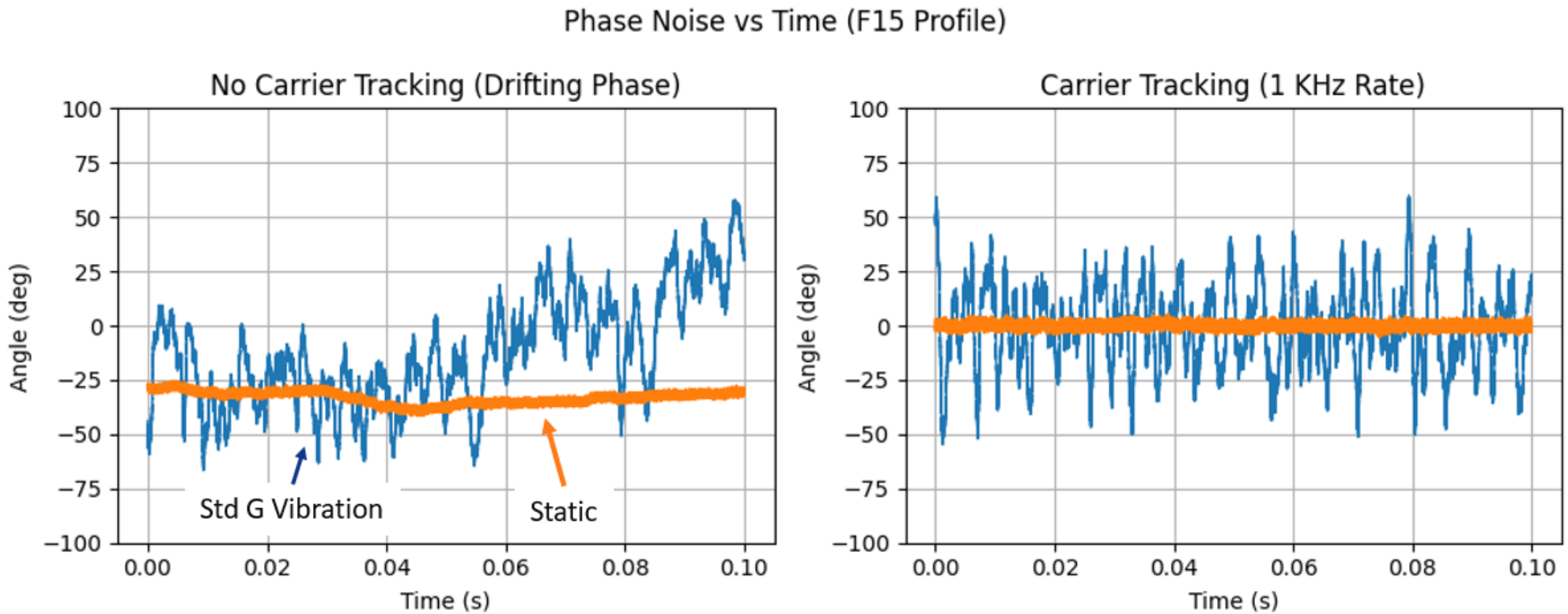
ADRV9009

50 MHz TCXO for reference clock

Std-g– 1 ppb/g

Low-g – 0.1 ppb/g – TX-709

Carrier Phase Tracking

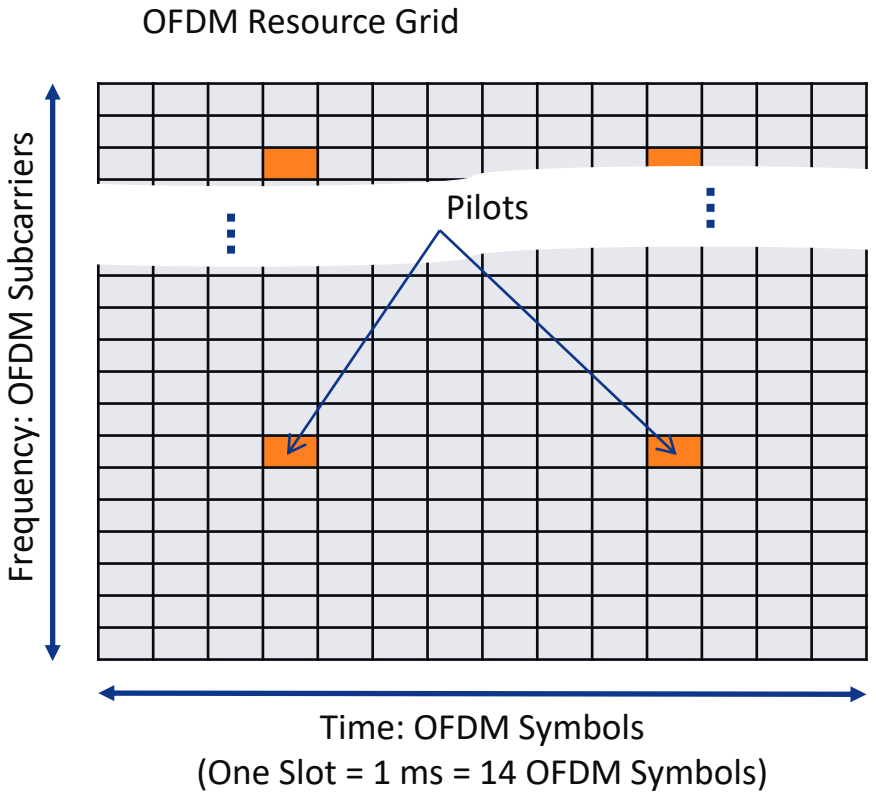


2

2

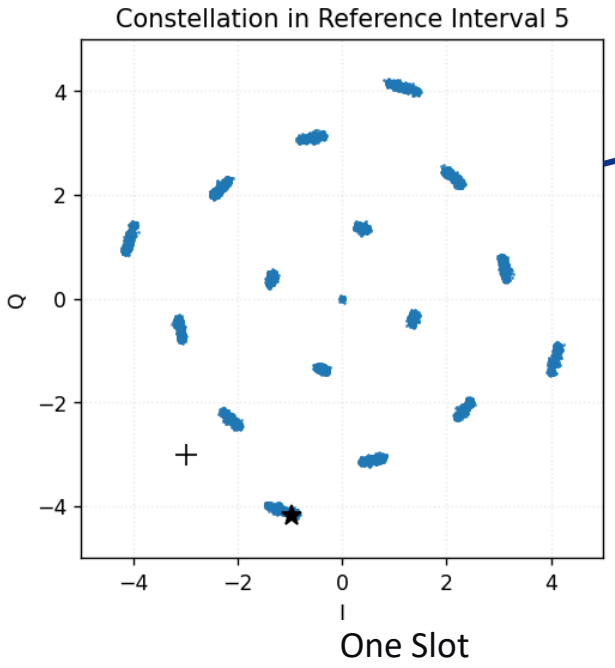
– How would this effect a 5G NR OFDM waveform?

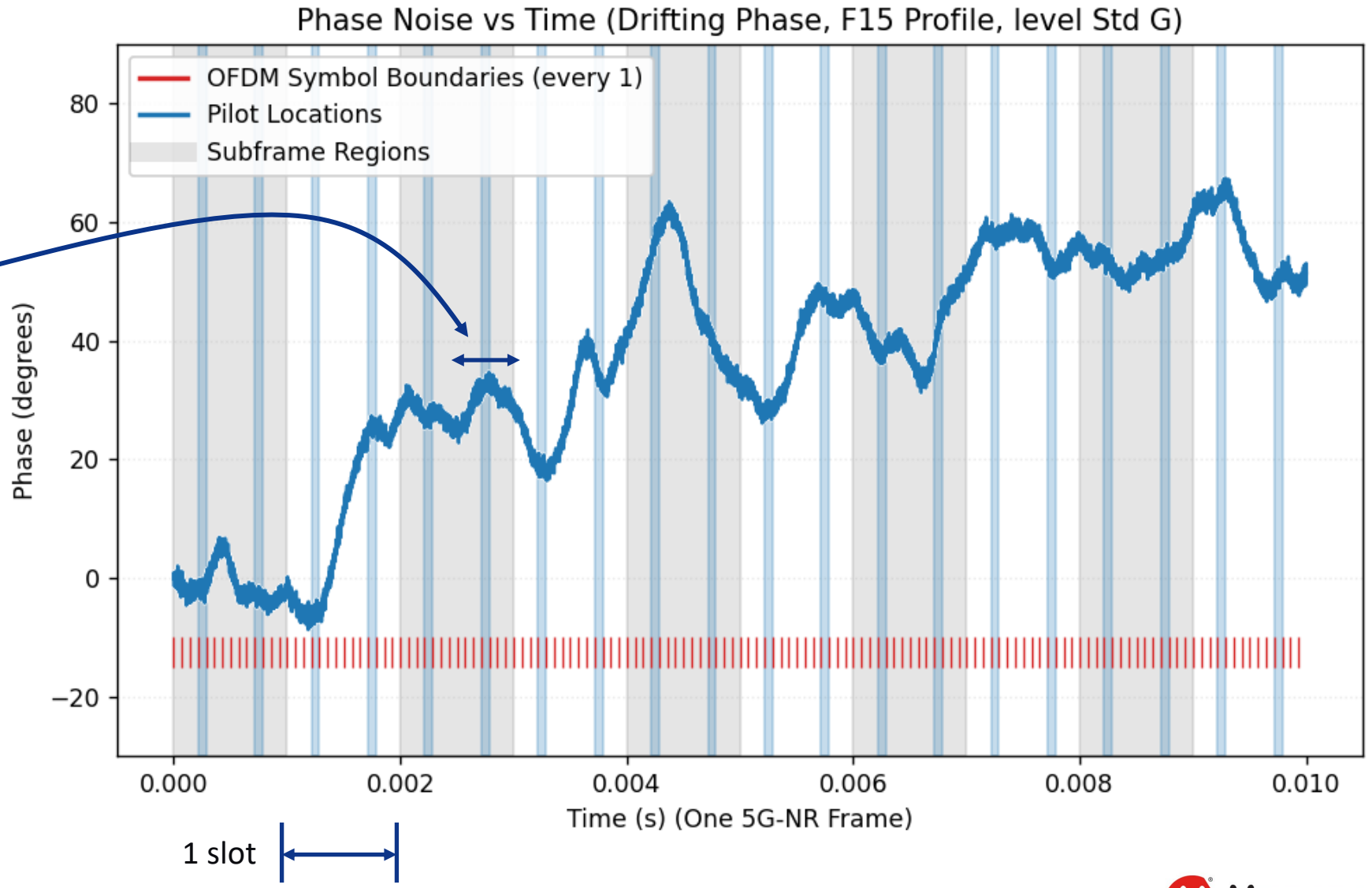
OFDM for 5G NR



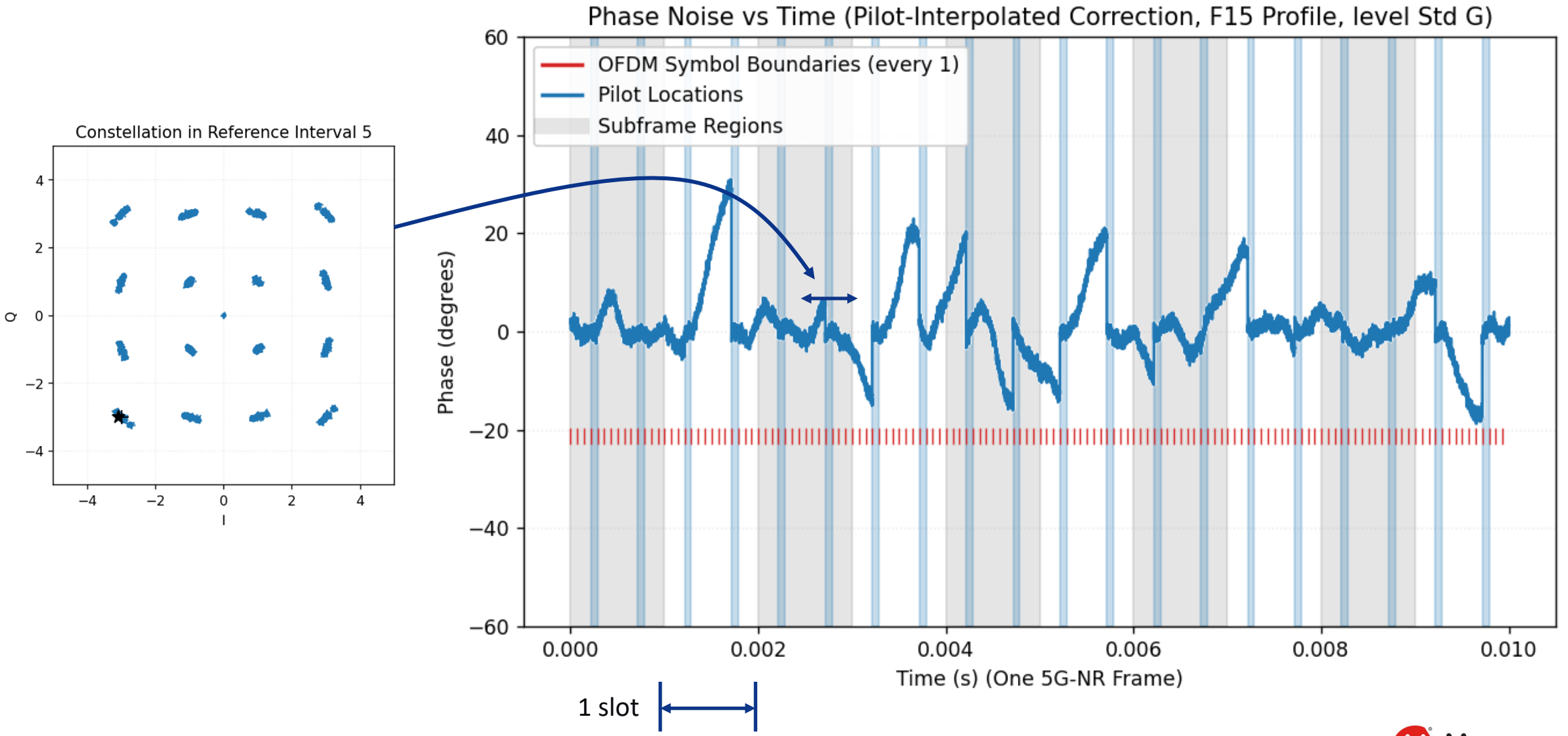
Ref: https://www.sharetechnote.com/html/5G/Handbook_5G_Index.html

Uncorrected Phase Noise

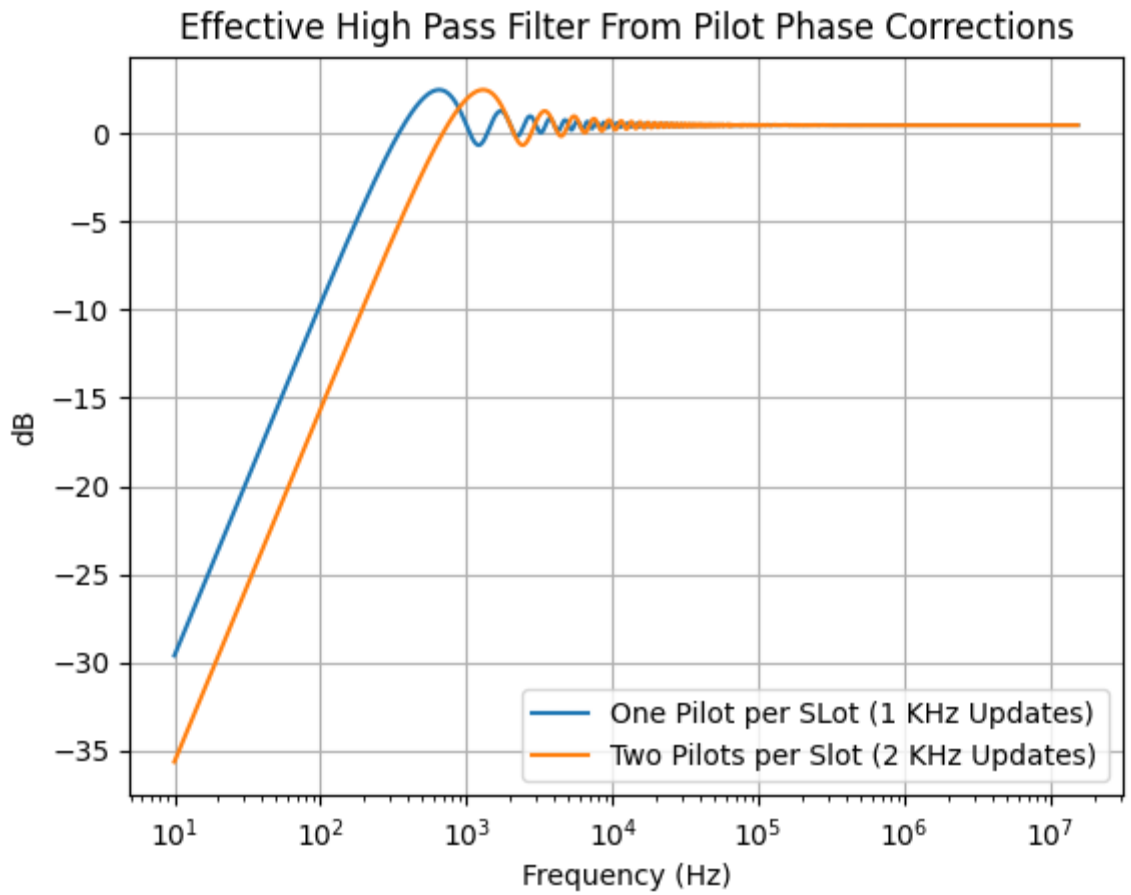




Pilot Corrected Phase Noise



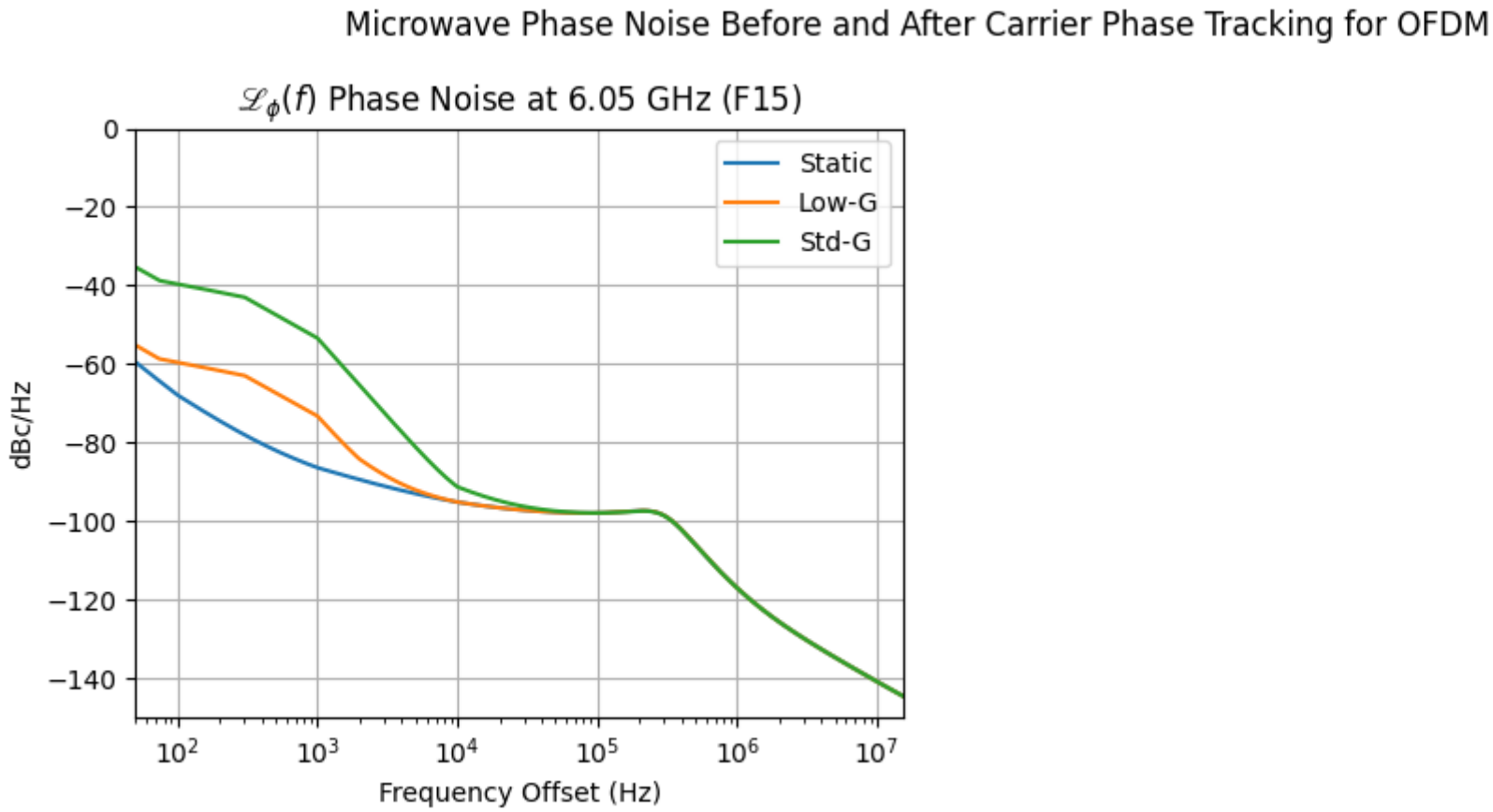
Phase Tracking is a High-Pass To Phase Noise



(For this simulation, the pilot was 2.6 dB stronger than RMS data and only one element per OFDM Symbol)

MICROCHIP

Impact of Carrier Phase Tracking on uW Phase Noise



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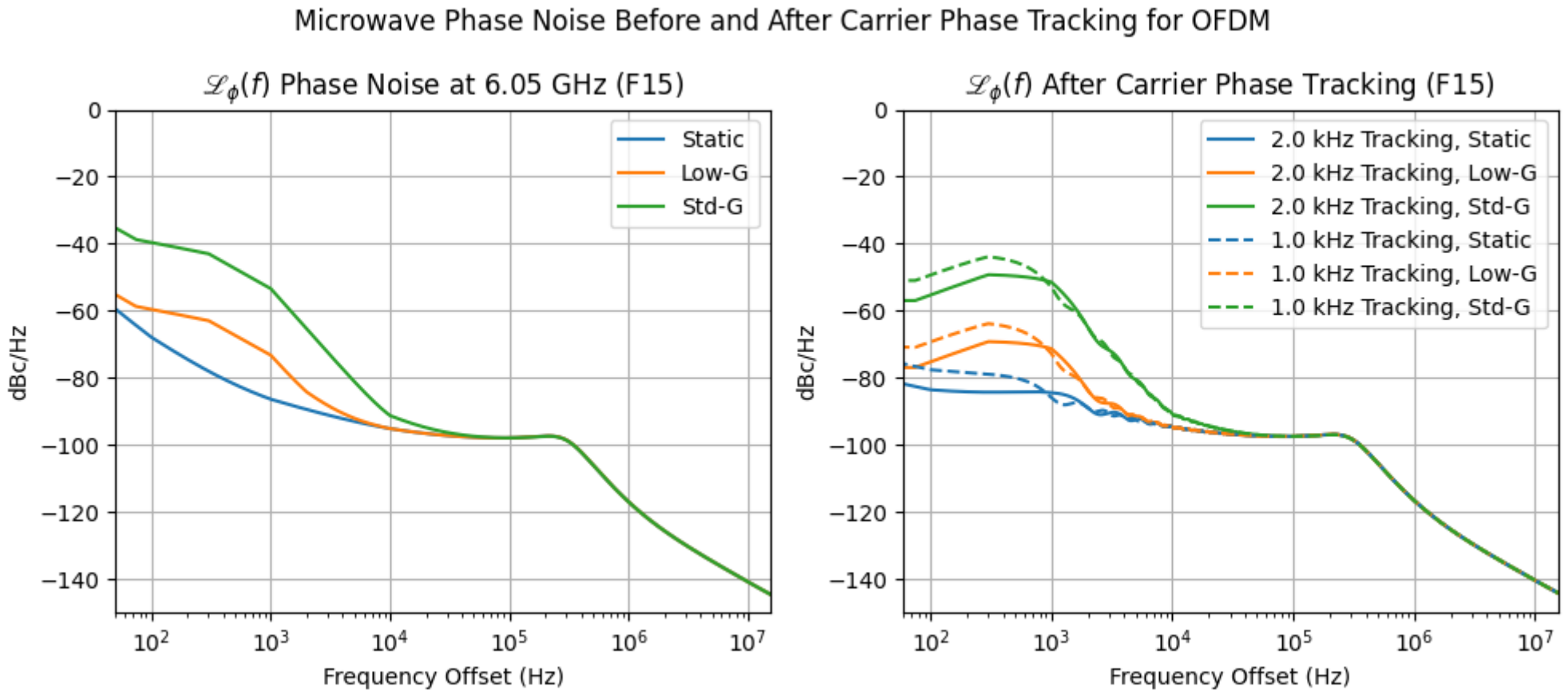
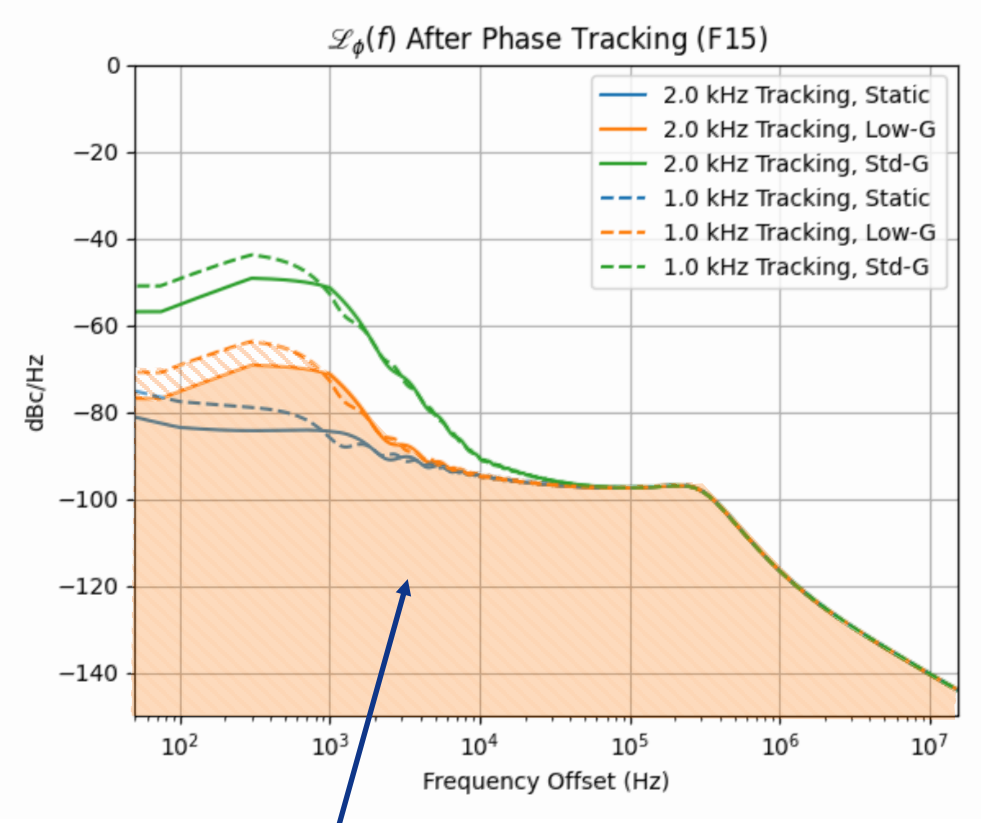


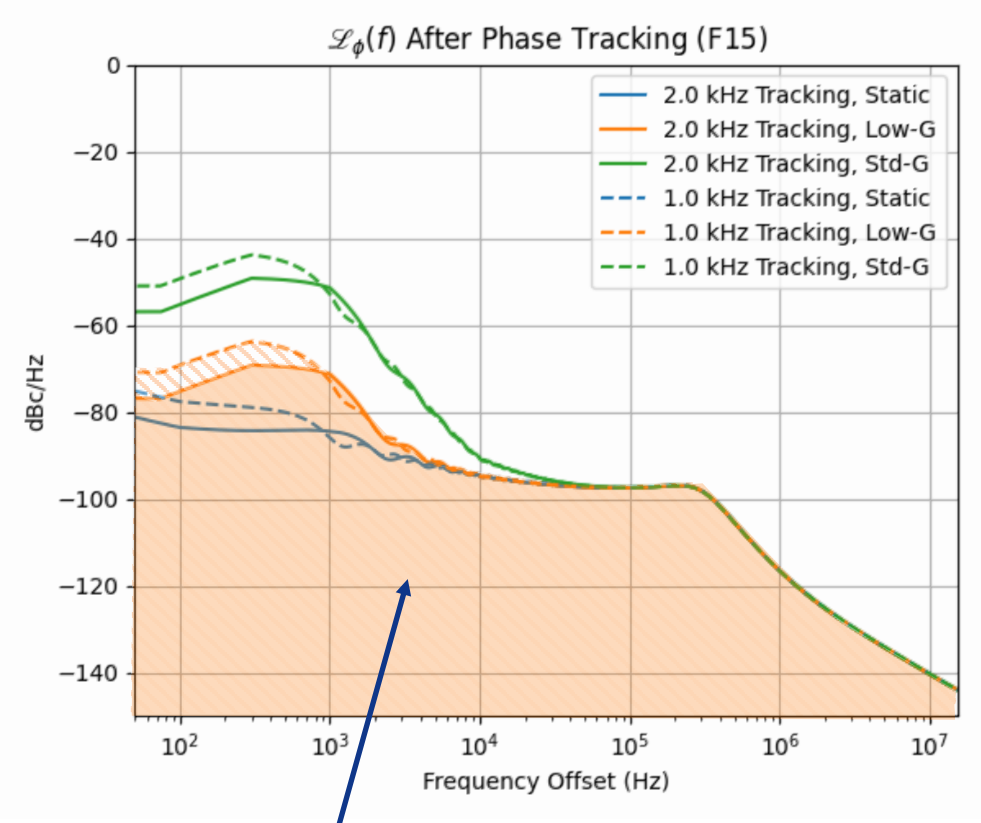
Phase Noise After Phase Carrier Tracking



The total integrated noise power under this curve is the EVM squared.

$$\mathrm{EVM} = 20\mathrm{Log}_{10}(\theta_{\mathrm{rms}})$$

Phase Noise After Receiver Carrier Tracking



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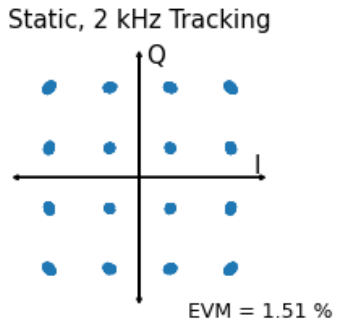
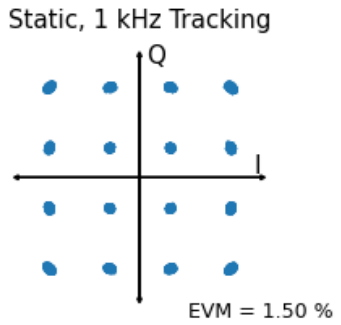
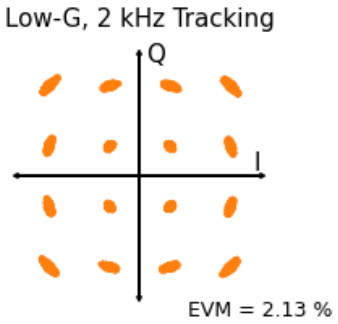
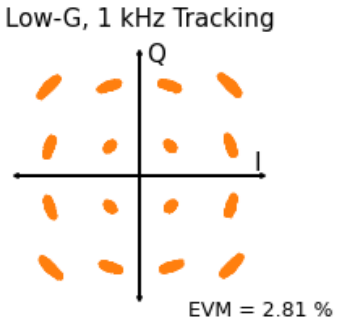
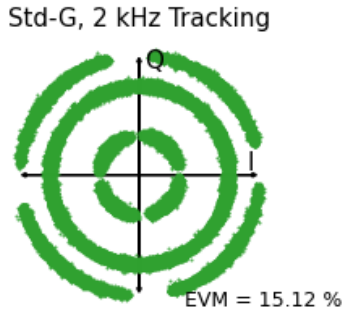
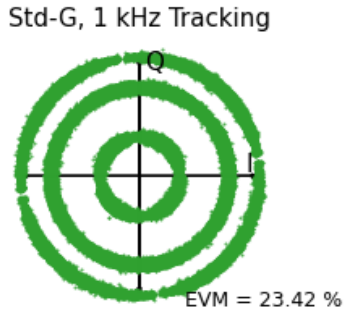






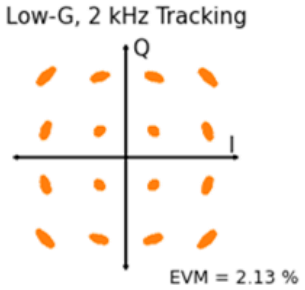


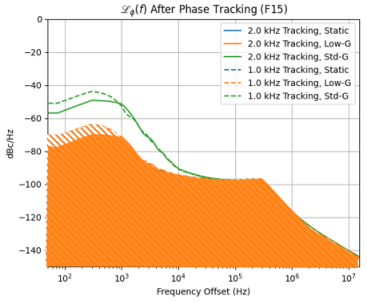




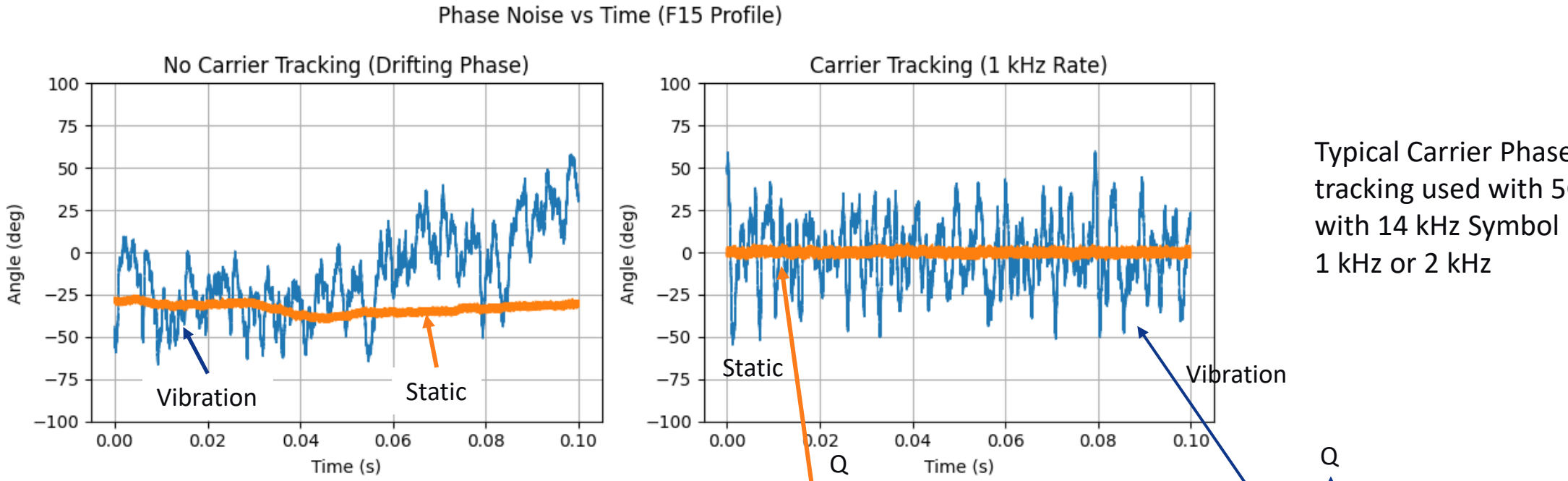
Prediction of EVM from Phase Noise PSD

	Simulated	Predicted
2 kHz Static	1.5%	1.3%
2 kHz Low G	2.1%	2.0%
2 kHz Std G	15.1%	14.8%
1 kHz Static	1.5%	1.4%
1 kHz Low G	2.8%	2.5%
1 kHz Std G	23.4%	21.0%





Phase Noise Impact - OFDM with 1024 QAM



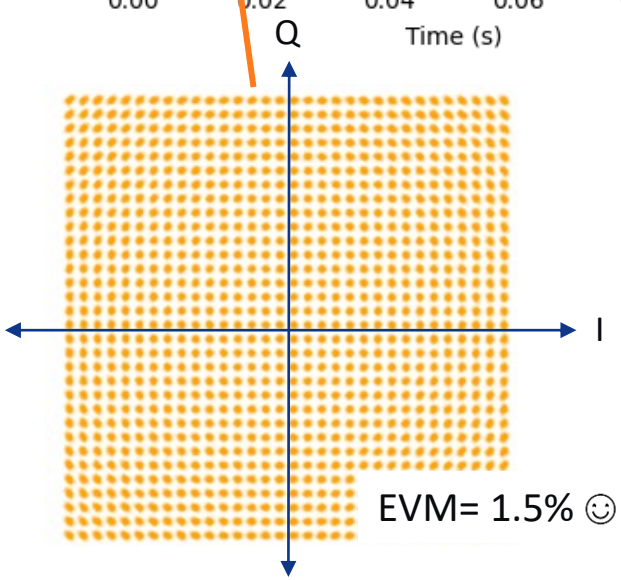
Typical Carrier Phase tracking used with 5G NR with 14 kHz Symbol Rate: 1 kHz or 2 kHz

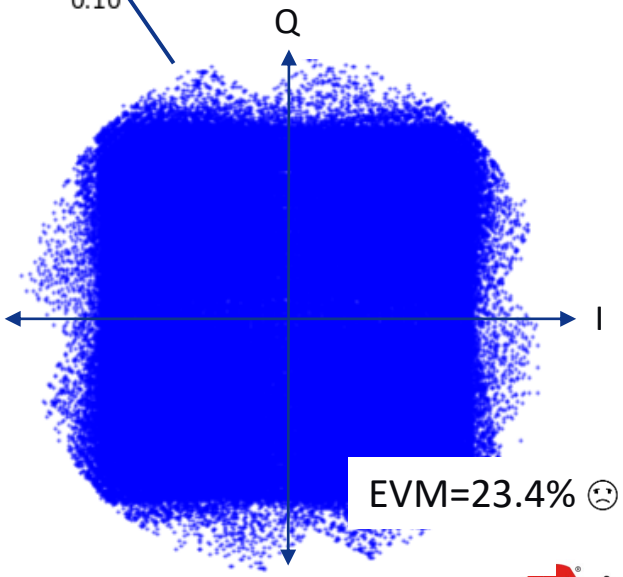
5G NR Waveform

6.05 GHz Carrier
OFDM with 15 kHz Subcarrier Spacing
14 kHz OFDM Symbol Rate
1024 QAM Subcarrier Modulation

5G NR EVM Requirements

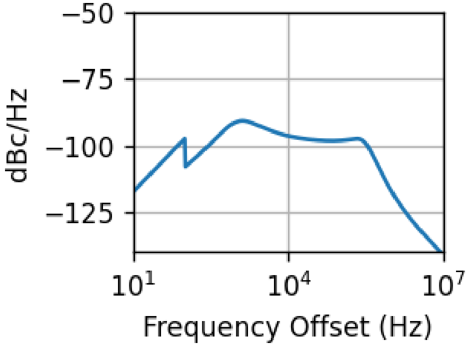
256 QAM: 3.5%, 1024 QAM: 2.5%
(ref: 3GPP TS 38.104)

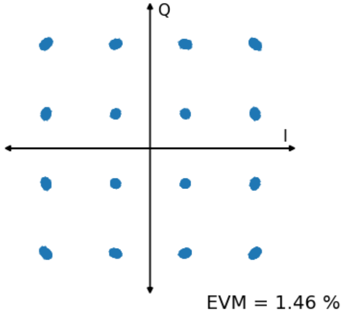




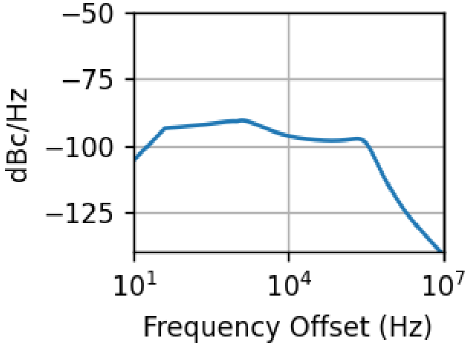
Phase Noise and EVM for Std-g TCXO

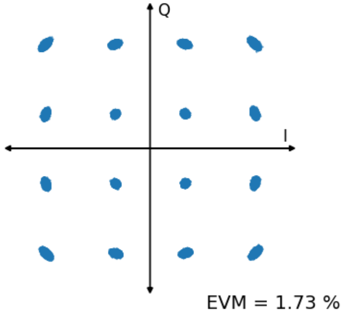
Naval Surface Vessel



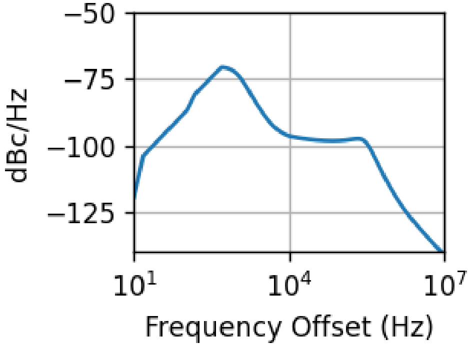


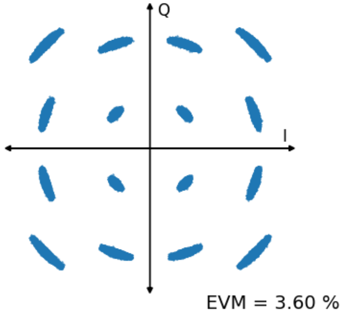
Road Vehicle



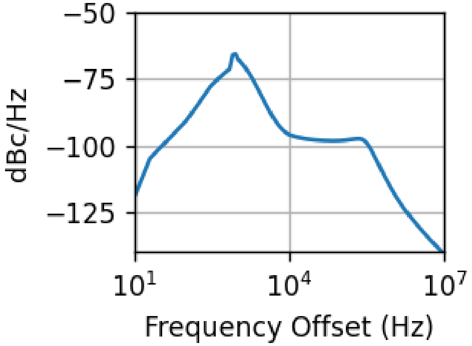


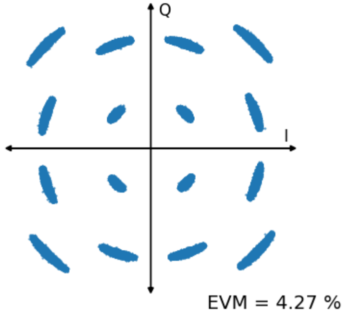
Commercial Airliner



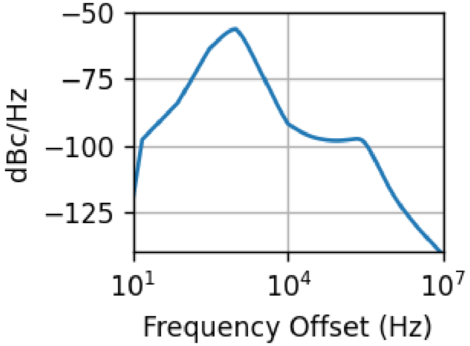


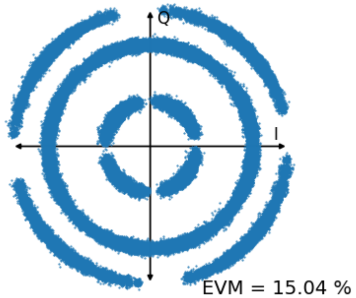
Rocket Payload





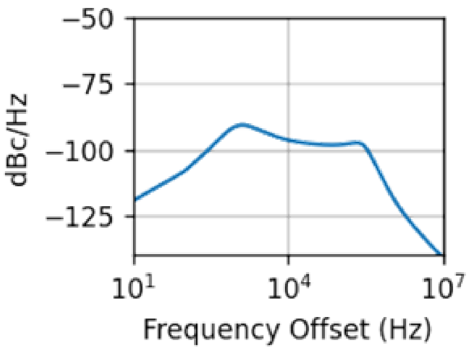
F15 (not cockpit)

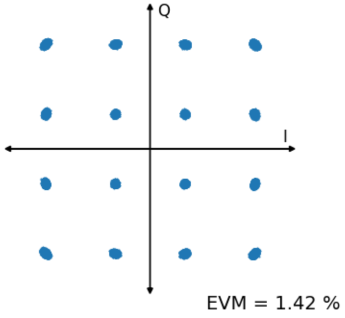




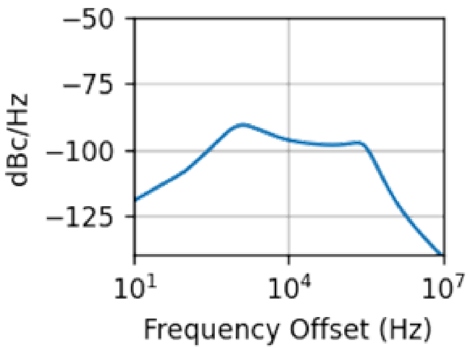
Phase Noise and EVM for Low-g TCXO

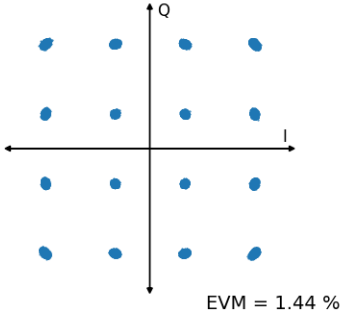
Naval Surface Vessel



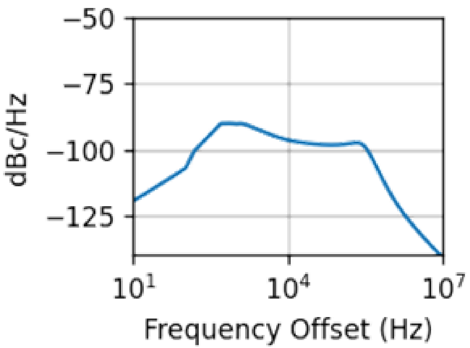


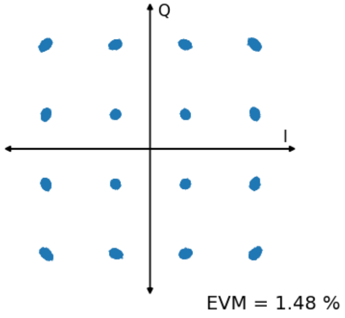
Road Vehicle



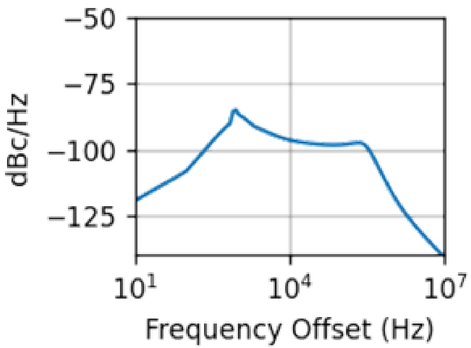


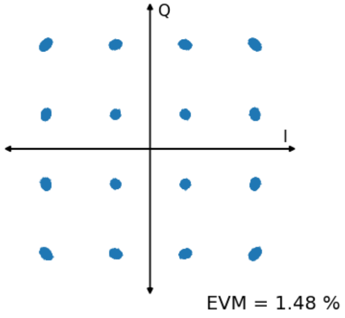
Commercial Airliner



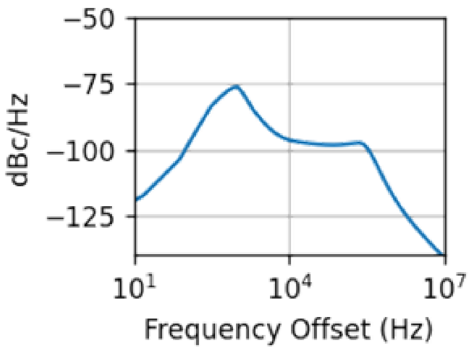


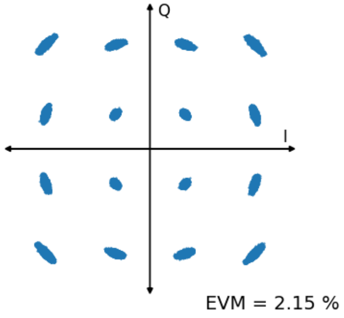
Rocket Payload





F15 (not cockpit)





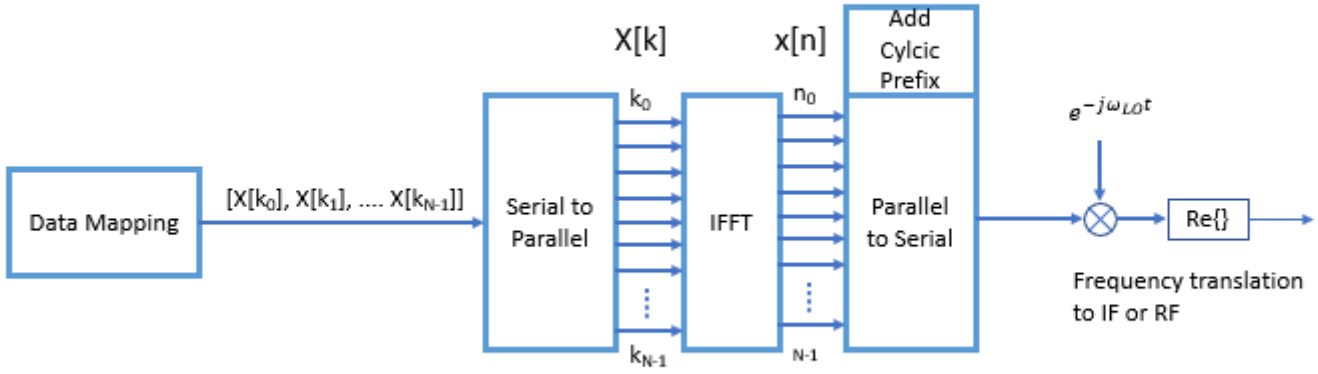
Summary

- Phase noise degradation due to vibration is most prevalent in the 10 Hz - 2 kHz range
- Low energy vibration past 2 kHz still affects phase noise
- Correctly choosing the correct phase carrier tracking can mitigate most significant effects for 5G and other similar architectures using QAM and OFDM
- Low g oscillators can effectively mitigate the EVM degradation in almost all cases
- EVM levels will only be more challenging at 4096 QAM and higher
- LO phase noise is only one source of EVM

Thank You

Backup Slides

OFDM Transmitter Implementation



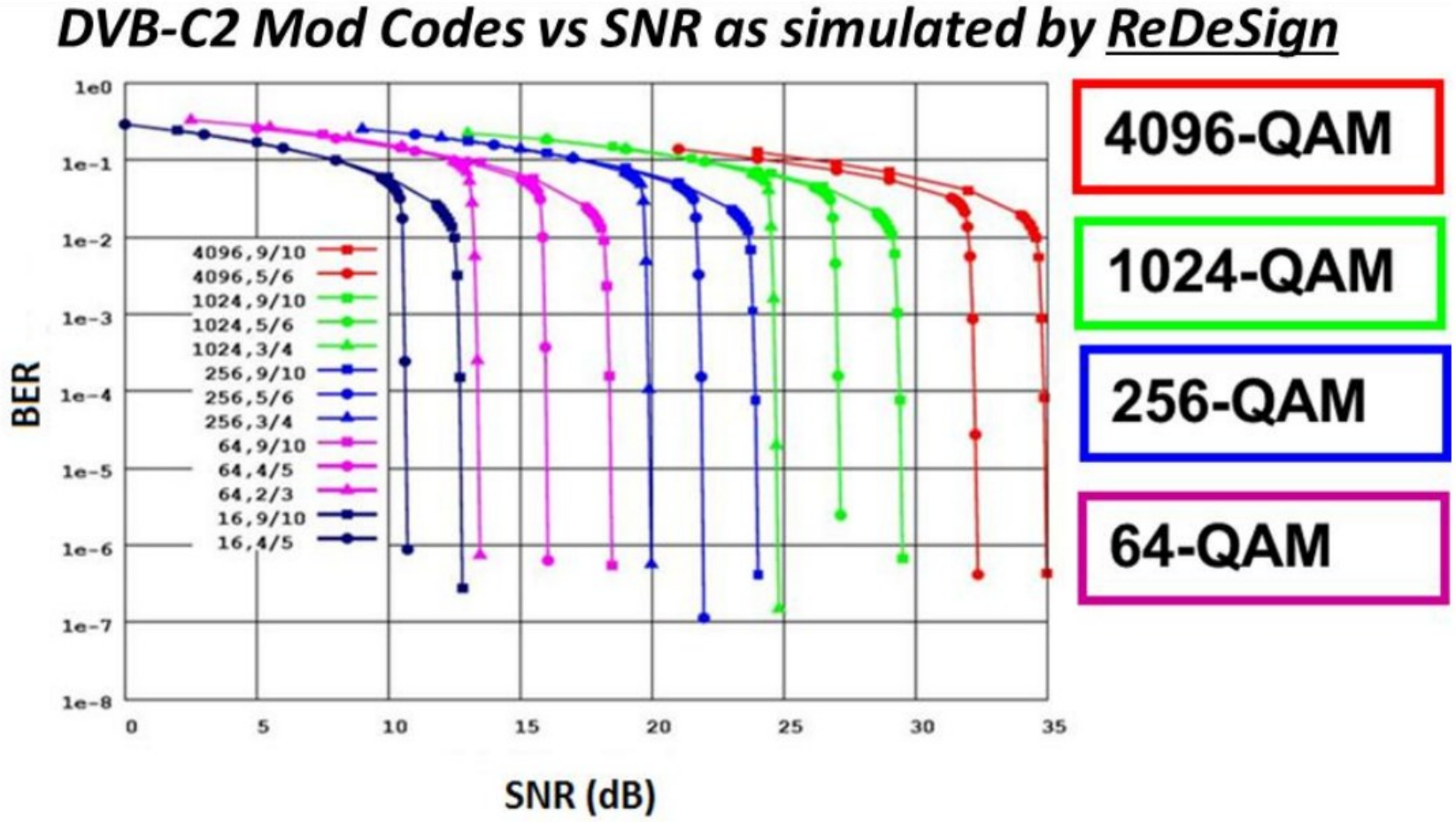


Figure 4 – SNR for OFDM with LDPC Forward Error Correction [6]

From: "Performance evaluation of advanced modulation and channel coding", ReDeSign–217014, 30 Nov 2009

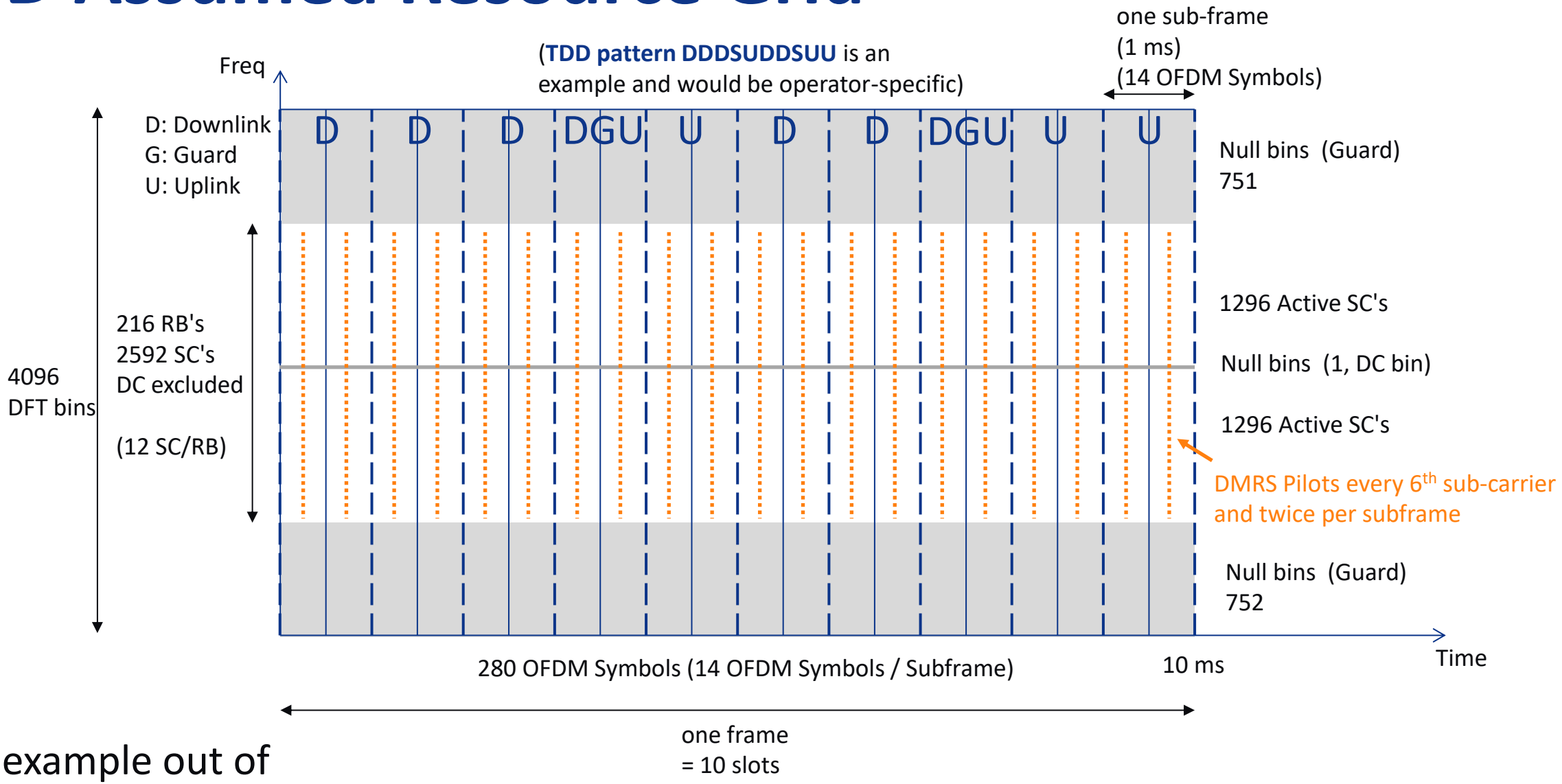
5G NR OFDM PDSCH Assumed Configuration

Band: NR Band n102
Center frequency: 6.05 GHz
Subcarrier Spacing (f_{scs}): 15 kHz
Channel BW: 40 MHz
Number of Resource Blocks = 216
Total active sub-carriers = 216 x 12 = 2592
Total number of sub-carriers (N): 4096 (including nulled carriers)
Sampling rate ($f_s = N f_{scs}$): 61.44 MHz
Null bins: 752 (guard), 1 (DC), 751 (guard)
Slot duration (T): 0.001 seconds
OFDM Symbols per slot: (M) 14 (standard cyclic prefix)
Cyclic Prefix (approx. $\text{int}\left(\frac{T f_s}{M}\right) - N$): 293 samples
- 320 for first symbol 0 in slot, 288 for symbols 1-13 in slot

DMRS Reference Interval: Typically every 6th subcarrier in FR1, remaining RE's carry PDSCH
- Once per slot (standard phase tracking)
- Twice per slot (enhanced phase tracking)

https://www.sharetechnote.com/html/5G/Handbook_5G_Index.html

TDD Assumed Resource Grid



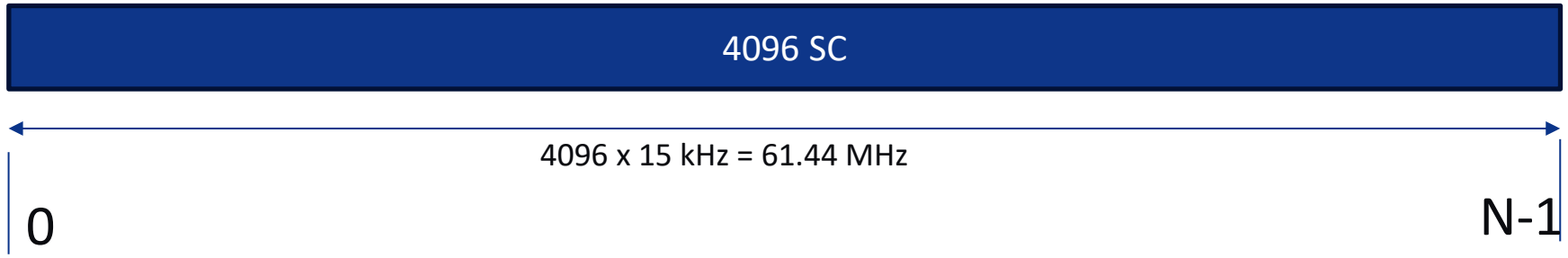
One example out of
MANY possibilities for 5G

5G NR OFDM Symbol ($\mu = 0$)

FFT bin 0 to bin N-1

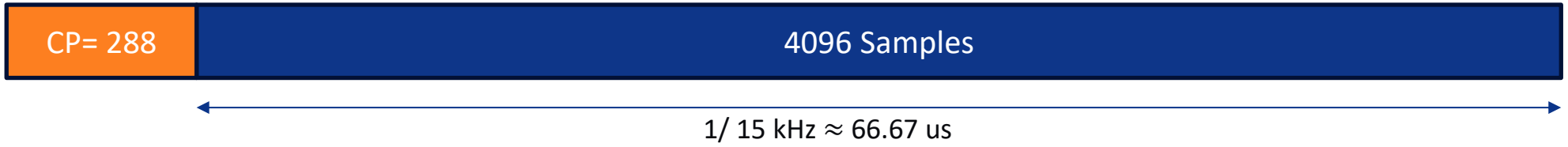
DC N= fs

Freq Domain



Time Domain

(sample rate: 4096/66.67e-6 = 61.44 MHz
if sampled at 1 sample per subcarrier symbol)



First Symbol in Slot = 320 + 4096=4416, Remaining 13 Symbols = 288 + 4096=4384. Total =4416+13*4384=61408 samples /slot

1 ms / 14 ≈ 71.43 us

61408 / 61.44E6 ≈ 1 ms

TDD Pattern over OFDM Frame (10 ms)

Slot #	Type	Comment
0	D	Full downlink slot
1	D	Full downlink slot
2	D	Full downlink slot
3	S	Special slot (40% DL, Guard, 40% UL)
4	U	Full uplink slot
5	D	Full downlink slot
6	D	Full downlink slot
7	S	Special slot (40% DL, Guard, 40% UL)
8	U	Full uplink slot
9	U	Full uplink slot

Example case assuming the following TDD Pattern: DDDSUDDSUU (10 slots) repeating every frame 60% DL 40% UL