AN1512: Using SiMG301 with a +20 dBm Front End Module

This Application Note covers the design steps and verification measurements for selecting the ideal Front End Module (FEM) with SIMG301 to target output powers up to 20 dBm and enhance RX performance. On top of the basic RF measurements, the FEMs are tested for the basic FCC and ETSI regulatory compliance measurements for both TX and RX operation. Finally, a matching network design method that allows TX-only FEM use with the SIMG301 (having a single TX/RX RF port) is presented.

Note: The measurement results in this Application Note are not validation measurements that can be used as reference, but rather indication of the RF performance that can be achieved with good FEM PCB design. Since the matching/filter network values and PCB design guidelines of the FEMs were developed and determined by Silicon Labs, they are not necessarily optimized to their full capabilities. The reader can use this Application Note as a starting point for their design, but in the event of any FEM RF performance discrepancy, the FEM manufacturer should be contacted and not Silicon Labs.

KEY POINTS

- RF metrics for optimal RF performance
- Types of FEMs and TX-only FEM matching network design
- RF performance comparison of different FEMs in conducted measurements

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1. Introduction

SIMG301 is a wireless MCU for BLE/802.15.4 application that supports 10 dBm maximum output power. Since wireless products often target 20 dBm output power, in the following chapters an analysis of multiple BLE/802.15.4 FEMs paired with the SIMG301 is presented.

2. RF Metrics for Optimal Performance

The aim of this application note is to show that adding a FEM to the design to extend the output power does not introduce any detrimental effects in TX regulatory and RX performance. A categorization of RF performance metrics is shown in the following section:

2.1 System level requirements

The complete design (SIMG301 + FEM) shall be evaluated based on the following typical RF transceiver metrics, and regulatory compliance measurements:

Table 2.1. Main system specific RF metrics to evaluate

TX	RX
Output power	Sensitivity
Harmonics	—
Current consumption	Current consumption
Band-Edge (FCC)	Blocking (ETSI)
In-Band Emissions (FCC)	Adjacent Channel Selectivity (ACS) (ETSI)

2.2 FEM Specific Parameters

While these parameters are not individually evaluated in this application note for each FEM, measurements directly on these devices can be a reliable first step to predict the eventual performance of the complete design. See the table below for the most important metrics of which most can be found in device datasheets.

Table 2.2. Main FEM specific metrics to consider

Parameter		Comment
Current consumption	TX	Control, SPI, and so on.
	RX	
	RX bypass	
	Sleep	
	Quiescent	
	GPIO	
TX parameters	Non-saturated gain	Over frequency, supply voltage, and, temperature
	Saturated gain	
	IP1dB	
	OP1dB	
	Max output power	
	Harmonics	
	Power variation	
	Power Added Efficiency (PAE)	
RX parameters	Non-saturated gain	Sens_new = Sens_default - (NF_SIMG301 – NF_total)
	Noise Figure (NF)	
	IP1dB	
	IIP3	
RX bypass parameters	Insertion loss	—
Impedance	Input	Given in reflection coefficient or VSWR
	Output	—
	Stability	Given in output load VSWR region

3. Hardware Design

3.1 Schematic and Layout

Dedicated PCBs were manufacturer for each FEM and connected after the SIMG301 Radio Board (BRD4410A) for the measurements. See the list below for the most important hardware design aspects:

- Silicon Labs Radio Board stack-up (0.325 mm FR-4 for the 1st dielectric).
- VDD and GPIO circuitry/filtering as per the datasheet/Evaluation Kit of the FEMs.
- Added 5 element CLCLC filtering/matching placeholders (0201 size SMD) on the output of the FEMs. Certain FEMs have high harmonic content that must be filtered for regulatory compliance.
- It is highly advised to add a footprint for an **RF shield** around the SIMG301 and the FEM to prevent potential radiated harmonic emissions.

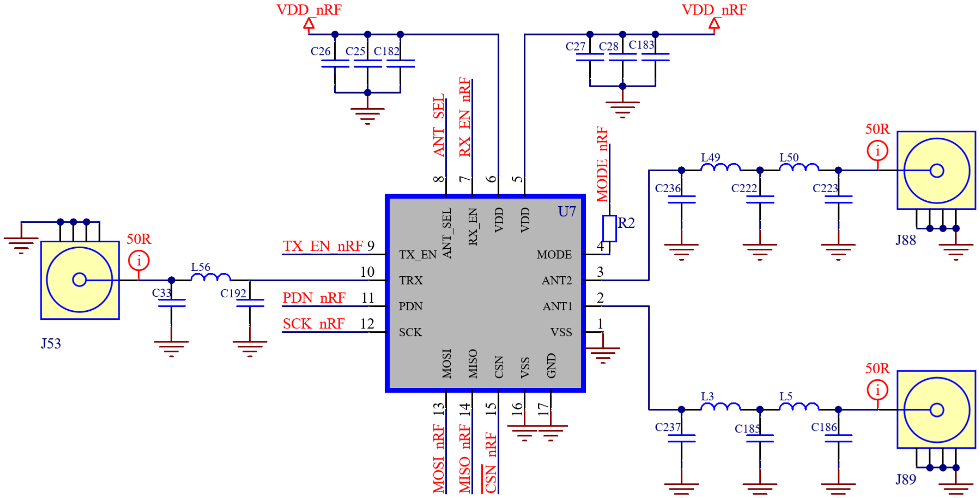


Figure 3.1. Typical schematic of a FEM Evaluation Kit

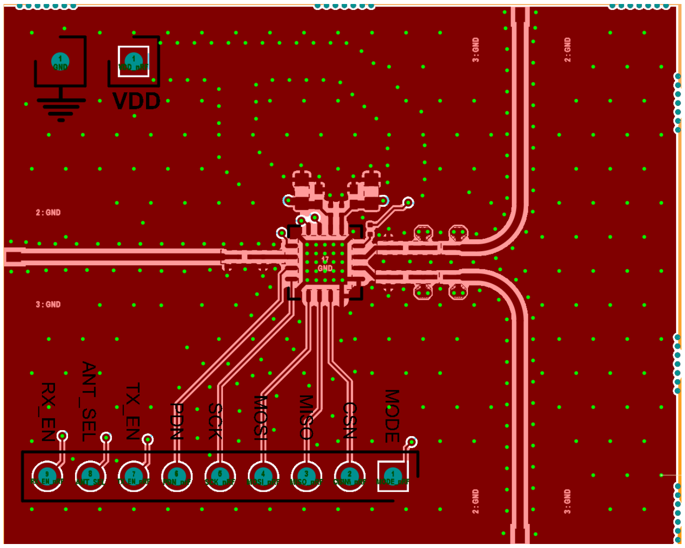


Figure 3.2. Typical layout of a FEM Evaluation Kit

3.2 Types of FEMs

Since SIMG301 and EFR32 devices have a single TX/RX RF port, only FEMs that have a single “left side” RF port were considered during the investigation. A typical FEM internal structure is shown in the following figure.

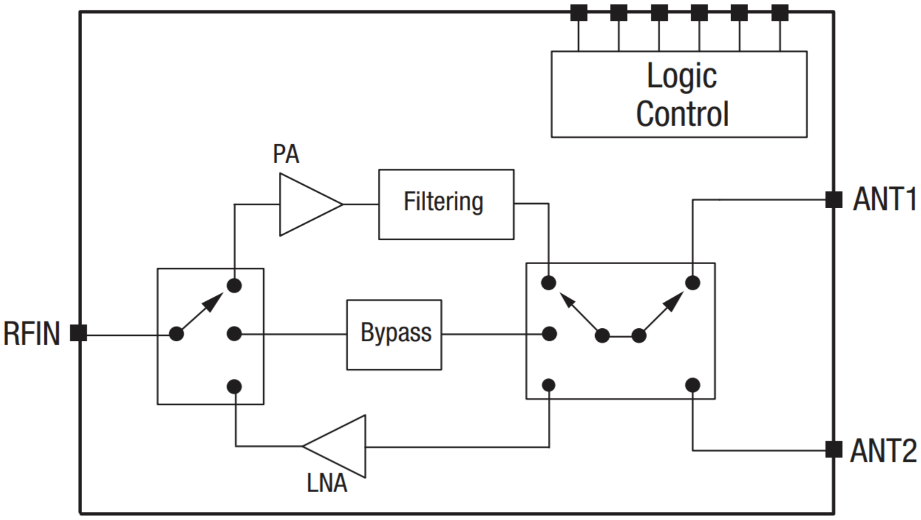


Figure 3.3. Typical structure of a FEM

There are two main types of FEMs, categorized by their internal RF path capabilities:

- Both ways, with optional bypass (TX and RX)
- One way (TX or RX)

The investigations in this document include all types except RX-only FEMs. While the hardware implementation of the 1st type is straight forward, for the 2nd type (TX-only FEMs), special RF design considerations must be applied, which are detailed in the next section.

3.3 TX-only FEM Design Considerations

Since SIMG301 and EFR32 devices have a single TX/RX RF port, the RF path right after the SIMG301 TX/RX matching network must be separated into two paths: one going into the FEM (TX path), and the other going around the FEM (RX) path which can be achieved by simply splitting up the PCB trace in two directions. This point is referred as the **Direct Tie Point**. Then, after the FEM, the two paths shall be joined back together in an RF Switch going into a single antenna, which is a necessary BOM addition to this design.

The schematic figure below shows the recommended hardware configuration/placeholder structure for TX-only use.

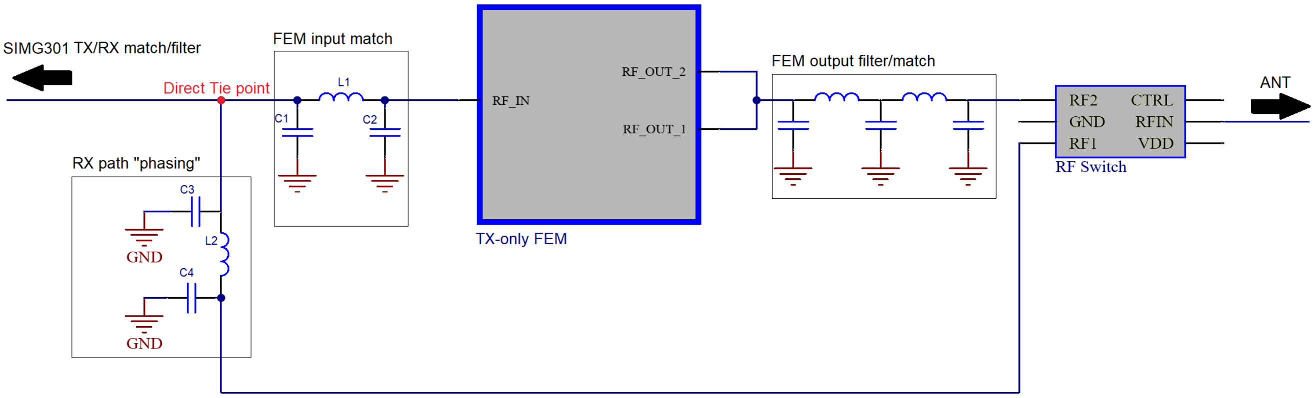


Figure 3.4. Recommended hardware configuration/placeholder structure for TX-only FEM use

Note:

- The RX path can also be used as the TX path with the FEM disabled, for a better power control in the < +10 dBm region. For this, the +10 dBm PA needs to be used.
- Worst case -2 dB TX and RX insertion loss (-1 dB mismatch and - 1 dB RF Switch loss) can be expected with this Direct Tie matching network, which is better than the bypass loss of most FEMs with bypass option. Therefore, this matching method can be used for any FEM with good effect. For most FEMs, TX power can still be kept above 20 dBm.

At the Direct Tie point:

1. In TX mode, the signal must flow in the direction of FEM, and not the RX path.
2. In RX mode, the signal must flow in the direction of the SIMG301 and not the FEM.

These two requirements translate into the following impedance terms at the Direct Tie point:

Table 3.1. Impedance requirements at the Direct Tie point

SIMG301 operation mode	FEM input match	RX path “phasing” match + RX trace
TX	Provide 50 Ω looking into the FEM	Provide high impedance looking into the RX path
RX	Provide high impedance looking into the FEM	Provide 50 Ω looking into the RX path

To design such matching networks that fulfill the requirements, the FEM and RX Switch input impedances in their ON and OFF modes must be known beforehand.

1. The FEM input match must transform the FEM ON and OFF mode impedance to 50 Ω, and high impedance, respectively.
2. The RX path “phasing” + RX trace must transform the RF Switch ON and OFF-mode impedance to 50 Ω, and high impedance, respectively.

For both cases, the further the ON (ideally 50 Ω) and OFF mode impedances are from each other, the better the impedance requirements can be fulfilled. Fortunately, good RF performance can be achieved with even with impedance relations that are seemingly far from perfect. While the FEM input match is mandatory, the RX path “phasing” functionality can completely be achieved by just the RX trace. This is because the OFF-mode impedance of the RF Switch is usually already relatively far from 50 Ω (~ on a high VSWR circle), so – on the Smith-chart - it just has to be rotated to the high impedance region. This transformation can be achieved by the RX trace with proper length. Only if the RX trace length is fixed (e.g., RX trace would need to be very long) is there a need to add the RX path “phasing” match. This network would have to emulate a 50 Ω transmission line with certain length, hence it should only change the phase and not the amplitude of the RX Switch impedance.

Table 3.2. Pros and cons of the two RX matching methods

Parameter	Pros	Cons
RX path “phasing” match + RX trace	• Any RX trace length can be used	• LC discrete components are needed that add: • insertion loss • BOM cost • More area on PCB
RX trace only	• Low insertion loss • For typical RF Switches, the length is realizable even on compact PCB designs (e.g., 12.2 mm)	• Length must be precise • RF Switch dependent • Due not nearby components, it’s not a “perfect” t-line, so online calculators can be inaccurate. Precise simulation might be required. Recommended to add LC discrete placeholders for potential lab tuning/correction.

The impedance of the RX trace can range from 50 to ~100 Ω, based on if RX or TX optimization is more important for the designer. A 50 Ω trace will help RX by “not touching” the 50 Ω RX Switch ON mode impedance but hurt TX as it cannot transform the RX Switch OFF mode impedance to high enough. A 100 Ω trace will hurt RX by touching 50 Ω RX Switch ON mode impedance but help TX by allowing to better fulfill the RX Switch OFF mode high impedance RX path requirement. This is true because it rotates the RX Switch OFF mode impedance around the 100 Ω point of the Smith-chart, allowing it to end up closer to the right side of the Smith-chart, which is the high impedance region. To put this into calculation we can consider the case of the RF Switch OFF mode impedance being 20 Ω. This can be - being purely and less than 50 Ω– transformed/rotated to high impedance (also purely real) by a trace with $\lambda_{eff}/4$ electrical length. A transmission line of this kind is the quarter wavelength transformer and happens to have an easy formula for its input impedance (Z_{IN}) which is a function of its characteristic impedance (Z_0) and its termination (Z_L = 20 Ω):

$$Z_{\mathrm{IN}} = \frac{Z_0^2}{Z_L}.$$

Z_0 = 100 Ω instead of 50 Ω gives Z_{IN} = 400 Ω instead of 100 Ω, which better fulfills the RX Switch OFF mode high impedance RX path requirement.

Silicon Labs uses a 50 Ω trace to maximize RX performance. This is because, ideally, the FEM can output +22 dBm output power, so +20 dBm can still be reached by simply using higher TX power code in the SIMG301 PA setting (to overcome the introduced TX loss).

Note: To calculate the physical length of the trace using online Grounded CPW transmission line calculators, ϵ_{eff} - instead of ϵ_r of the FR-4 substrate - must be used which was already hinted using λ_{eff} instead of λ. Reason being is that the EM wave in a GCPW structure propagates party in the air and not just the FR-4. The value of ϵ_{eff} can be accurately estimated by:

$$\epsilon_{\mathrm{eff}} = \frac{(\epsilon_r + 1)}{2} = \frac{(4.3 + 1)}{2} = 2.7$$

The following step-by-step guide shows the described TX and RX matching network design steps of the CC2595 FEM and BGS12SN6 RF Switch.

1. **Prerequisites for the most accurate simulations**
    - Determine PCB parasitic using the methods described in setion 3.4 in AN1423.
    - Use S-parameter files of the 0201 SMD components (Murata parts)
2. **Measure the FEM and RF Switch ON and OFF mode impedance values**

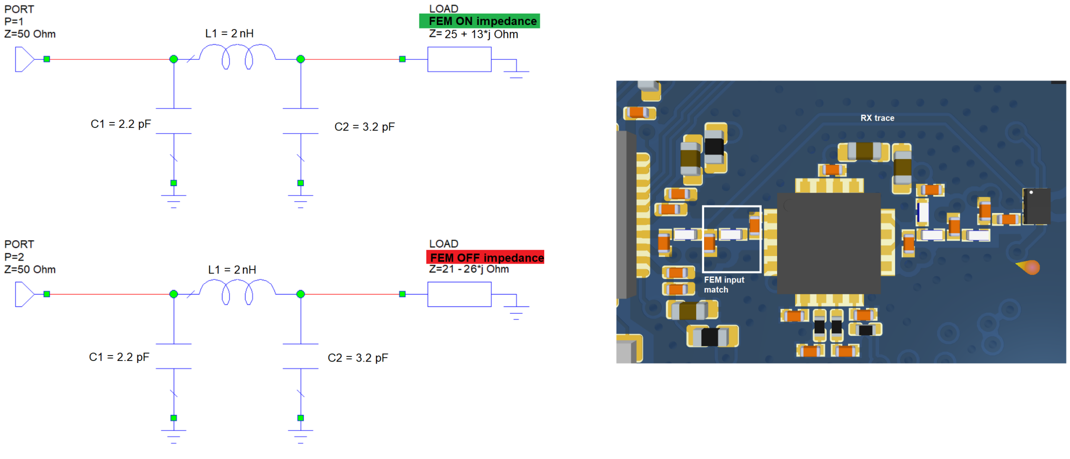
    Measure the FEM and RF Switch ON and OFF mode impedance values in the 2.4 GHz band. The 2.45 GHz center value – or, to also evaluate bandwidth properties, the S-parameter files – can be used. The following table shows the measurements for the CC2595 FEM and BGS12SN6 RF Switch.

Table 3.3. Measured ON and OFF mode impedances of the FEM and RF Switch

Mode	FEM	RF Switch
ON	55 + 13j Ω	50 Ω
OFF	21 – 26j Ω	9 + 18j Ω

3. **Design the FEM input match with simulation (and verify with lab VNA measurements)**

The figures below show the recommended FEM input match and the Smith-chart considerations that help determine it. The initial values were calculated with AWR simulations (with the Prerequisites of *step 0* applied), but the final values are the result of fine tuning in the lab with VNA measurements. The validity of the design is confirmed in Chapter 4) with TX and RX measurements.



a)

b)

Figure 3.5. a) FEM input match in AWR simulation and b) PCB layout design (RX trace also shown)

The Smith-chart figure below show that the designed matching network does not transform the 50 Ω ON mode, and does transform (to adequately high impedance) the 21 – 26j Ω OFF mode termination impedance of the CC2595 FEM.

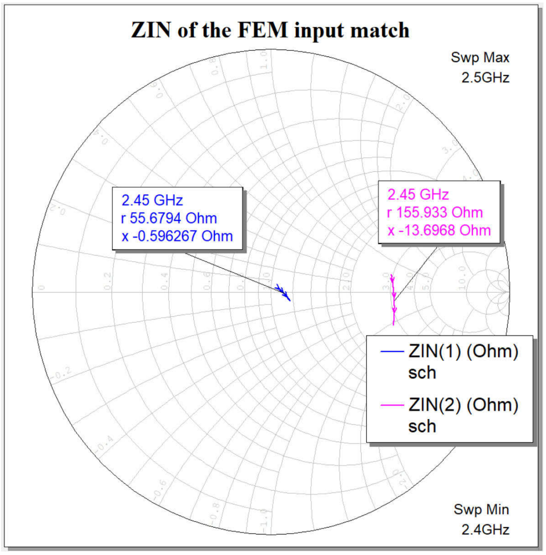


Figure 3.6. Effect of the FEM input match on the FEM ON and OFF mode termination impedances

This essentially means that the TX operation is expected to be unaffected, and the RX operations slightly degraded with the FEM input match as it only transforms the FEM OFF mode impedance to 155 Ω instead of *infinite* Ω. It is possible for the reader to tune the match so that pink point gets closer *infinite* Ω, but that results in the blue point starting to deviate away from 50 Ω which compromises TX output power.

Note: For this simulation, the RX trace (determined in the next chapter) was already included on the PCB layout as the entire reason for its length tuning to make it practically “non-existent” when the RF Switch is in OFF mode. Consequently, the results of this sub-chapter are the same regardless of if it is there or not.

4. **Select the proper length and impedance for the RX trace (and verify with lab VNA measurements)**

   The online calculator *Coplanar Waveguide Analysis/Synthesis Calculator* is a handy tool to use to calculate the required RX trace length and its physical dimensions for the desired characteristic impedance (Z_0).
   To determine the required length, convert the RF Switch OFF mode impedance (9 + 18j Ω) to S_{11} reflection coefficient format (-0.55 + 0.47j) to translate it to the cartesian coordinate system. Then, calculate its phase angle (phase (S_{11}) = 139.4°), from which the electrical length (EL) of the trace can be determined (phase (S_{11})/2 = 69.2°) that will it rotate/transform phase (phase (S_{11})/2) to the high impedance right side region of the Smith-chart (phase S11 = 0°). Electrical length can also be assessed as simply phase (S_{21}) in a simple 2-port measurement/simulation. In the online tool, *L* = 13.9 mm results in EL = 69.2°, but *L* = 12.2 mm gave the best results based on the CST Studio EM simulator results. The latter was used on the Silicon Labs PCB design.

   To determine the characteristic impedance (Z_0), a wide range of trace dimensions can be considered for Z_0 = 50 Ω (or any higher impedance of choice). For example, in the online tool, *W* = 0.4 and *S* = 0.1 gives Z_0 = 50 Ω. However, in CST, possibly due to obstructed GCPW structure (TX trace close at its input, etc...), *W* = 0.225 and *S* = 0.1 showed the best results with input $|S_{11}| < -30$ dB, which gives around Z_0 = 51 Ω. The latter was used on the Silicon Labs PCB design.

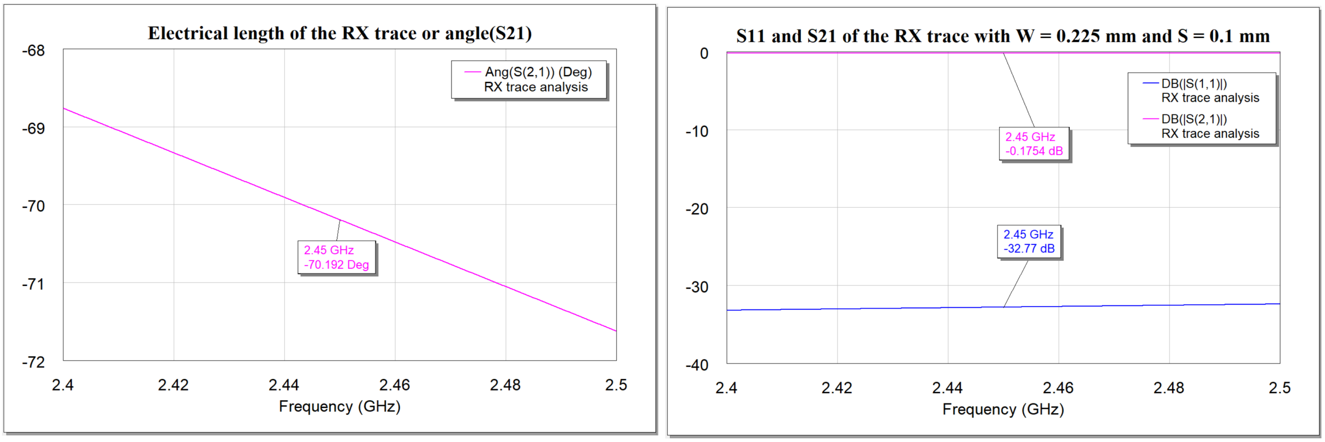


Figure 3.7. RX trace parameters after simulation optimization in CST Studio EM solver

4. RF performance comparison of FEMs

4.1 FEM output matching/filtering networks

On the FEM Evalkits, Silicon Labs used the following FEM matching/filtering network structure.

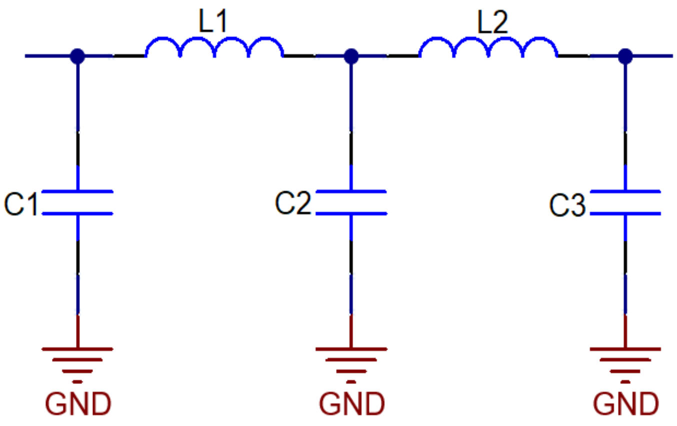


Figure 4.1. TX match/filter network placeholder structure

The component values were determined separately for each FEM as a result of lab-tuning on a VNA/Spectrum Analyzer to yield +20 dBm output power while keeping the conducted harmonics comfortably below the -41.2 dBm FCC limit. Consequently, the presented matching networks are not necessarily optimized for maximum power (which would allow lowering the power code for better current consumption), but rather for FCC harmonics compliance. The part number series was LQ03HQ for the inductors and GRM0335 for the capacitors.

Table 4.1. Tested FEMs and recommended developed output matching/filtering networks

		Matching network/filter values				
		C1 [pF]	**L1 [nH]**	**C2 [pF]**	**L2 [nH]**	**C3 [pF]**
Skyworks	SKY66118	1.2	2.4	1.8	—	—
	SKY66112	1.2	2.4	1.8	0R	0.2
	SKY66403					
	RFX2411C	1.3	2.1	1.5	2.9	1
Texas Instruments	CC2595	0.4	1.3	2.2	2.2	0.6
Nordic	NRF21540	—	1.9	2	3	1
BeRex	8TR8210	0.6	1.5	3.1	2.4	1.5
	8TR8217					
kxcomtech	KCT8206L	1.3	2.2	3.1	2.6	1.5

Note:

1. No input matching networks were used.
2. Some FEMs show better performance with a non-50 Ω matching networks (CC2595, nRF21540, RFX2411).
3. For CC2595, the special Direct Matching network with an RF Switch was used (refer to Chapter 3.3).
4. For nRF21540, the high gain PA was used.
5. For RFX2411, the high efficiency PA was used.

4.2 Conducted TX measurements and TX regulatory compliance

The plots below show a comprehensive comparison of all the FEMs that Silicon Labs have tested with SIMG301 (BRD4407A). The Silicon Labs device was powered from 3.3V, while the supply for the FEMS were swept from 1.8 V to their absolute maximum limit. The 0 dBm SIMG301 PA was also operated from minimum to maximum raw power (0 to 31 raw). For the total SIMG301 + FEM TX current vs. raw power plot, the performance of EFR32MG24 was also plotted at 20 dBm, 17 dBm and 13 to 14 dBm. It is visible, that the TX current consumption using a FEM is significantly better at 20 dBm, and noticeably better at 17 dBm than that of the EFR32MG24. At 14 dBm, the performance is similar.

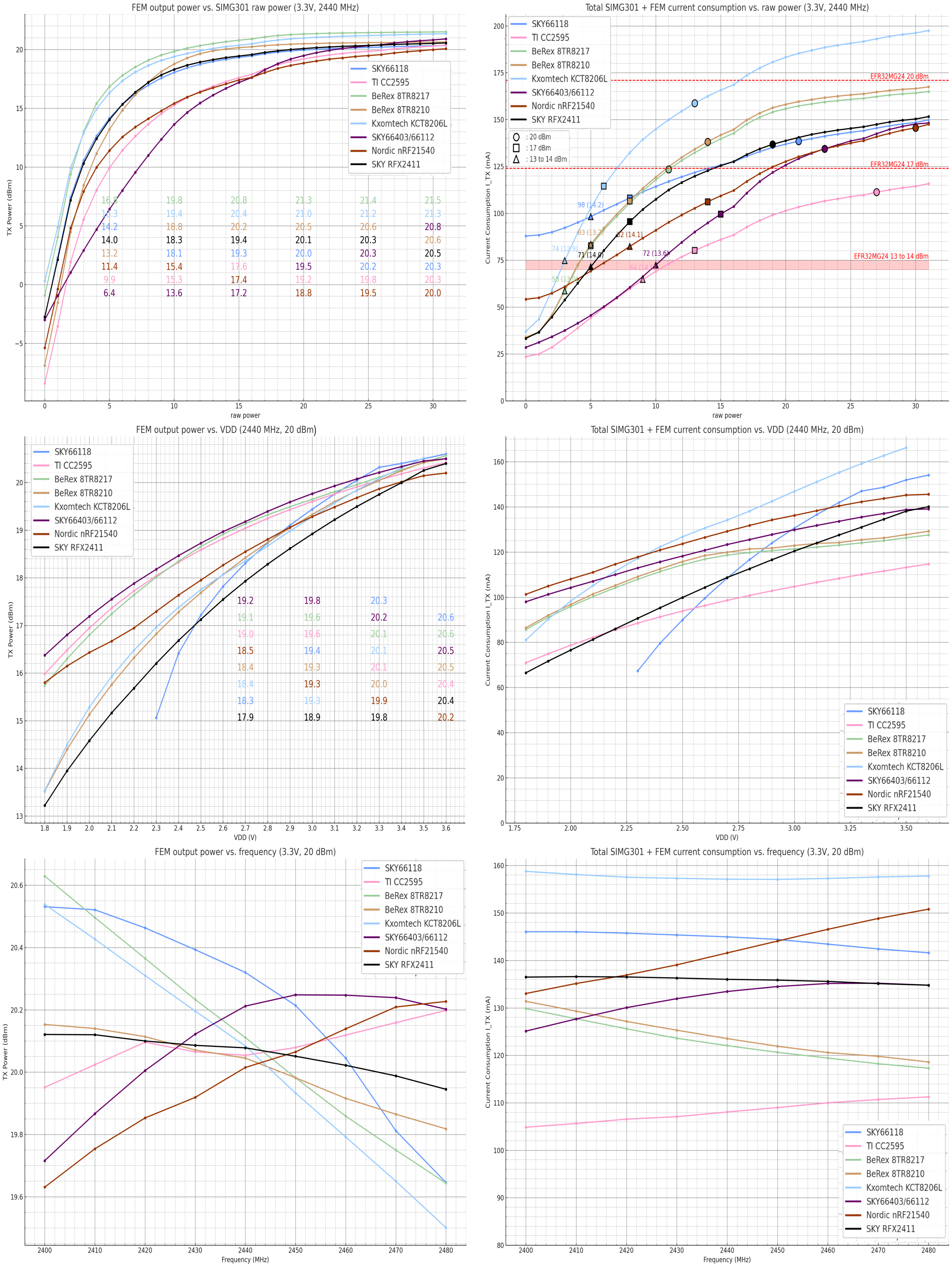


Figure 4.2. Conducted TX performance of the FEMs across raw power setting, voltage, and frequency (CW tone)

The following figure shows the conducted harmonic power levels, verifying FCC compliance.

Note: The 7th harmonic is in a non-restricted band where a much less stringent -20 dBc (~0 dBm) limit applies.

Moreover, since the measurmenets were with a CW tone, additional margin can be considered for modulated signals (see EFR32xG24 2.4 GHz 20 dBm Antenna Diversity Radio Board BRD4188B Reference Manual for typical harmonic power relaxation factors for the BLE modulations).

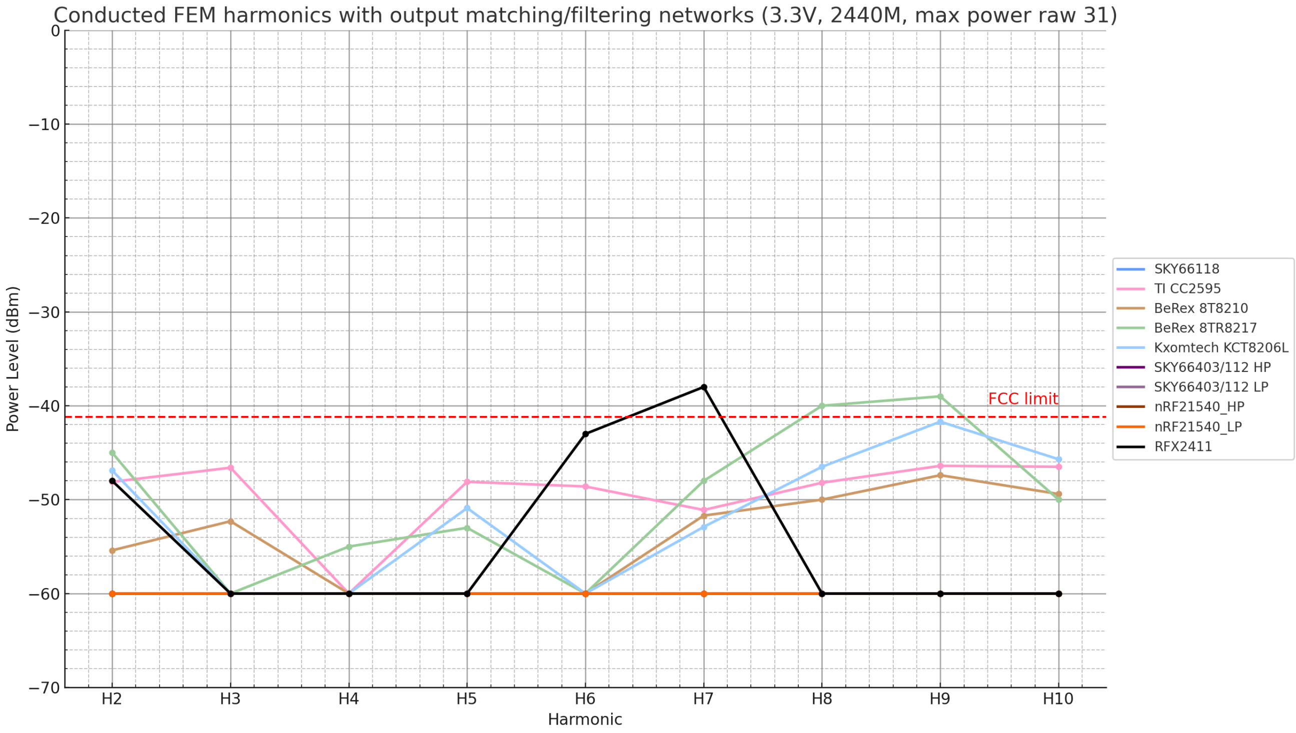
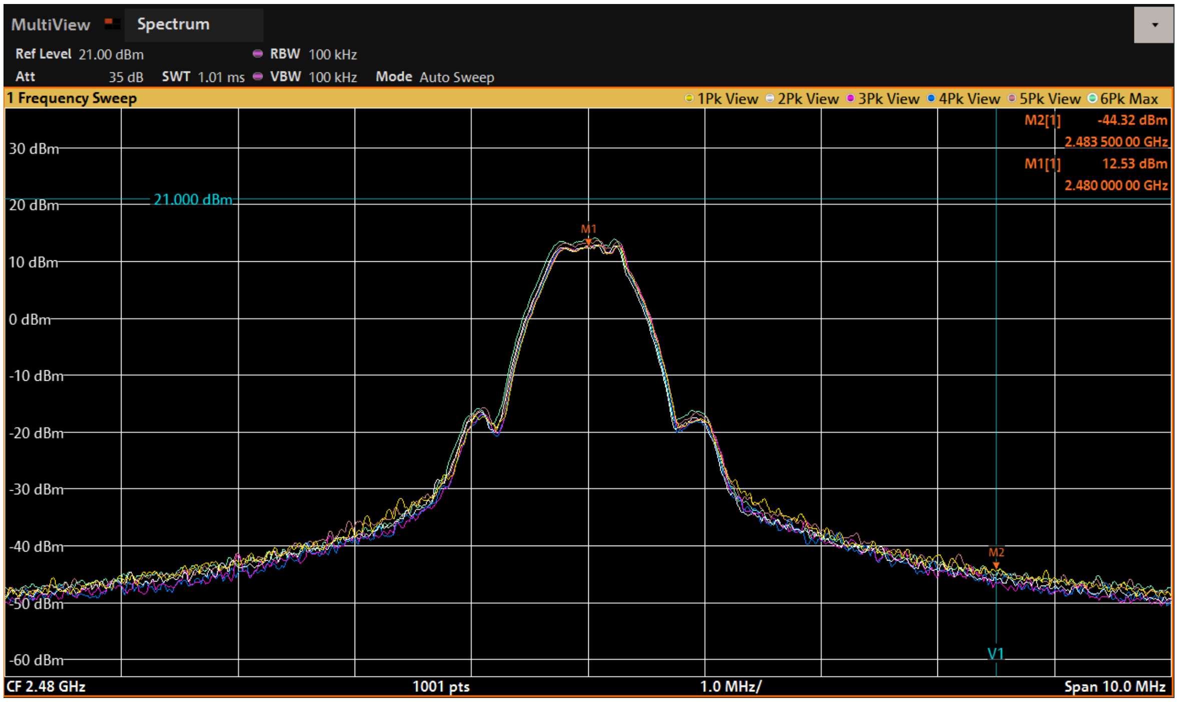


Figure 4.3. Conducted TX harmonics of the FEMs across raw power setting, voltage, and frequency (CW tone)

The figure below shows an overlap of TX spectrums using the FEMs in Table 4.1 Tested FEMs and recommended developed output matching/filtering networks on page 13 with a BLE 1M on CH39 test signal using Rail test.

The purpose of the test is to assess FCC Band-Edge and In-Band Emission (PSD) properties. The yellow plot is for EFR32MG24 20 dBm part with power on CH39 where FCC band-edge still shows 2.2 dB margin (12.5 dBm fundamental and -44.3 dBm Band-Edge power). The power setting when using the FEMs was manually selected for each FEM to output equal, or slightly more than 12.5 dBm.

It is visible that both FCC specifications are well under control, compared to the EFR32MG24 spectrum (yellow plot). In fact, they are slightly better with the FEMs, which holds true for all channels (CH0 to CH39) and all modulations (BLE 2M, 1M, 500k, 125k and 802.15.4 Zigbee). The In-Band Emission (~Adjacent Channel Power) properties of the spectrum at +20 dBm output power are not plotted, but the similar observations can be made on them as at +13 dBm output power, comparing to EFR32MG24.



Ref Level 21.00 dBm RBW 100 kHz
Att 35 dB SWT 1.01 ms VBW 100 kHz Mode Auto Sweep

M2[1] -44.32 dBm 2.483 500 00 GHz
M1[1] 12.53 dBm 2.480 000 00 GHz

CF 2.48 GHz 1001 pts 1.0 MHz/ Span 10.0 MHz

Figure 4.4. BLE 1M spectrum on CH39 (2480 MHz) with the FEMs and with EFR32MG24 20 dBm part

4.3 Conducted RX measurements and RX regulatory compliance (ETSI)

The RX performance of the FEMS can be seen in the figures below. For each FEM, all RX path options were tested (LNA(s), bypass). Together with their current consumption.

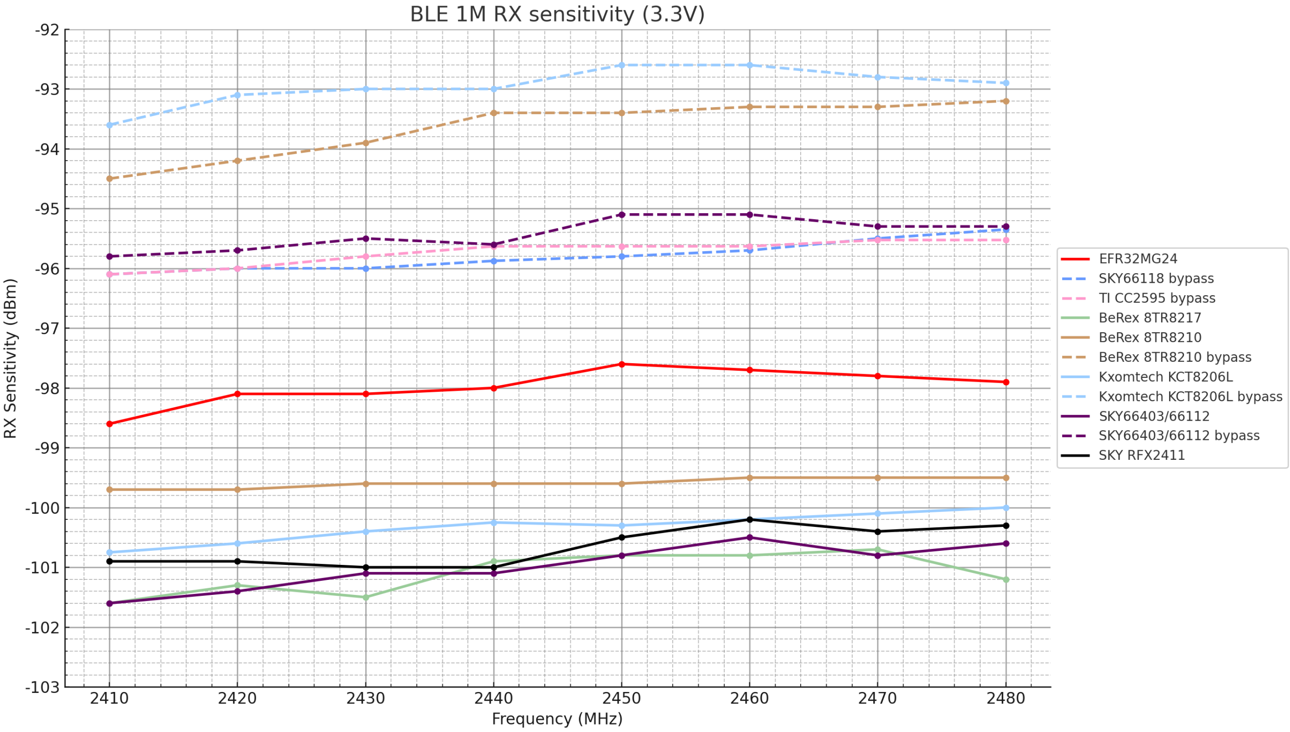


Figure 4.5. BLE 1M sensitivity using the FEMs in their respective modes (LNA or bypass)

The following figure shows an overlap of blocking results of the using the FEMs with in Table 4.1 Tested FEMs and recommended developed output matching/filtering networks on page 13 with an LNA. The BLE 1M PHY was used with Rail test, with the help of RF signal generator for the desired BLE signal, and a CW interferer for blocker CW signal.The following figure shows the blocking performance using different frequency interferer signals. The results are compared to that of the standalone BRD4407A Radio Board (which was the board also used for the FEM Evalkits). “Blocking” is a certain dB value that describes how much larger the interferer CW signal (that is added to our desired RX signal with a power splitter/combiner) needs to be to start to have significant detrimental effects in RX sensitivity. The measurement process starts with setting a desired signal that is 3 dB larger than the sensitivity value (e.g., where PER = 10 %) determined in the blocking HW setup beforehand, with no blocking signal. This should result in a perfect PER = 0 % statistic, which is then methodically ruined by adding the CW blocking signal with increasing strength, to the point where PER = 10 % is reached. Here, the difference between the blocking signal power and the original sensitivity value is calculated, which is referred to as the blocking. The larger the better, as it means that the radio can still work with larger interferes around.Only the FEMs with LNA modes were tested for this measurement.

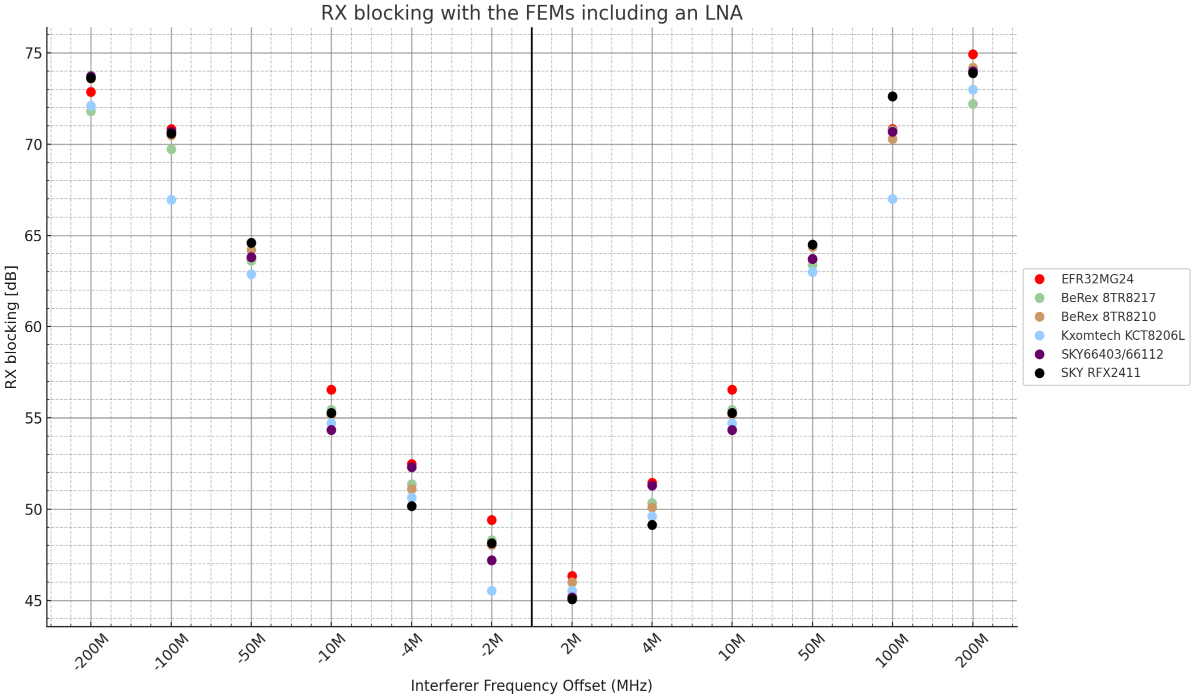


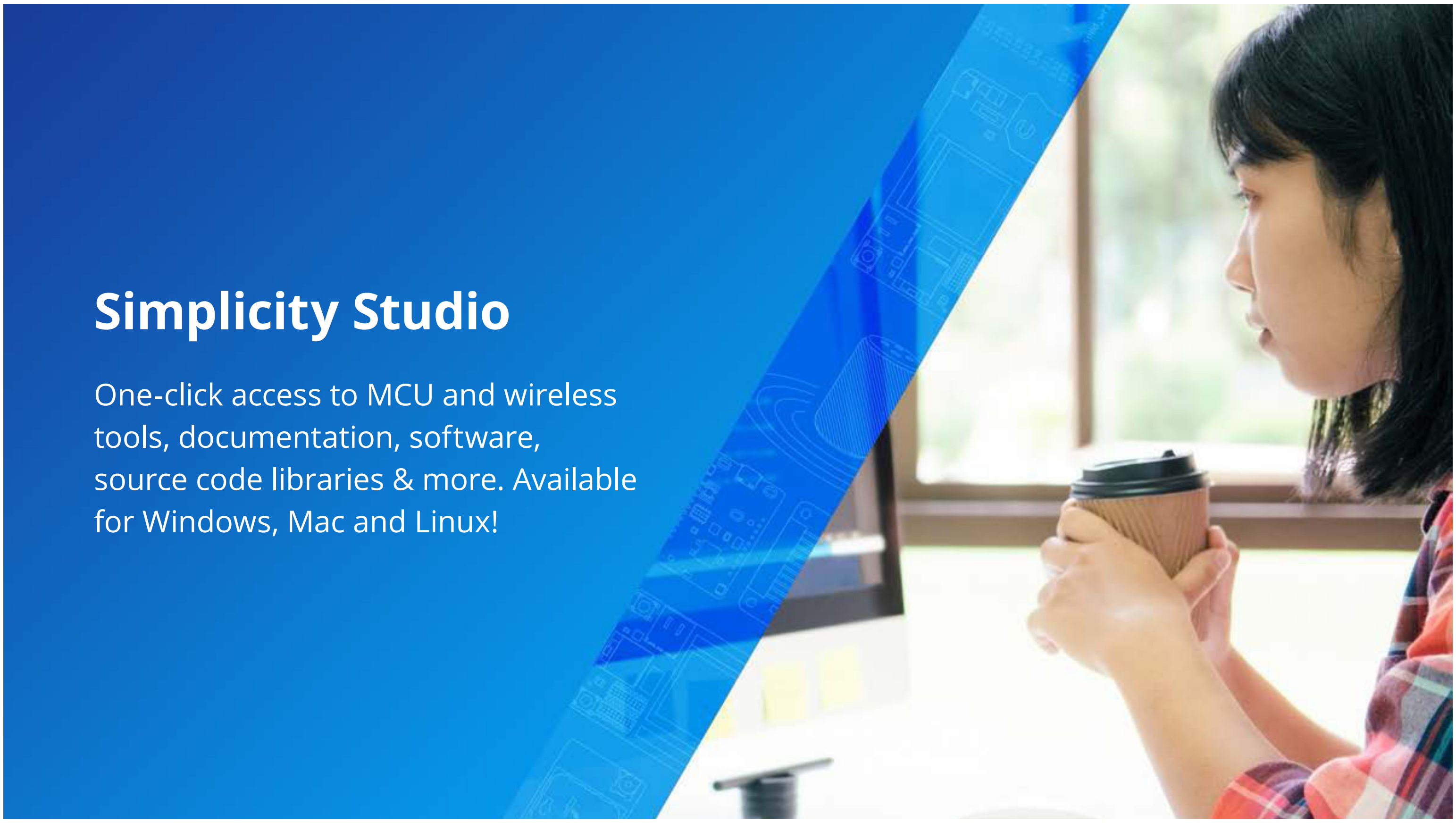
Figure 4.6. BLE 1M RX blocking using the FEMs with LNA modes

5. Revision History

Revision 1.0

September, 2025

Initial release.



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