Choose Proper Parameters in Frequency Spread Spectrum Design

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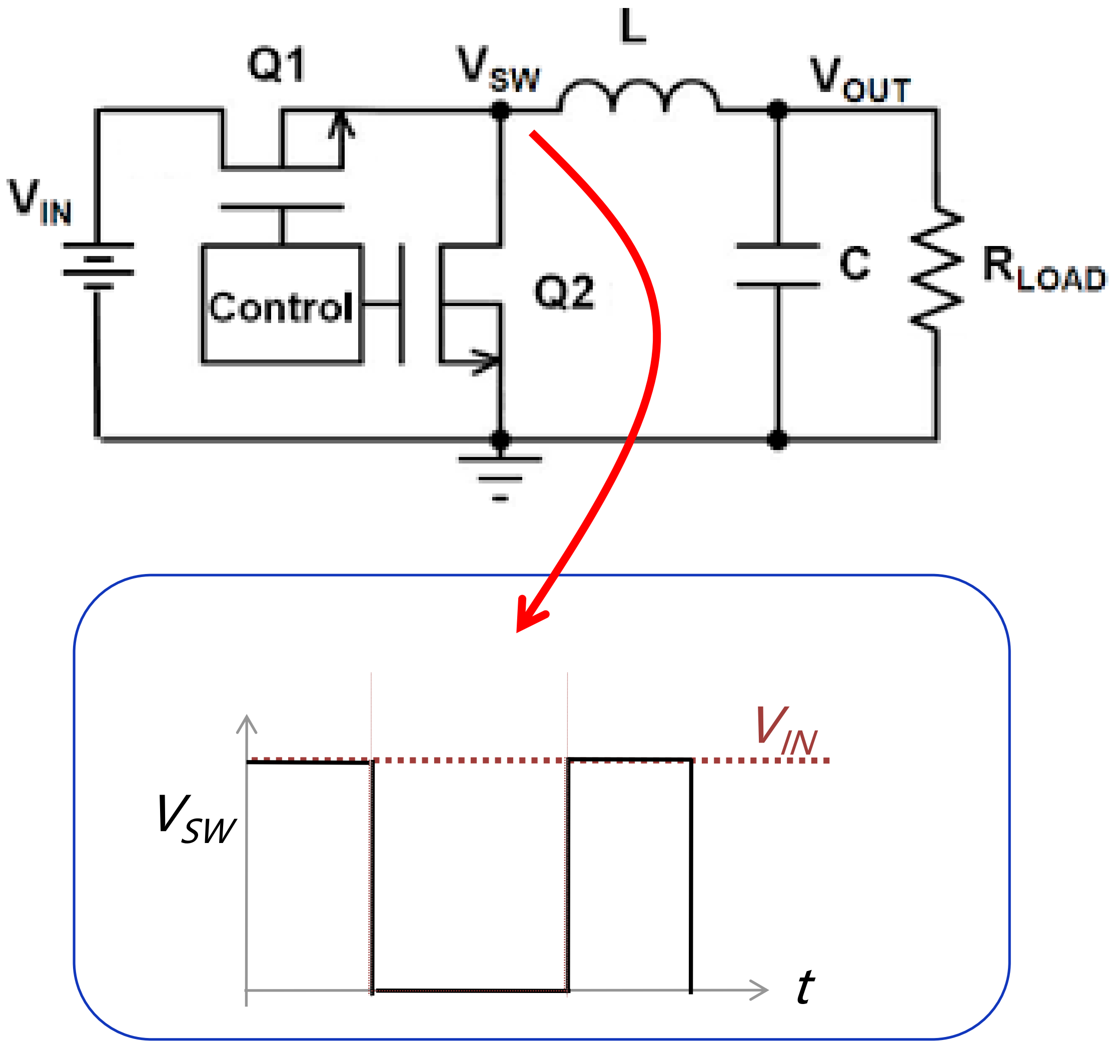
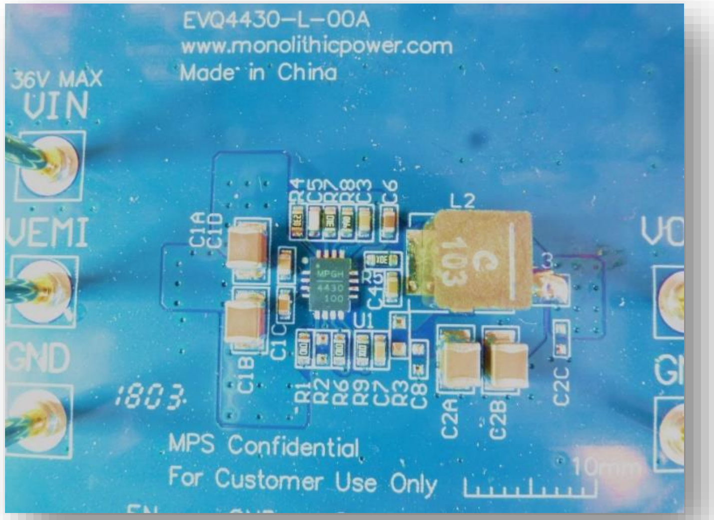
Agenda

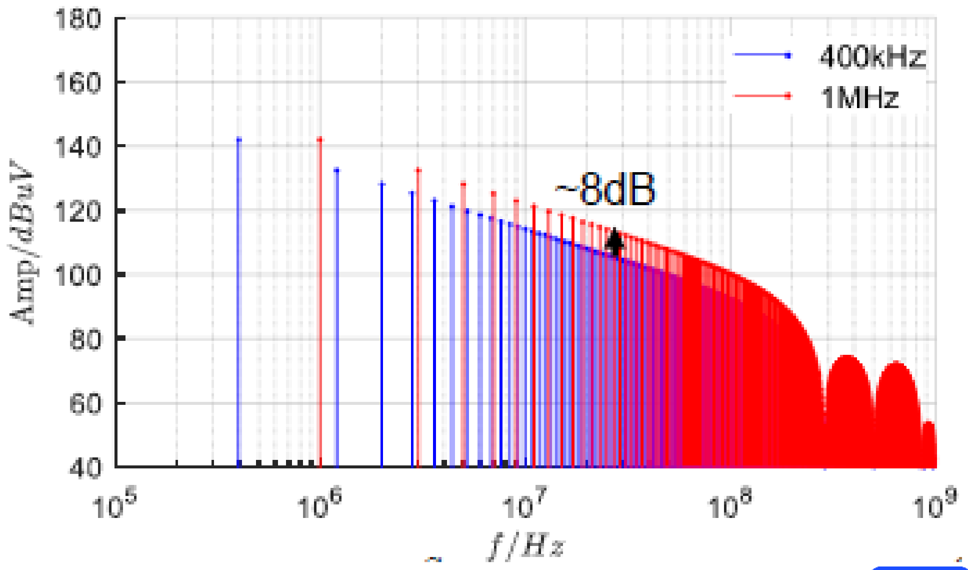
- Introduction to Frequency Spread Spectrum (FSS)
- Practical Methods to Evaluate FSS
- Choosing the Proper Parameters in FSS
- FSS Consideration for Various Applications

Introduction to Frequency Spread Spectrum

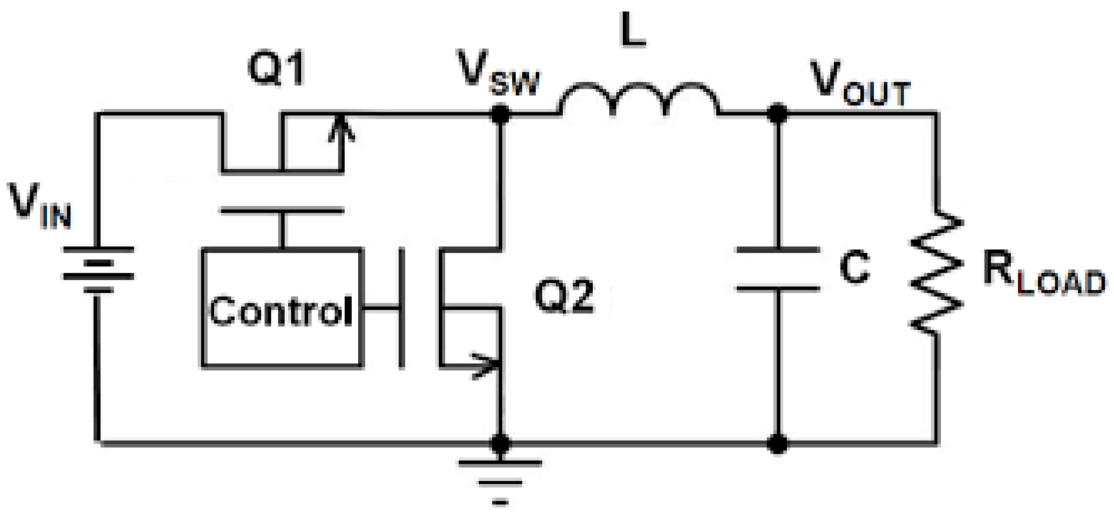
EMI Noise Source

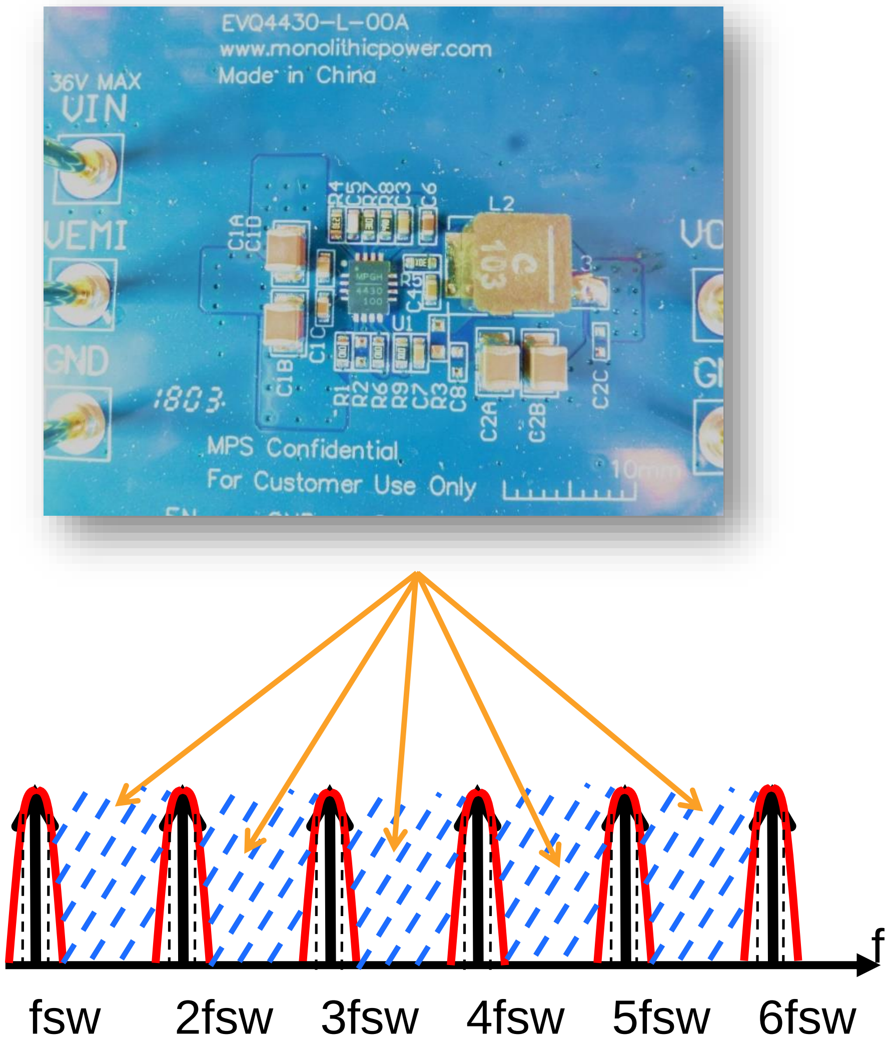


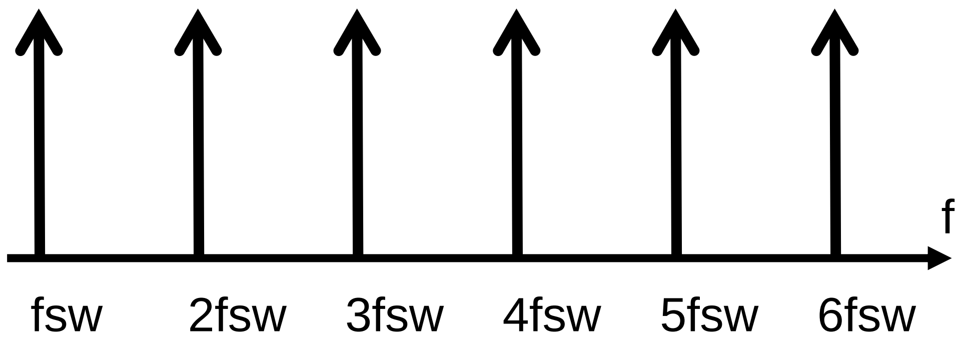




Applying Frequency Spread Spectrum

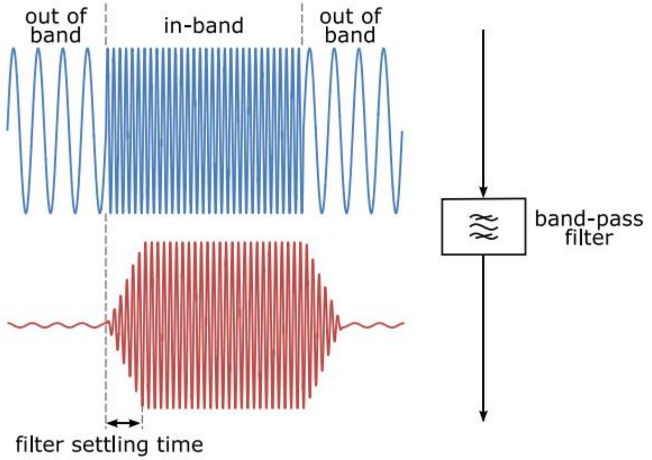






General Questions on FSS

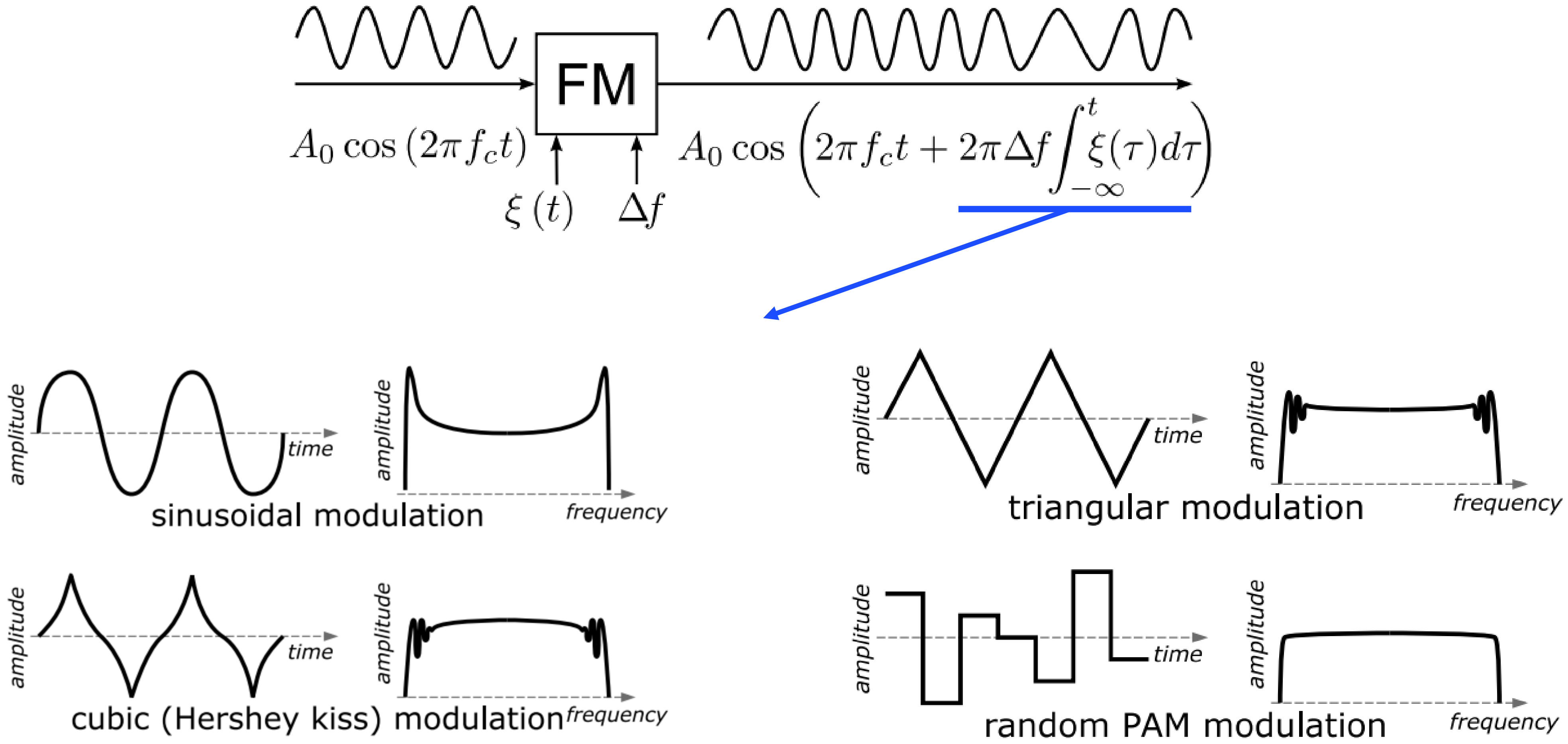
- Is FSS effective or just a trick?
  - Frequency Domain: EMI victim circuit is sensitive to only a few frequency ranges, where FSS helps to reduce the power density on these ranges.
  - Time Domain: EMI victim circuit has a settling time. If the time interval for the sensitivity frequency band signal is shorter than the settling time, the interference will be reduced [1].



- Is there any disadvantage or trade-off of FSS?
  - The FSS may influence the DC/DC output **ripple**.
  - Large FSS span may influence the **stability** of the converter, and may violate the sensitive bands such as **AM band**.
  - FSS may generate audible noise if the modulation frequency is located at the **audible band**.

[1] F. Pareschi, R. Rovatti and G. Setti, "EMI Reduction via Spread Spectrum in DC/DC Converters: State of the Art, Optimization, and Tradeoffs," in *IEEE Access*, vol. 3, pp. 2857-2874, 2015.

Mathematical Expression of FSS



[1] F. Pareschi, R. Rovatti and G. Setti, "EMI Reduction via Spread Spectrum in DC/DC Converters: State of the Art, Optimization, and Tradeoffs," in *IEEE Access*, vol. 3, pp. 2857-2874, 2015.

Practical Methods to Evaluate FSS

Simulation & Experiment

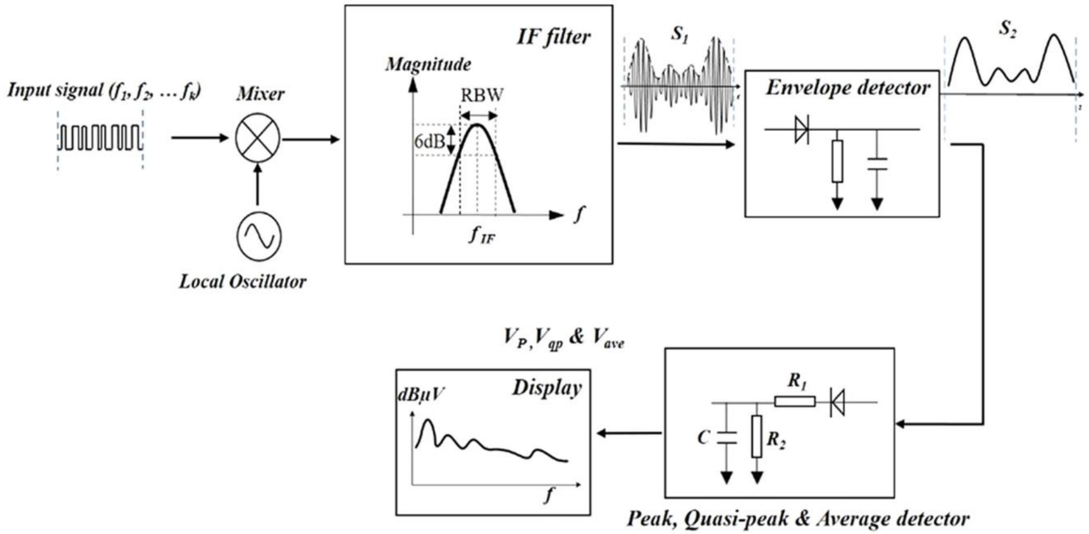
Evaluation Methods

- Simulation: Based on EMI receiver principles
- Experiment: Based on Real Silicon
- Experiment: Based on Signal Generator

Diagram of a Spectrum Analyzer

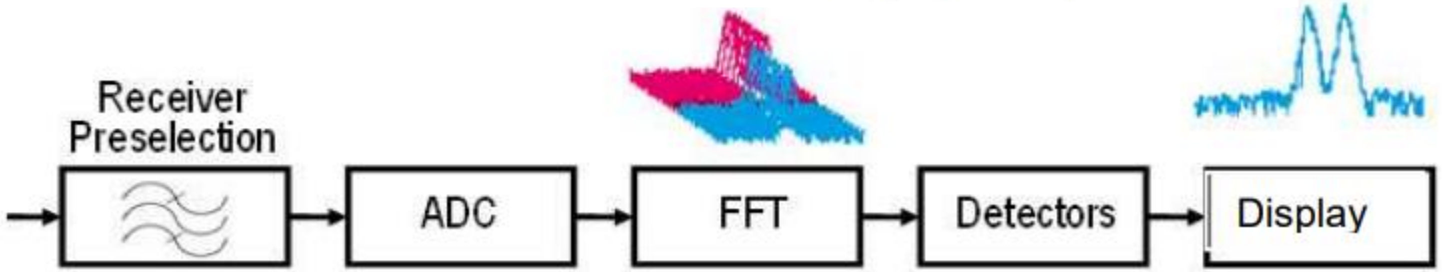
The FSS simulation shall be preformed based on the principle of EMI receivers, instead of simple FFT.

Frequency-stepped EMI receiver



[2]

Time-domain EMI receiver



[3]

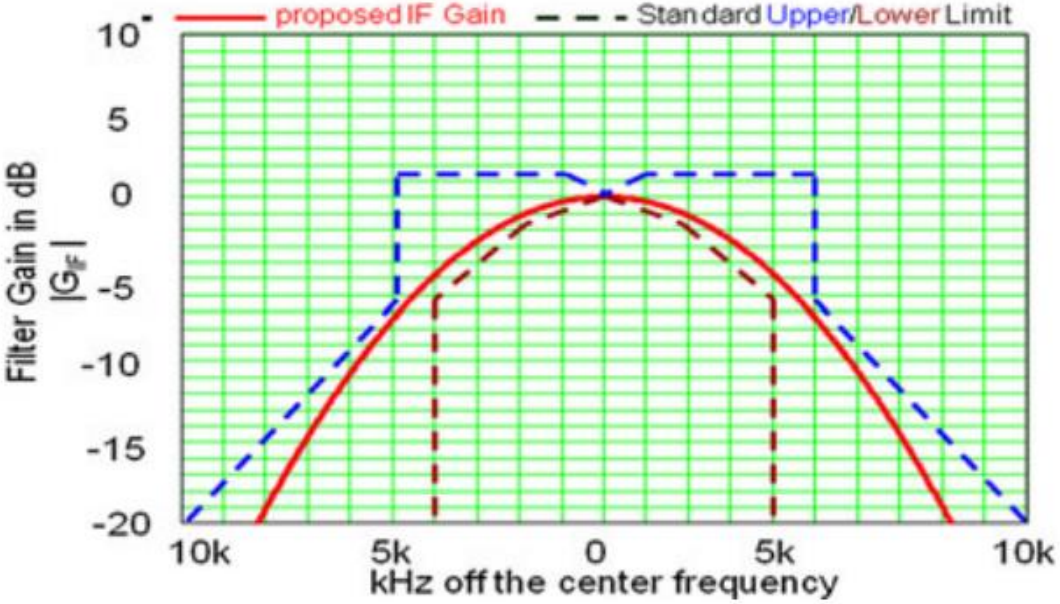
[2] L. Yang, S. Wang, H. Zhao and Y. Zhi, "Prediction and Analysis of EMI Spectrum Based on the Operating Principle of EMC Spectrum Analyzers," in IEEE Transactions on Power Electronics, vol. 35, no. 1, pp. 263-275, Jan. 2020.

[3] “Comparison of Time Domain Scans and Stepped Frequency Scans in EMI Test Receivers”, Rohde & Schwarz.

Resolution Bandwidth (RBW)

The IF filter can be regarded as a band-pass Gaussian filter to extract the components around the targeted frequency.

The resolution bandwidth (RBW) is defined as -3dB (or -6dB in CISPR) of the filter. The IF gain is also regulated by CISPR.



[4]

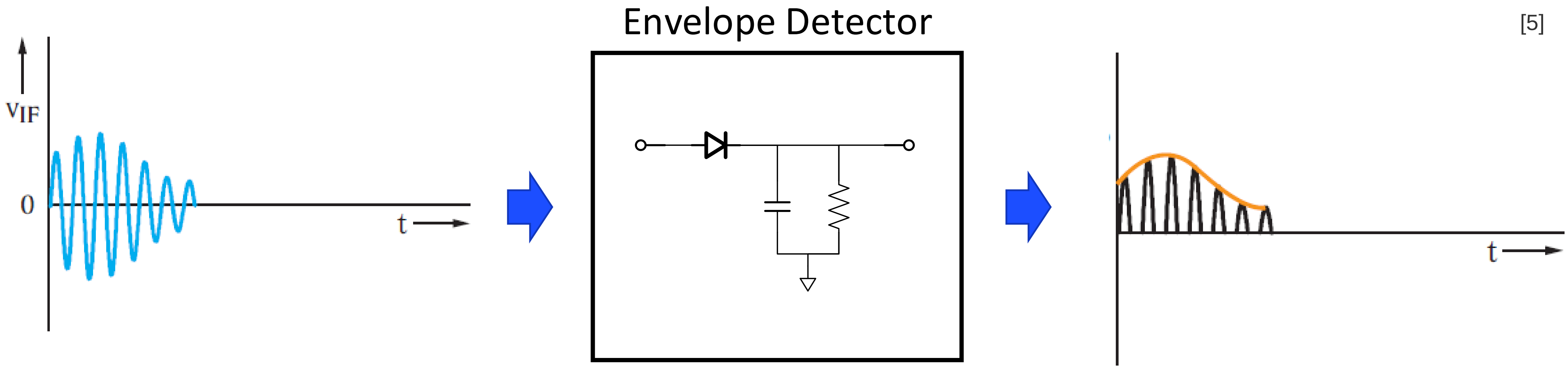
The behavior of the IF filter can be modeled in the simulation.

$$|G_{\mathrm{IF}}(f, f_{\mathrm{IF}})| = e^{-(f-f_{\mathrm{IF}})^2/c^2}$$

$$c = \frac{\mathrm{RBW}}{2\sqrt{\ln 2}}.$$

[4] Z. Wang, S. Wang, P. Kong and F. C. Lee, "DM EMI Noise Prediction for Constant On-Time, Critical Mode Power Factor Correction Converters," in IEEE Transactions on Power Electronics, vol. 27, no. 7, pp. 3150-3157, July 2012.

Envelope Detector



Note: The output of envelope detector can be regarded as the magnitude of the input signal over time. This process can be modeled in simulation.

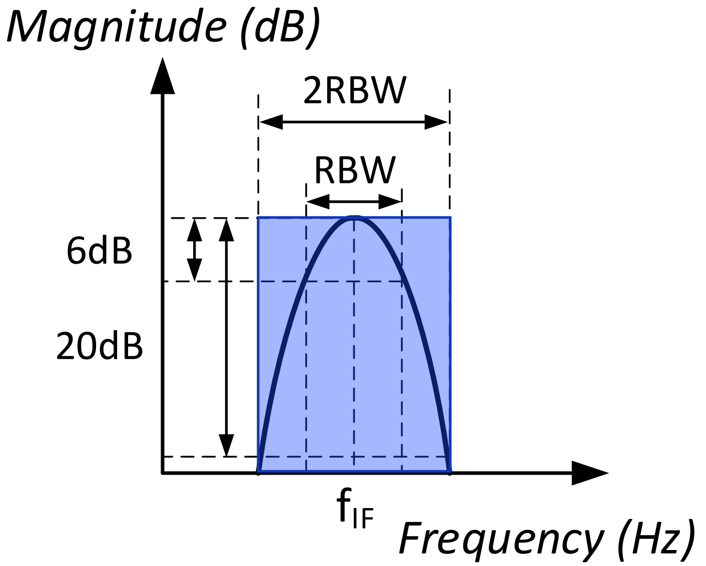
[5] “Fundamentals of Spectrum Analysis”, Rohde & Schwarz.

Modeling Envelope Detector

$$v_{sig\_IF}(t) = \sum_{i=1}^{2k+1} A_i \cos(\omega_i t + \varphi_i)$$

$$\omega_1 = 2\pi f_1 > 2\pi(f_{IF} - RBW)$$

$$\omega_{k+1} = 2\pi f_{IF}$$



Envelope based on f_{IF}:

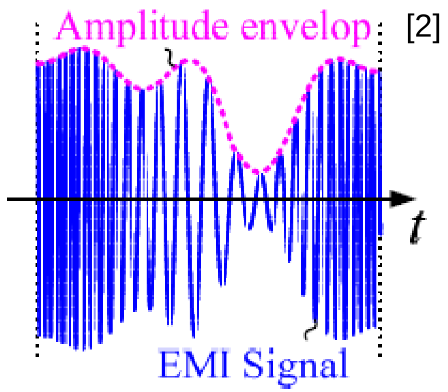
$$v_{sig\_IF}(t) = \sum_{i=1}^{2k+1} A_i \cos(\omega_{k+1} t + \alpha_i) \qquad \alpha_i = (\omega_i - \omega_{k+1})t + \varphi_i$$

$$v_{sig\_IF}(t) = e(t) \cdot \cos(\omega_{k+1} t + \varphi') = \sqrt{\left(\sum_{i=1}^{2k+1} A_i \cos(\alpha_i)\right)^2 + \left(\sum_{i=1}^{2k+1} A_i \sin(\alpha_i)\right)^2} \cdot \cos(\omega_{k+1} t + \varphi')$$

Envelope

$$e(t) = \sqrt{\sum_{i=1}^{2k+1} A_i^2 + \sum_{m=1}^{2k+1} \sum_{n=1}^{2k+1} [A_m A_n \cos(\omega_m t - \omega_n t + \varphi_m - \varphi_n)]}$$

DC AC

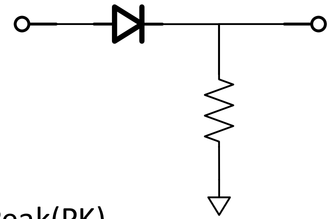


[2] L. Yang, S. Wang, H. Zhao and Y. Zhi, "Prediction and Analysis of EMI Spectrum Based on the Operating Principle of EMC Spectrum Analyzers," in IEEE Transactions on Power Electronics, vol. 35, no. 1, pp. 263-275, Jan. 2020.

Noise Detector: PK, AV and QP

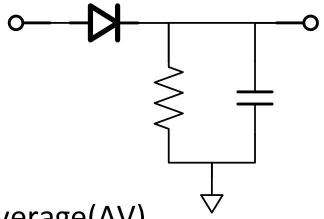
Actual Filter

Equivalence in Simulation



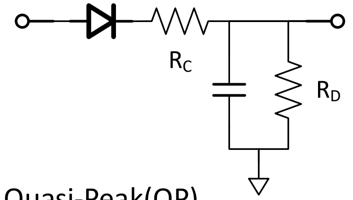
Peak(PK)

$$Peak(PK) = \max(V_1, V_2, \dots, V_N)$$



Average(AV)

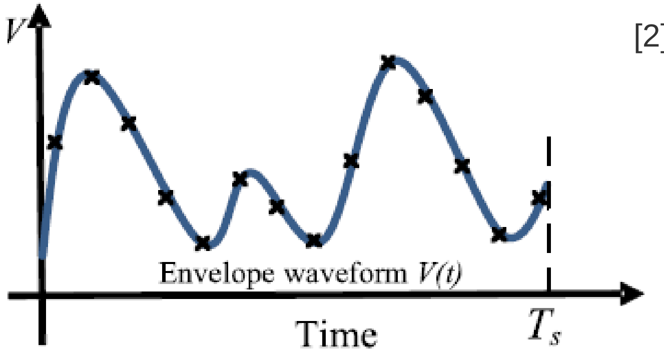
$$Average(AV) = \frac{1}{N}\sum_{i=1}^{N} V_i$$



Quasi-Peak(QP)

$$Quasi - Peak(QP) = V_{QP}$$

$$\frac{\sum_{i=1}^{Q}(V_i - V_{QP})}{R_C} = \frac{N \times V_{QP}}{R_D}$$



[2]

$$N = \frac{T_s}{t_s}$$

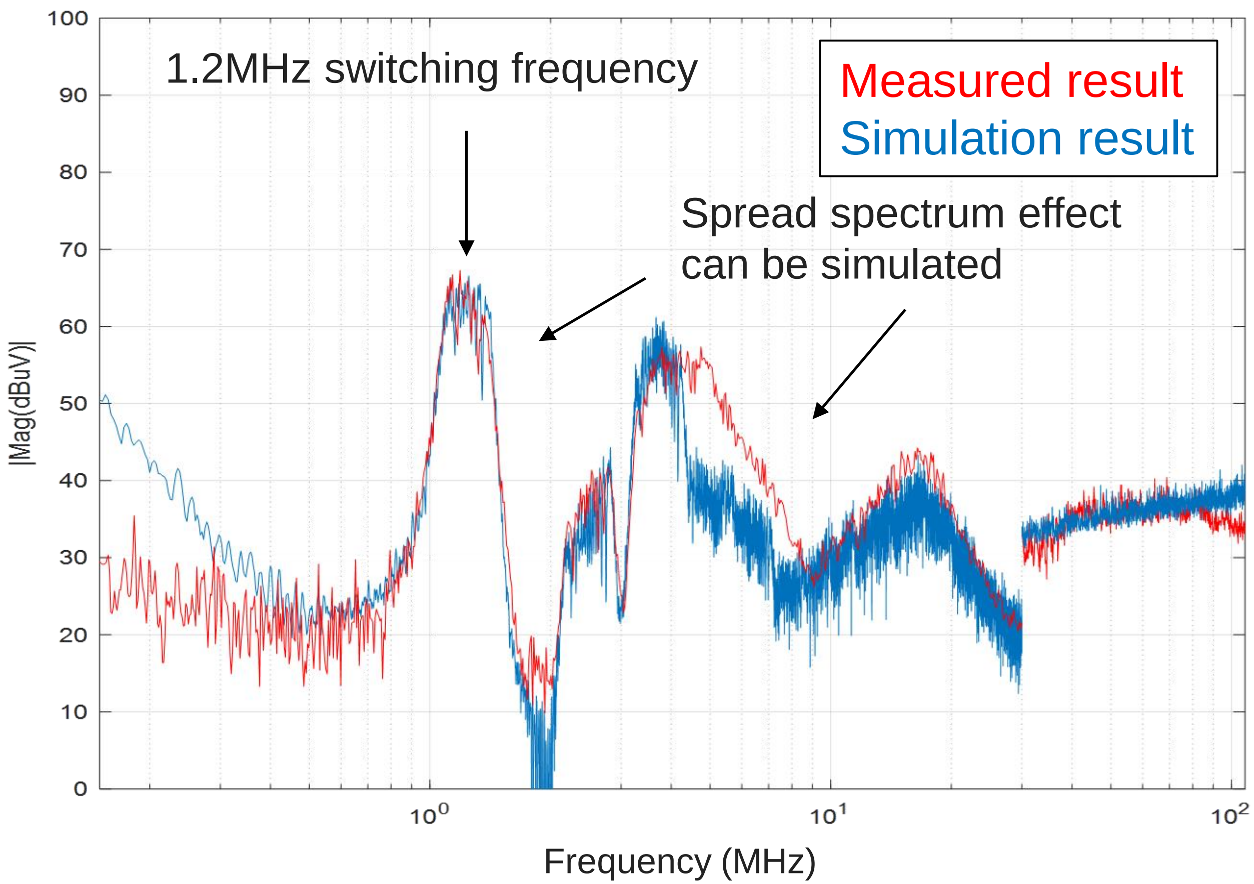
T_s: *Sampling Interval*

t_s: *Sampling Time*

[2] L. Yang, S. Wang, H. Zhao and Y. Zhi, "Prediction and Analysis of EMI Spectrum Based on the Operating Principle of EMC Spectrum Analyzers," in IEEE Transactions on Power Electronics, vol. 35, no. 1, pp. 263-275, Jan. 2020.

Simulated Result Considering EMI Receiver's Influence

DUT: MPQ7200

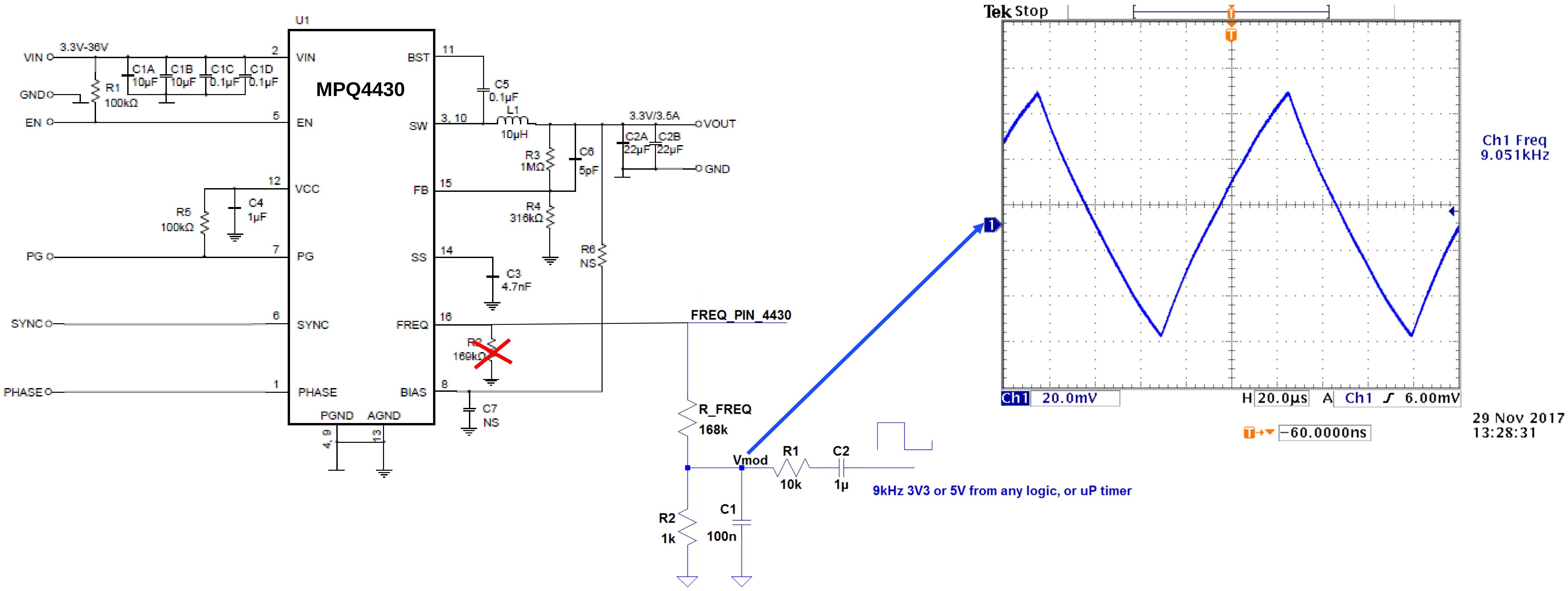


Conclusion: It is feasible to simulate the FSS performance.

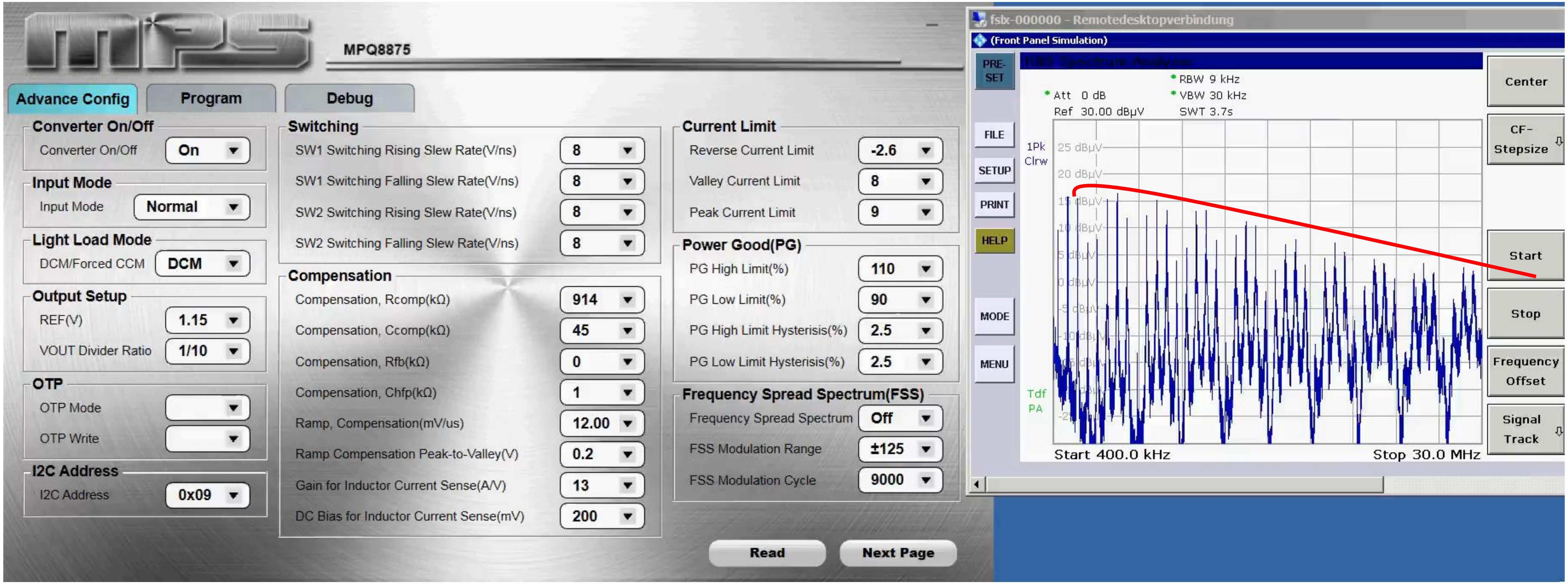
However, it is time-consuming to model the circuit and process with simulation software.

Spread Spectrum Implementation for Parts with FREQ pin

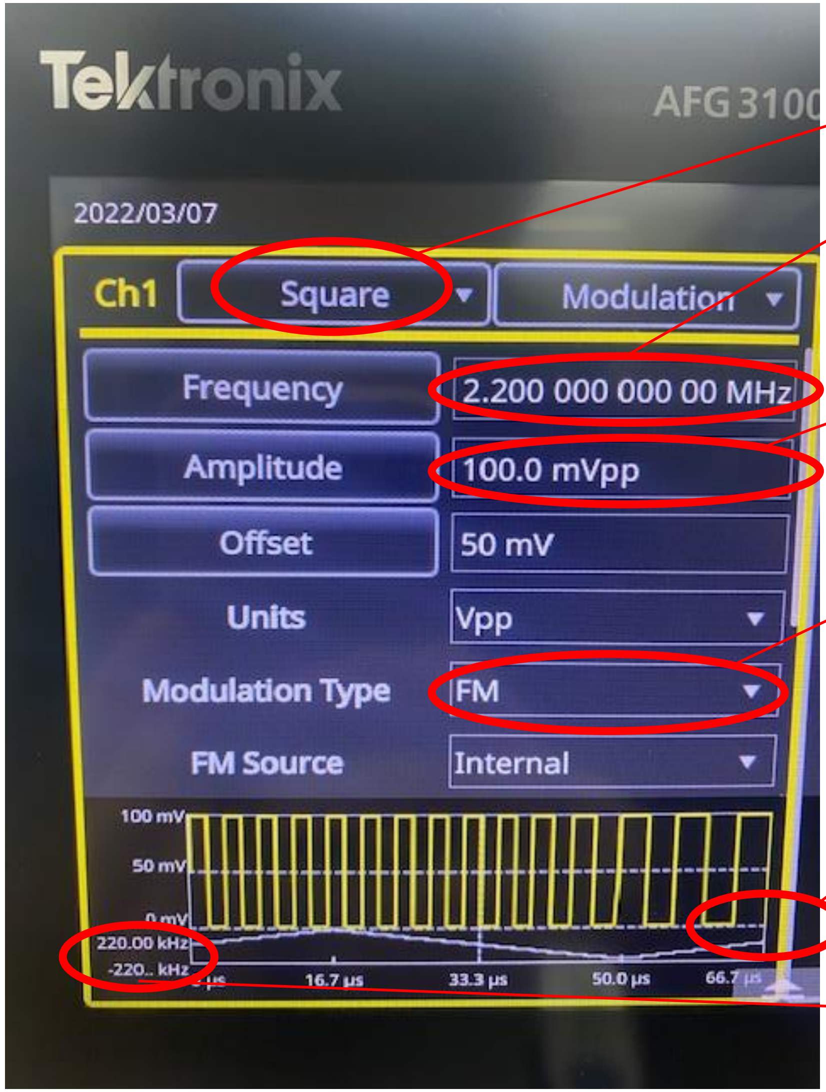
If the IC has a resistor program **FREQ** pin:



Part with Digital Options



Evaluate FSS with Arbitrary Signal Generator



Square waveform at fsw to emulate switching

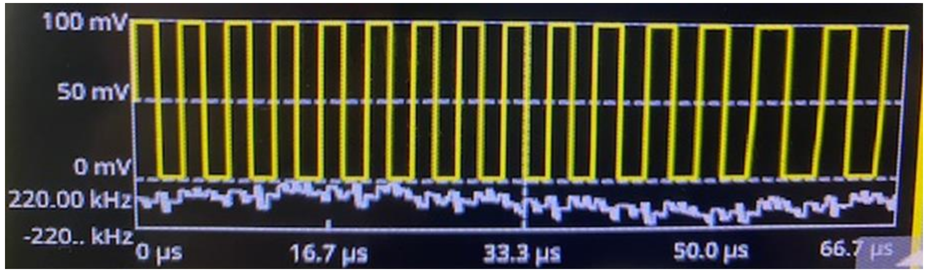
Apply a small value to protect EMI receiver

Set FM mode to implement FSS

Modulation frequency can be adjusted

Deviation can be adjusted

Can also import pre-defined code as modulation waveform



Measure the Signal with a EMI Receiver

Signal Generator | EMI Receiver | PC for Result Display

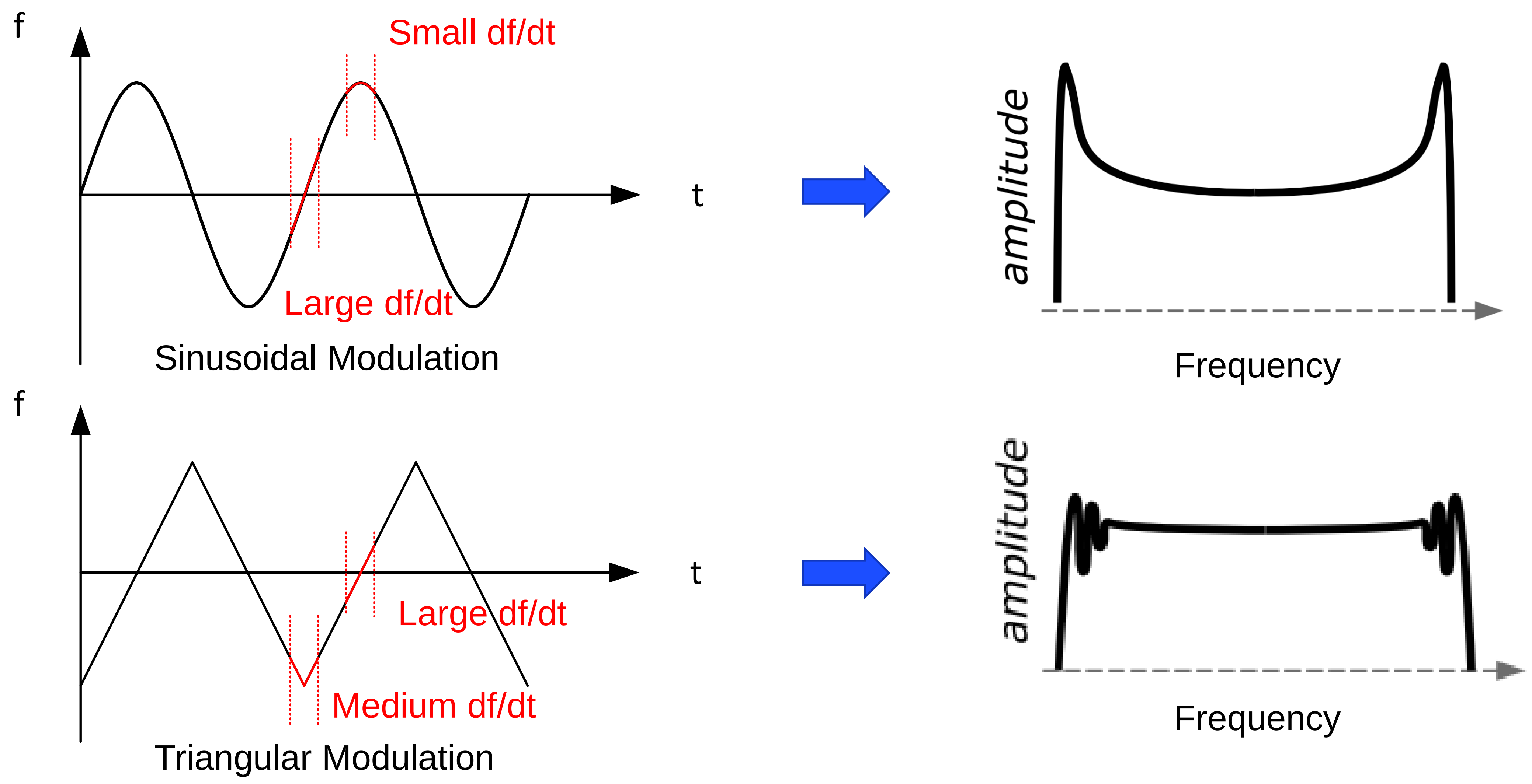
Spectrum Analyzer/EMI Receiver Setup shall follow the CISPR regulation, such as:

Apply CISPR Filter (-6dB)
RBW = 9kHz for 150kHz to 30MHz;
RBW = 120kHz for 30MHz to 108MHz;

CISPR Peak / Average detectors can be selected.

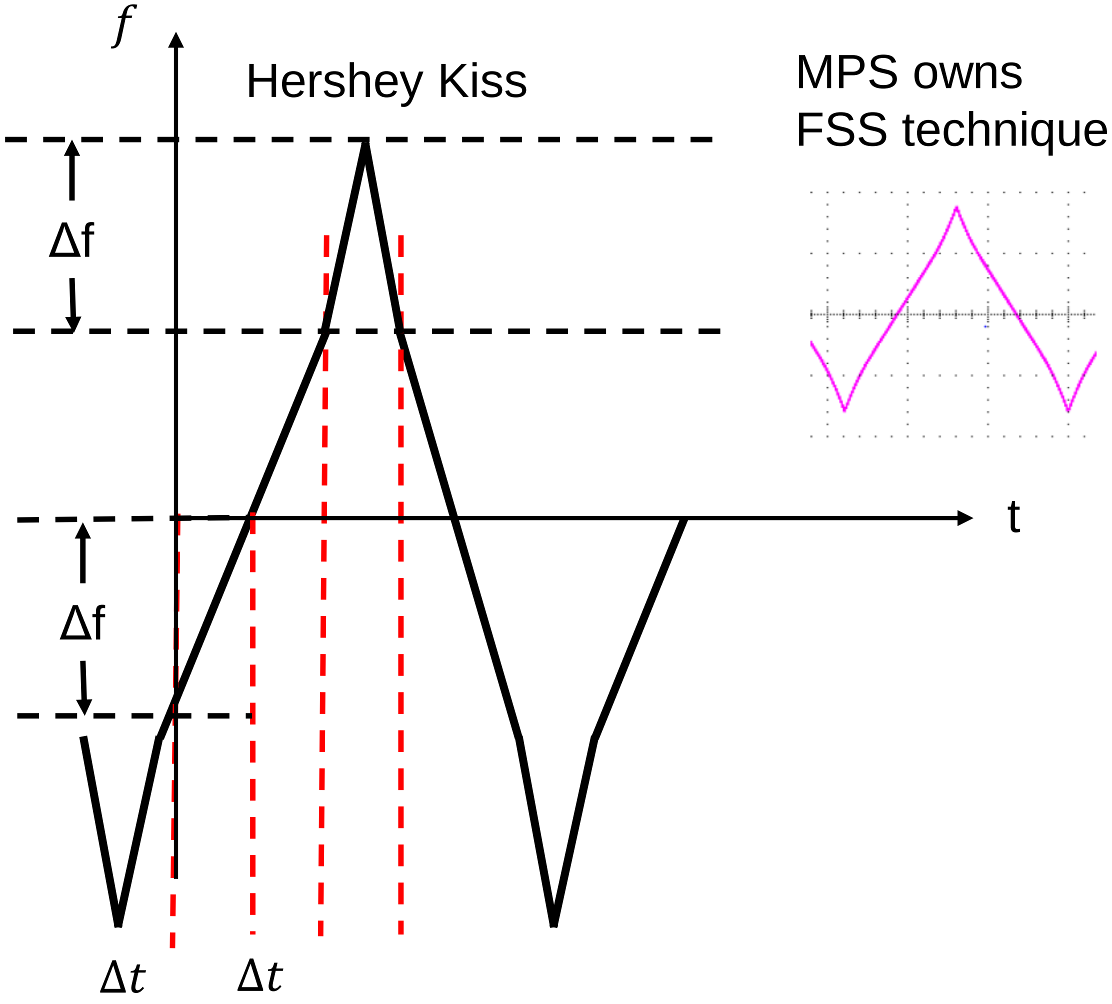
Choosing the Proper Parameters in FSS

Modulation Shape

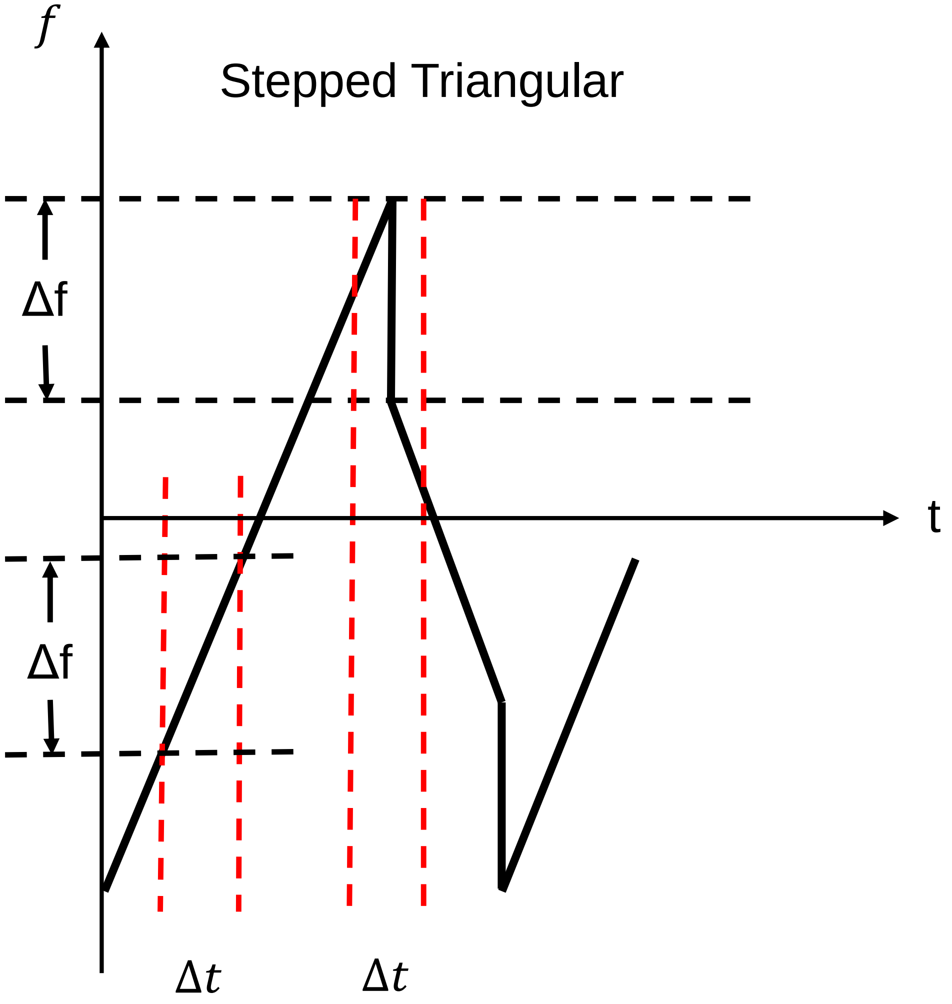


Note: The df/dt is preferred to be constant along with time. Usually Triangular modulation has good effort, which is widely applied in power supply design.

Improvement of Modulation with df/dt



MPS owns
FSS technique



Note: Both modulation has a constant df/dt – further 1-2dB improvement compare to triangular modulation.

Modulation Frequency and Frequency Span

- Modulation Frequency, f_M:

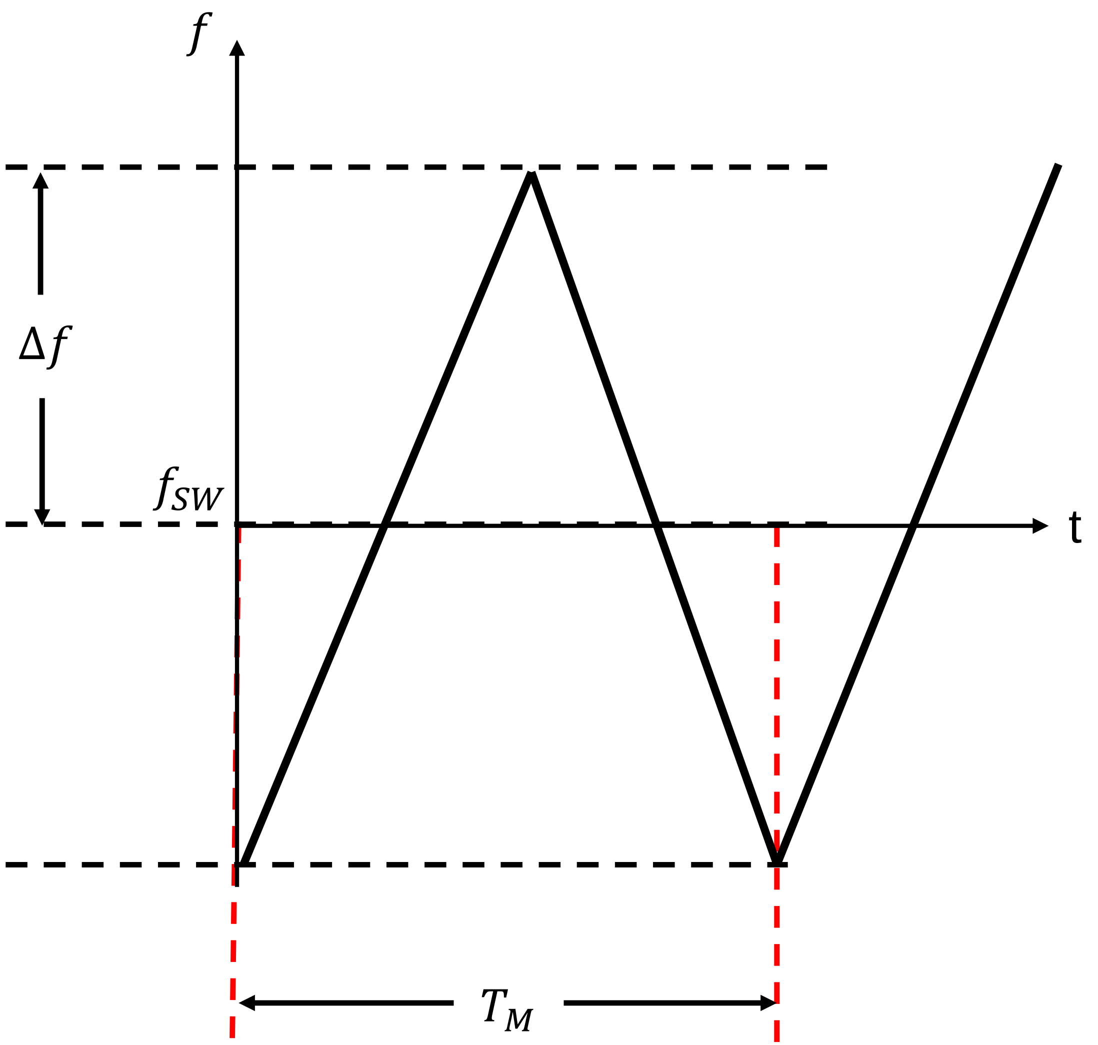
$$f_M = \frac{1}{T_M}$$

- Modulation Frequency Span, $Span$:

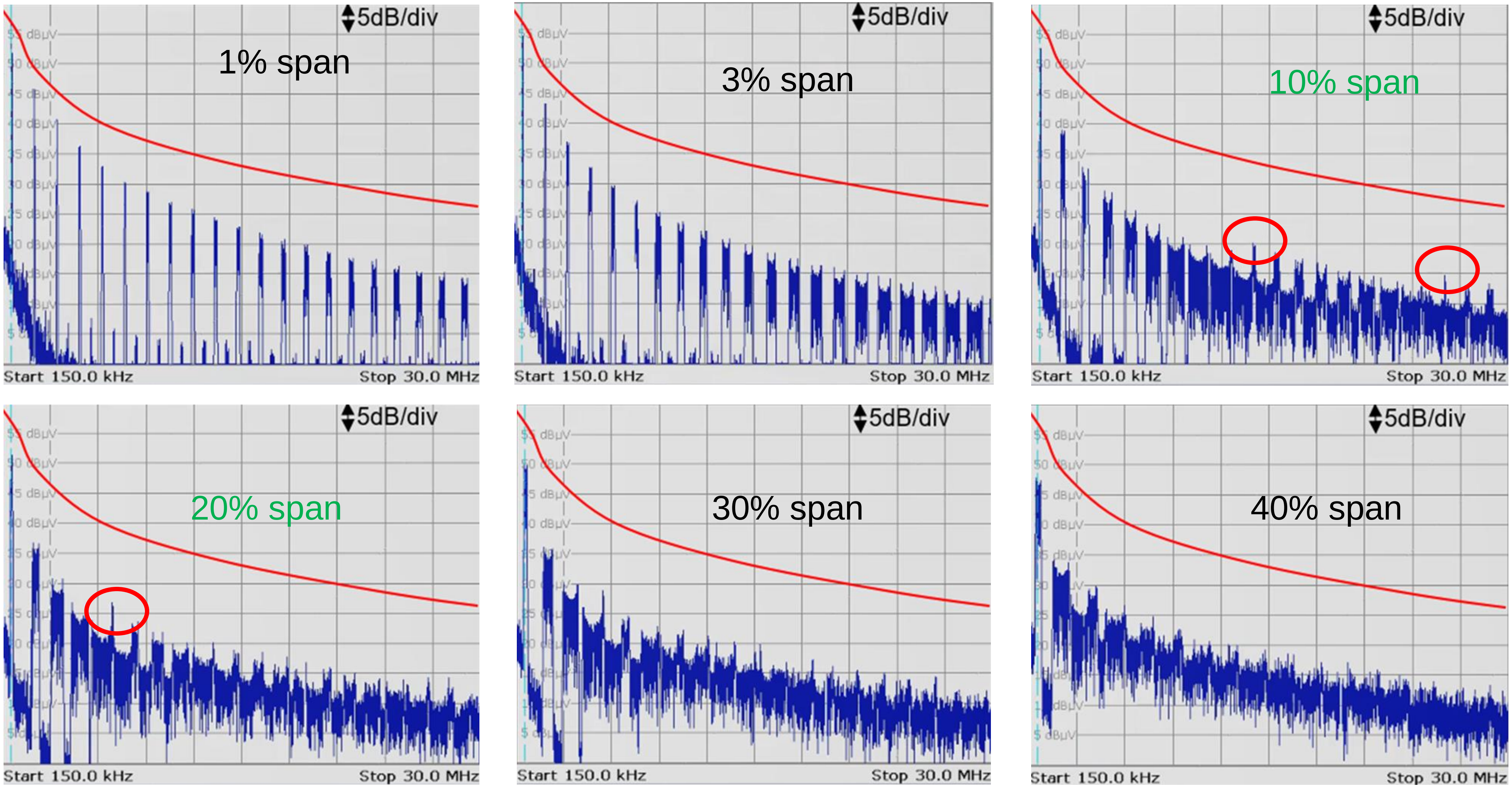
$$Span = \frac{2\Delta f}{f_{SW}}$$

- Modulation Index:

$$m = \frac{\Delta f}{f_M}$$

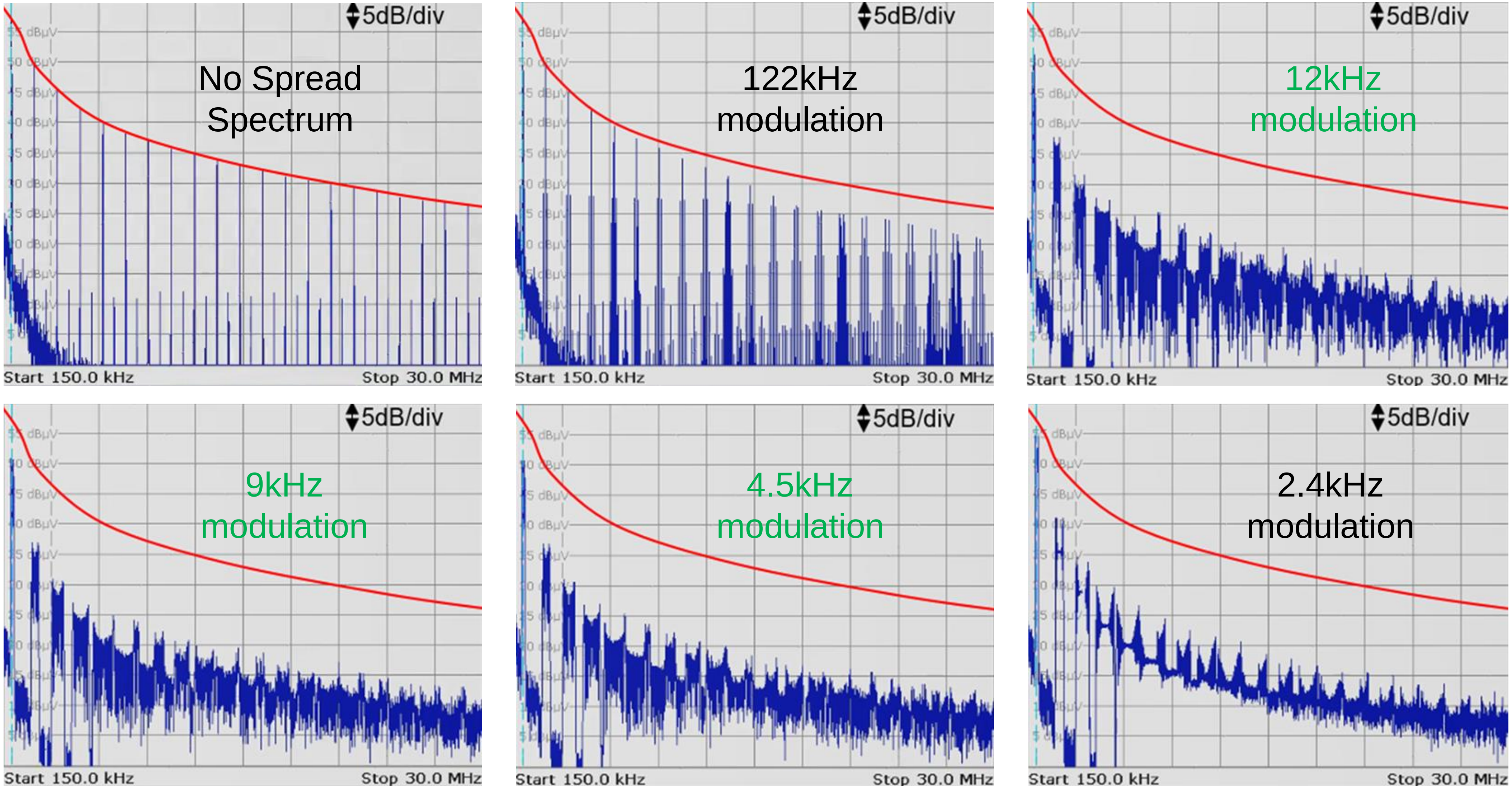


What is the Best Frequency Span?



Note: Increasing the frequency span helps to reduce the noise until the adjacent harmonics start to overlap, which occurs at frequency close to fsw/span. Besides, fsw needs to avoid sensitive frequency bands.

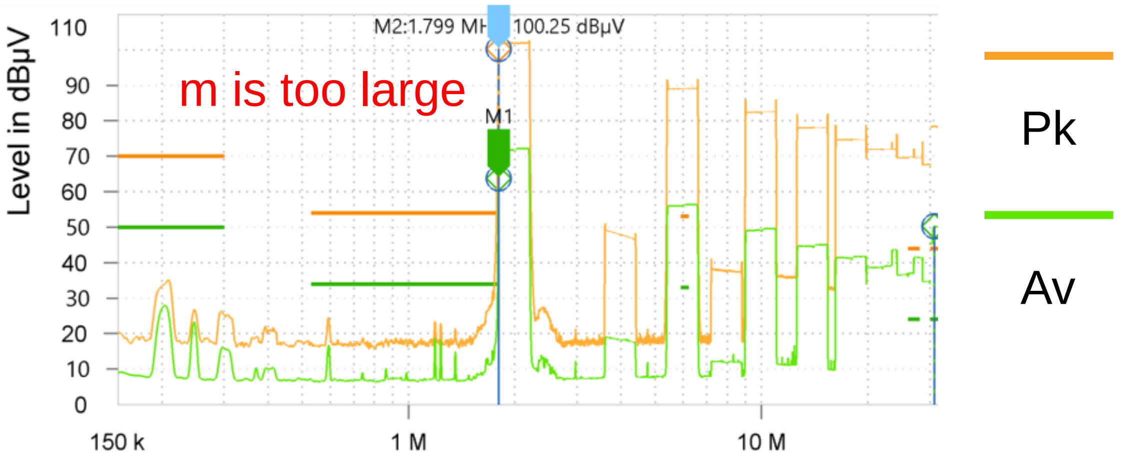
What is the Best Modulation Frequency?



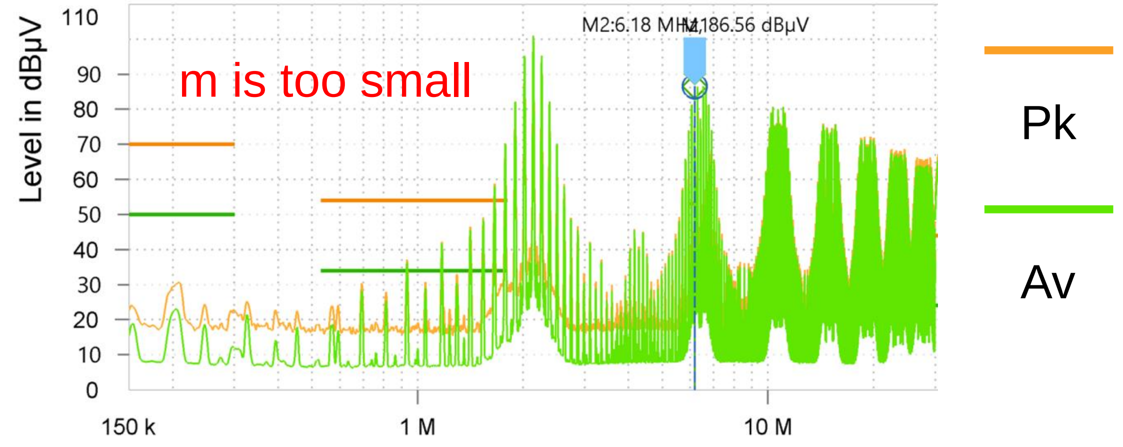
Note: For the fixed RBW, there is a "best modulation frequency" for peak EMI noise, which is usually around RBW in practice.

More General Conclusion for Peak

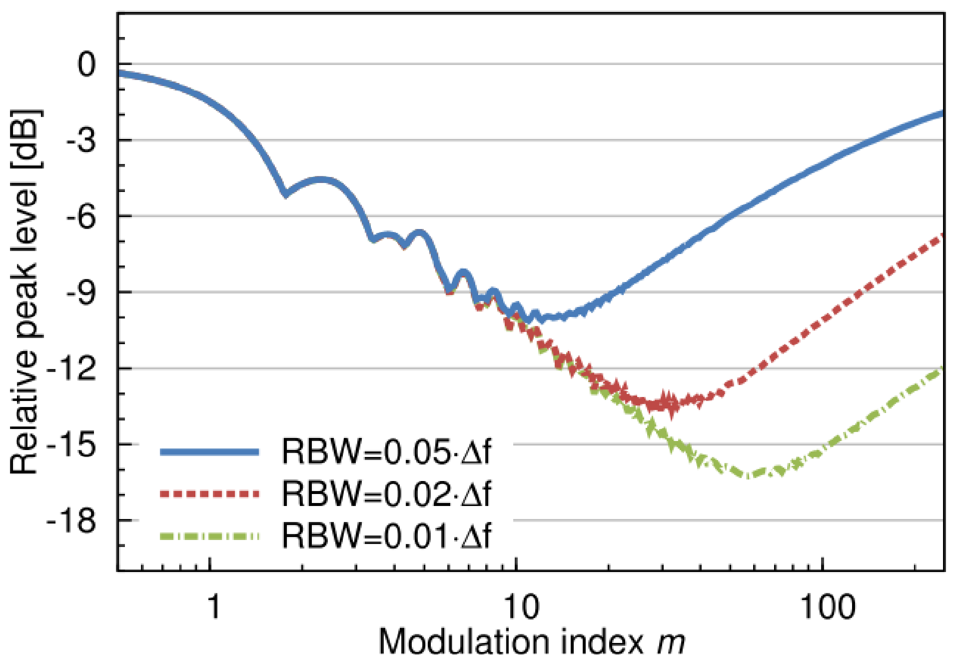
$\Delta f = 200\text{kHz}, f_M = 100\text{Hz}, m = 2000$



$\Delta f = 200\text{kHz}, f_M = 120\text{kHz}, m = 1.67$



PK EMI vs. Modulation Index [6]

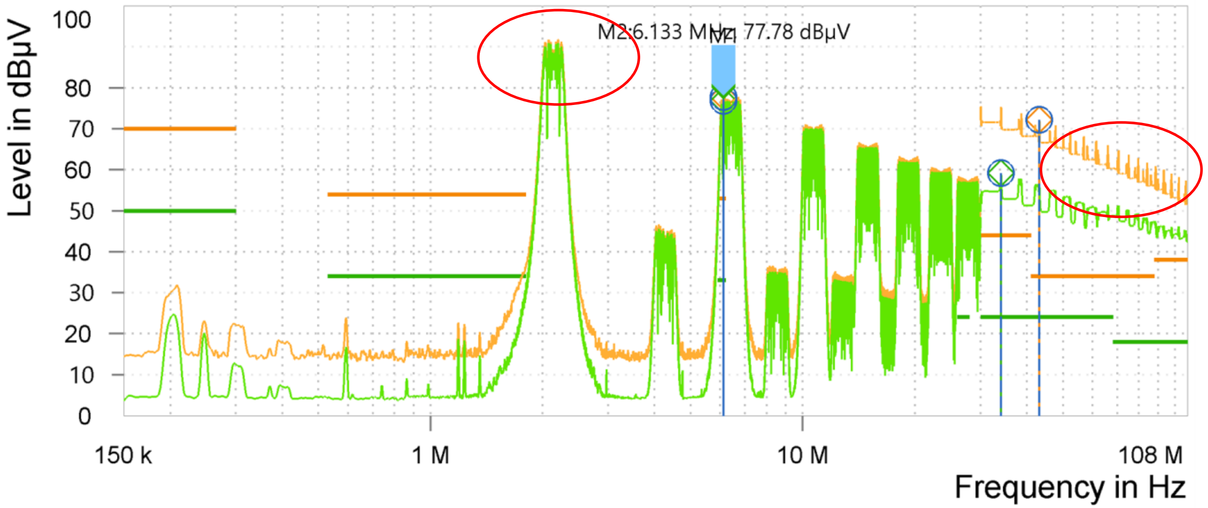


$$m = \frac{\Delta f}{f_M}$$

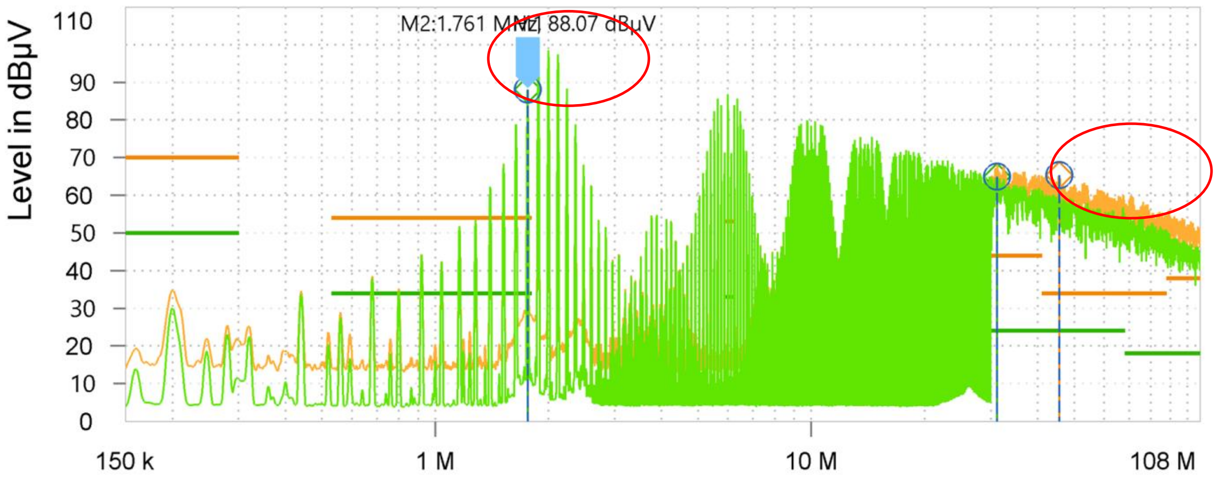
[6] F. Pareschi, G. Setti, R. Rovatti and G. Frattini, "Practical Optimization of EMI Reduction in Spread Spectrum Clock Generators With Application to Switching DC/DC Converters," in *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4646-4657, Sept. 2014,

Influence of RBW

$\Delta f = 200\text{kHz}, f_M = 9\text{kHz}$



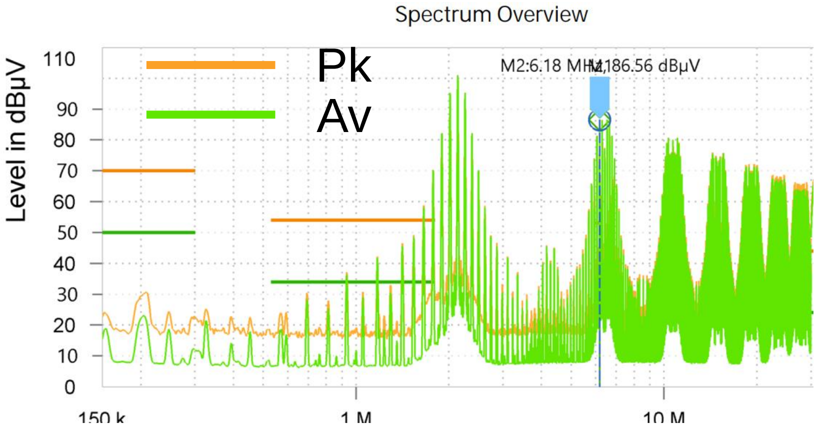
$\Delta f = 200\text{kHz}, f_M = 120\text{kHz}$



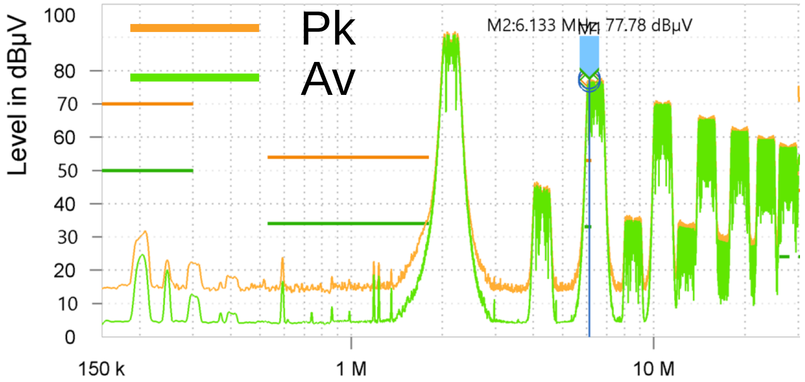
Note: With a high f_M value, the result between 30MHz and 108MHz is better, as the RBW for the band from 30MHz to 108MHz is 120kHz.

How About Average Detector?

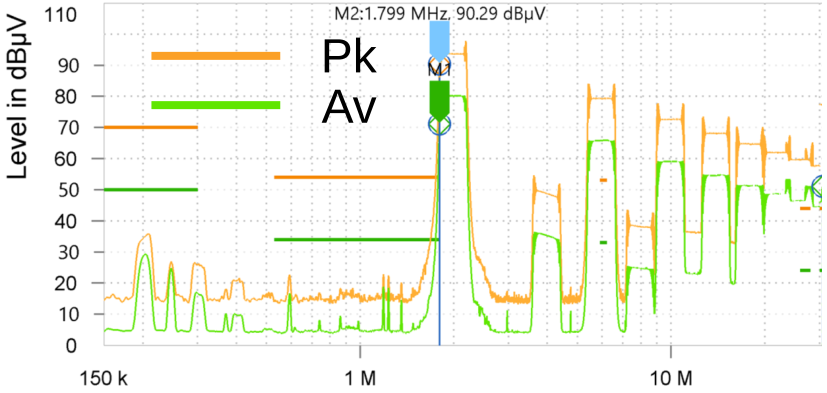
$\Delta f = 200\text{kHz}, f_M = 100\text{kHz}, m = 2$



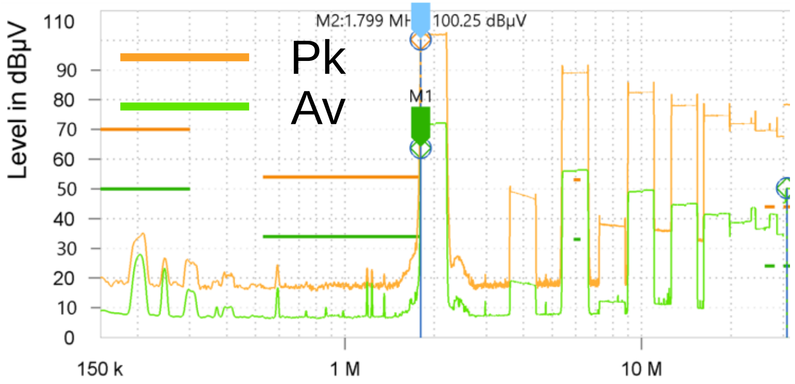
$\Delta f = 200\text{kHz}, f_M = 9\text{kHz}, m = 22$



$\Delta f = 200\text{kHz}, f_M = 1\text{kHz}, m = 200$



$\Delta f = 200\text{kHz}, f_M = 100\text{Hz}, m = 2000$



Note: For the average detector, when the modulation index increases, the result is getting better.

Trade-Off: Detector and Frequency

$$f_{sw} = 2.2MHz, \Delta f = 220kHz, test\ with\ EMI\ receiver$$

FSS Modulation	EMI (PK) Reduction (dBuV)		EMI (AV) Reduction (dBuV)	
	LF (2.2MHz)	HF (108MHz)	LF (2.2MHz)	HF (108MHz)
No Modulation	**0dB**	**0dB**	**0dB**	**0dB**
Triangle, 100Hz	**0dB**	**+2dB**	**28.5dB**	**27.5dB**
Triangle, 1kHz	**5dB**	**+1.5dB**	**23dB**	**23.5dB**
Triangle, 9kHz	**11dB**	**3dB**	**12dB**	**15.5dB**
Triangle, 120kHz	**2dB**	**7.5dB**	**2dB**	**14.5dB**

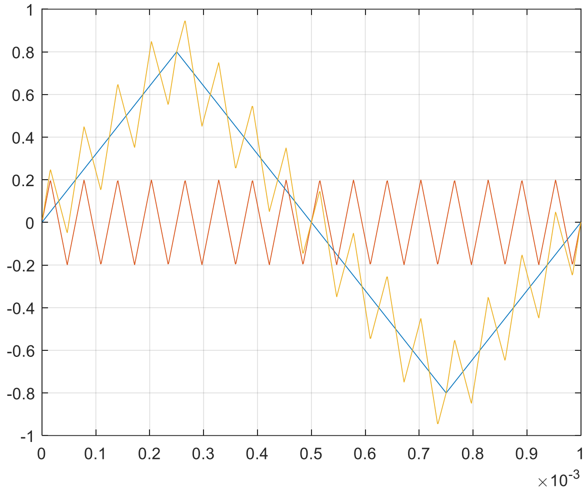
Conclusion:

A larger modulation index is better for AV EMI noise, but worse for PK EMI noise.
A higher modulation frequency is better for high-frequency band, but worse for low-frequency band.

It is preferred to choose the reasonable FSS parameters based on the specified application. MPS has IC that supports options for different modulation frequency and span.

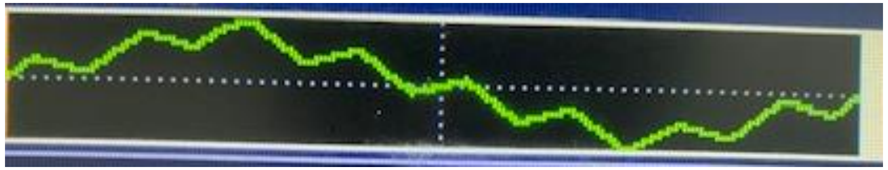
Consider to apply Dual Frequency

LF Triangle + HF Triangle

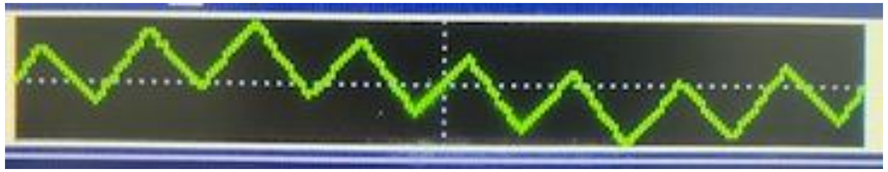


FSS waveforms with signal generator

LF : HF = 4:1



LF : HF = 1:1



Note: A modulation with dual frequency components can be generated for evaluation to reach a balance between high frequency and low frequency performance.

Results and Comparison

FSS Modulation	EMI (PK) Reduction (dBuV)	
	LF (2.2MHz)	HF (108MHz)
Triangle, 15kHz	**0dB**	**0dB**
Triangle, 15kHz:120kHz = 4:1	**+0.5 dB**	**1.5dB**
Triangle, 15kHz:120kHz = 1:1	**+1 dB**	**4dB**

Conclusion:

For 150kHz to 30MHz, as the ratio of LF:HF decreases, the EMI noise increases. For 30 to 108MHz, as the ratio of LF:HF decreases, the EMI noise also reduces. Therefore, this method can be applied to do the trade-off between LF and HF EMI.

FSS Consideration for Various Applications

Application of Radar Sensor

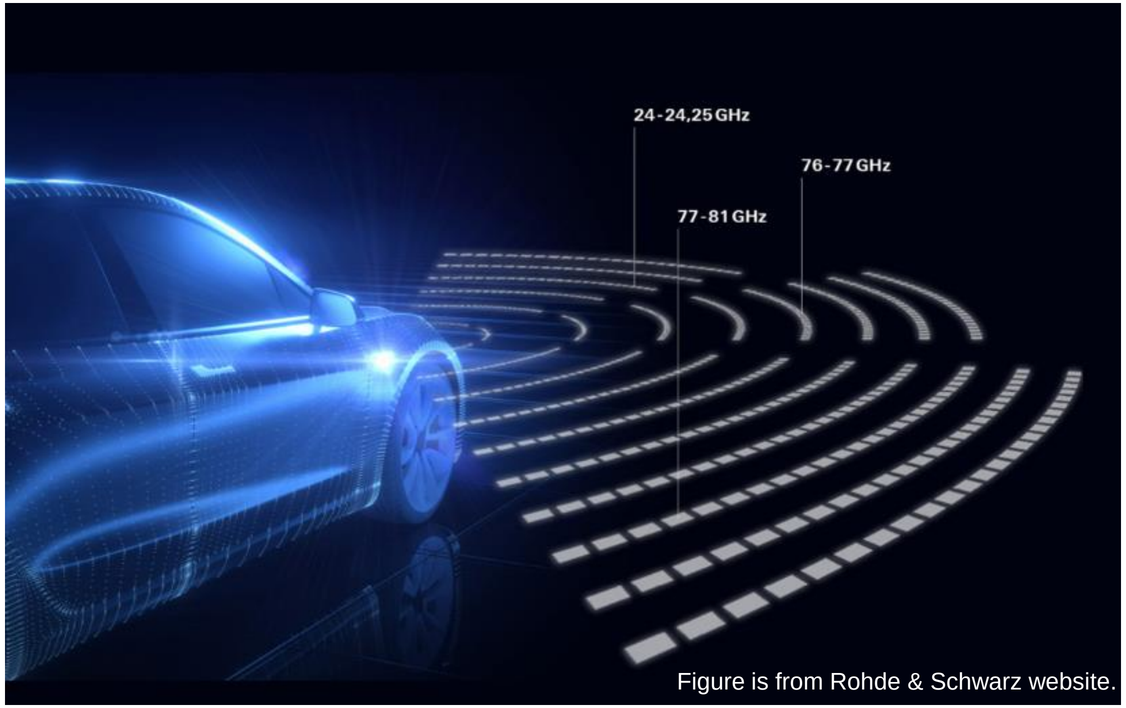
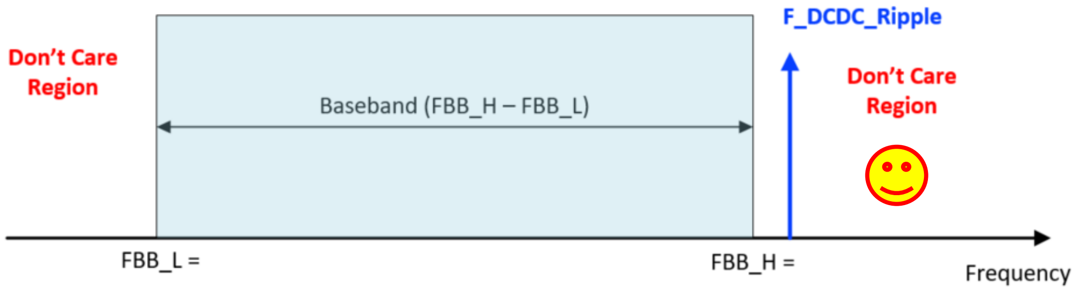


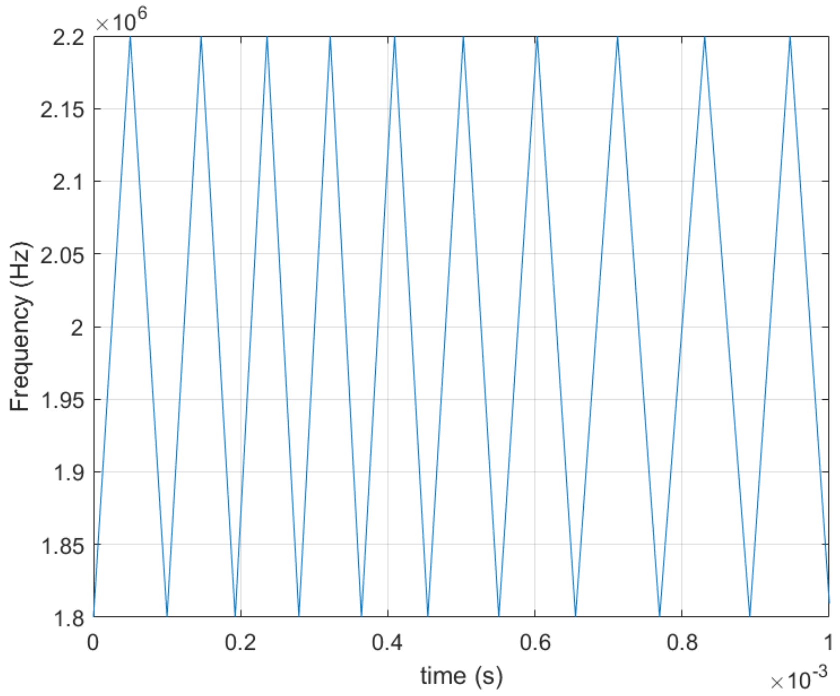
Figure is from Rohde & Schwarz website.



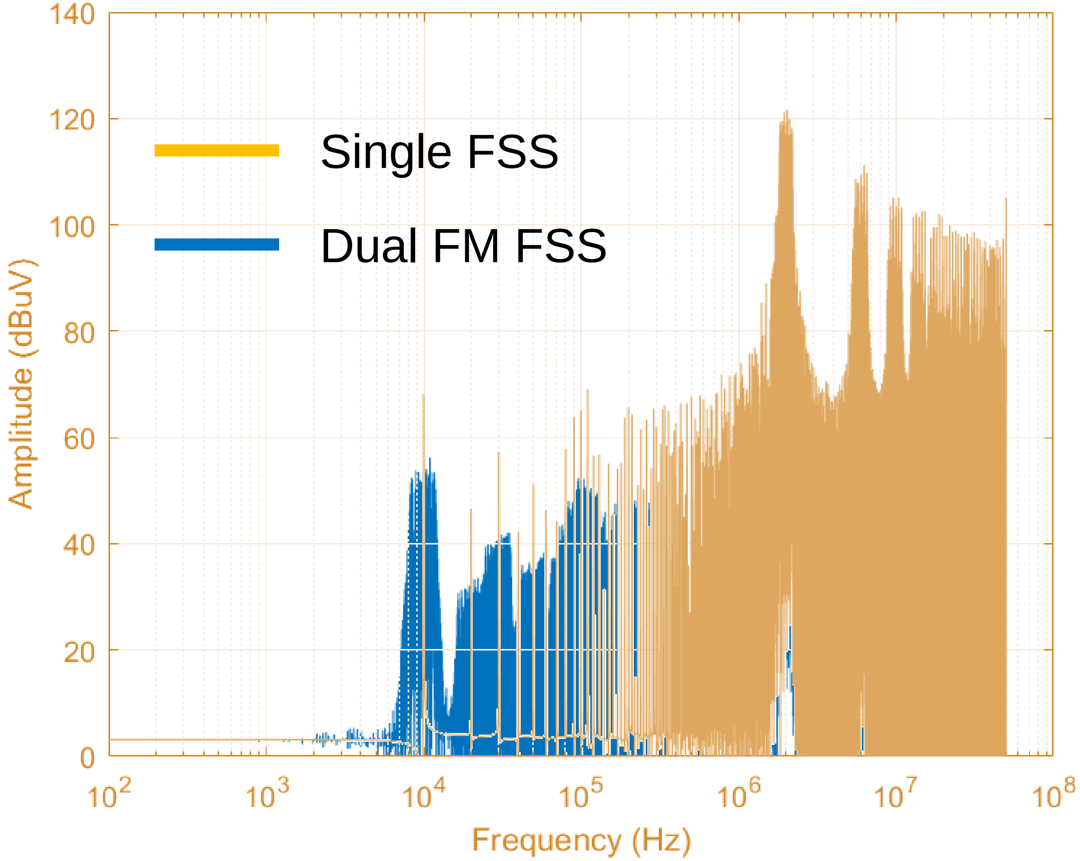
Note: The RF rails of a radar sensor are sensitive to power supply ripple and noise in baseband (~10kHz to ~MHz) because these supplies feed blocks such as the PLL, baseband ADC and synthesizers.

Dual FM FSS

Primary $f_M = 9kHz$, Secondary $f_M = 100Hz$
Secondary Modulation Amplitude = $\pm 20\%$
Modulation Shape: Triangle



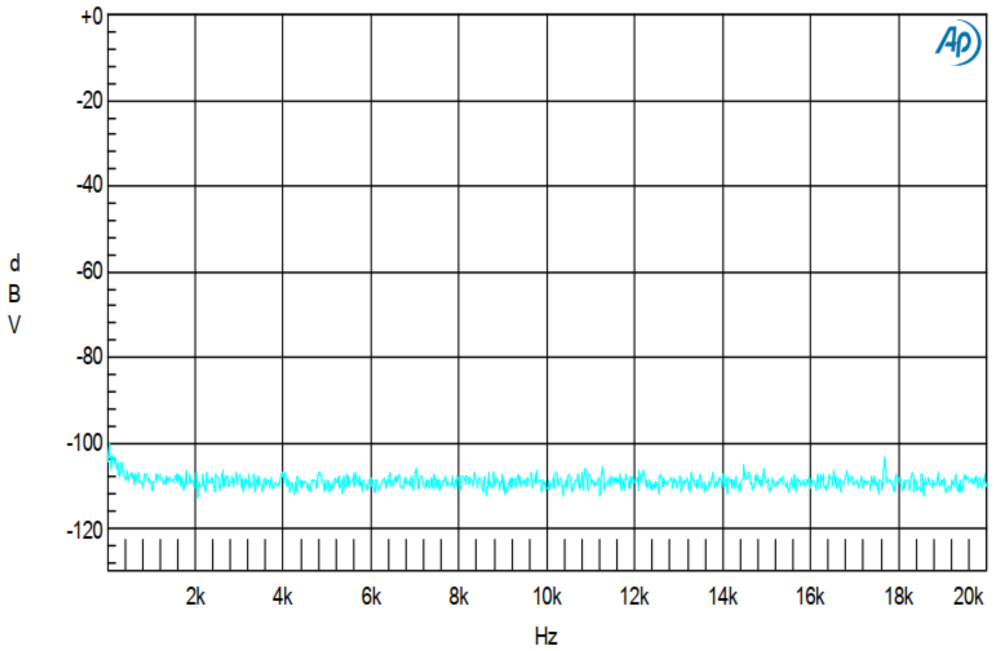
Comparison of the low-frequency spectrum



Note: The Dual FM FSS helps to reduce the noise level at the baseband.

Application of Class-D Amplifier

Class-D Output Noise Spectrum Test



Note: The Class-D audio band (20Hz to 20 or 40kHz) are sensitive to power supply noise, which needs to be avoided. As this band is very wide, the FSS modulation frequency needs to be higher than this band (35-50kHz for 20kHz band; 70~100kHz for 40kHz band).

Conclusion

- FSS is an effective way to reduce EMI
- The FSS can be evaluated via simulation based on the operation principles of EMI receivers
- The FSS can also be evaluated with IC or signal generator and an EMI receiver
- The modulation shape, span, frequency and modulation index will influence FSS performance
- There are trade-off between high/low frequency band and PK/AV EMI Noise
- For different applications, different FSS techniques shall be applied
- MPS provides various and flexible FSS techniques

Questions and Feedback

Thank you!