APPLICATION NOTE

AN1461: Enhancing Harmonic Suppression in SKY664xx Front-End Modules for Bluetooth® Applications

Introduction

The SKY66409-11, SKY66407-11, SKY66411-11, and SKY66415-11 front-end modules (FEMs) are widely used in size-constrained Bluetooth®-enabled products such as hearing aids, cochlear implants, and other wearable devices. These FEMs feature integrated output harmonic filtering to comply with Bluetooth harmonic emissions requirements while minimizing external component count.

In most applications, the integrated filtering provides sufficient harmonic suppression to meet regulatory and Bluetooth qualification requirements.

However, system-level operating conditions can reduce available compliance margin. In these situations, an external matching or filtering network can be used to further improve harmonic attenuation.

This application note discusses the harmonic filtering performance of the SKY66409-11, SKY66407-11, SKY66411-11, and SKY66415-11 FEMs and provides guidance for implementing supplemental external filters when additional margin is required.

Harmonic Filtering

Transmitters with Bluetooth functions operating under ETSI EN 300 328 must comply with spurious emissions limits, including a maximum harmonic emission level of –30 dBm/MHz. The harmonic performance of a Bluetooth transmitter is determined by the combined response of the SoC and the FEM.

Depending on the device and operating conditions, the SoC may provide limited harmonic suppression at its RF output, often on the order of 20 dB below the fundamental signal. Additional attenuation is therefore required to achieve regulatory compliance with adequate margin.

When the SoC is cascaded with an FEM, the FEM provides additional suppression of harmonic energy generated by the SoC. The SKY66409-11, SKY66407-11, SKY66411-11, and SKY66415-11 FEMs feature internal filtering to suppress second- and third-order harmonics while maintaining high transmit efficiency.

Under normal operating conditions with a well-matched antenna, these FEMs provide sufficient harmonic attenuation to pass compliance testing with margin.

Table 1 summarizes the 2.4 to 2.483 GHz output power and harmonic performance of each device.

Table 1. FEM Output Power and Harmonic Attenuation

FEM Part Number	Parameter	Conditions	Min	Typ	Max	Units
SKY66409-11	Power output	VCC = 3.3 V		12		dBm
	TX gain	VCC = 3.3 V		12.5		dB
	Second harmonic	Pout = +10 dBm, CW		–45	–39	dBm/MHz
	Third harmonic	Pout = +10 dBm, CW		–35	–30	dBm/MHz
SKY66407-11	Power output	VCC = 3.3 V		12		dBm
	TX gain	VCC = 3.3 V		13		dB
	Second harmonic	Pout = +10 dBm, CW			–40	dBm/MHz
	Third harmonic	Pout = +10 dBm, CW			–30	dBm/MHz
SKY66411-11	Power output	VCC = 2.4 V		8		dBm
		VCC = 3.0 V		10		dBm
	TX gain	VCC = 2.4 V		10		dB
		VCC = 3.0 V		12		dB
	Second harmonic	Pout = +8 dBm (2.4 V), CW		–35	–33	dBm/MHz
		Pout = +10 dBm (3 V), CW		–35		dBm/MHz
	Third harmonic	Pout = +8 dBm (2.4 V), CW		–35	–33	dBm/MHz
		Pout = +10 dBm (3 V), CW		–35		dBm/MHz
SKY66415-11	Power output	VCC = 1.8 V		11		dBm
	TX gain	VCC = 1.8 V		11		dB
	Second harmonic	Pout = +11 dBm (BDR-DH1)		–35		dBm/MHz
	Third harmonic	Pout = +11 dBm (BDR-DH1)		–35		dBm/MHz

FEM Harmonic Gain (S21)

The harmonic performance summarized in Table 1 is enabled by the SKY664xx FEM integrated filtering. The effect of this filtering can be visualized in the S21 frequency response, often referred to as harmonic gain or harmonic attenuation. S21 represents the device forward transmission characteristic as a function of frequency. At the second- and third-harmonic frequencies, it indicates the attenuation provided by the FEM.

Figure 1 presents wideband S21 plots up to 8.1 GHz, showing the attenuation at the second (4.8 to 4.966 GHz) and third harmonic (7.2 to 7.449 GHz) frequencies relative to the Bluetooth operating band (2.4 to 2.483 GHz).

These plots illustrate how the SKY664xx FEMs help suppress harmonic content, reducing or eliminating the need for additional output filtering in many applications.

Notice that the Skyworks SKY66411-11 and SKY66415-11 demonstrate significantly improved harmonic performance compared to other FEMs.

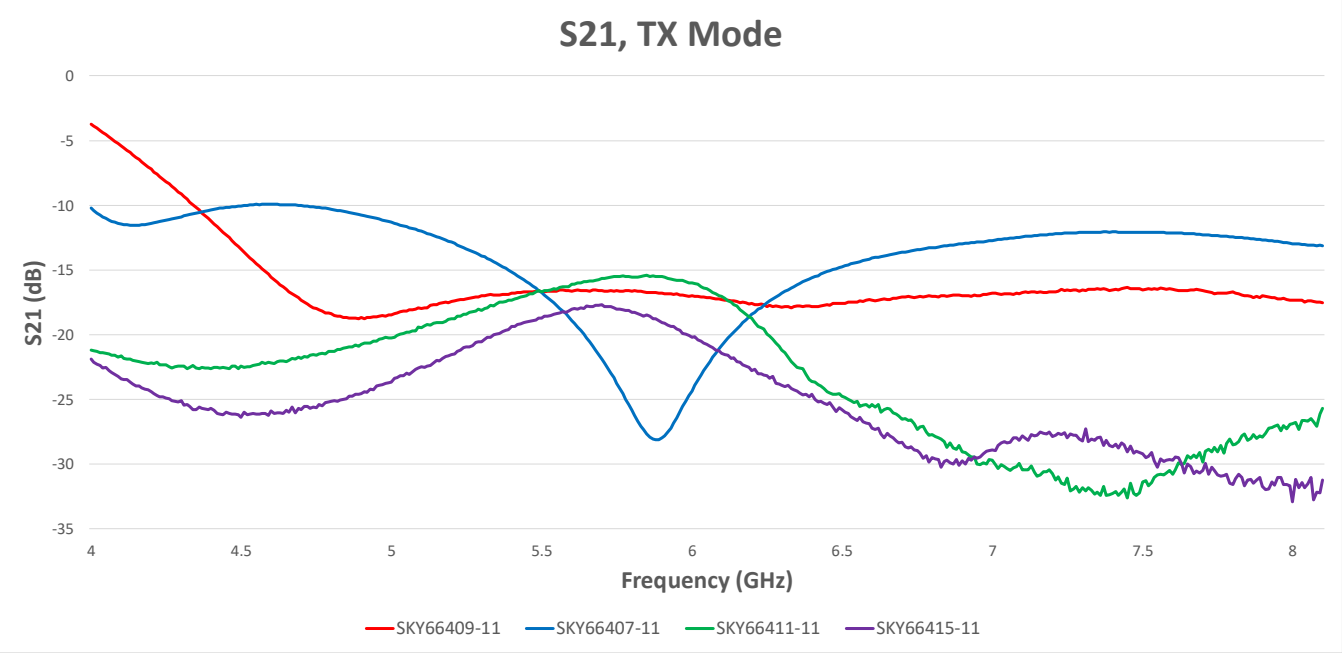


Figure 1. Comparison of Second- and Third-Harmonic Performance Using S21 Parameters From 4.0 to 8.1 GHz

External Filter Options

Although the integrated filtering provides substantial harmonic attenuation, overall system performance is influenced by several external factors:

- **Antenna impedance:** Mismatch at the antenna can increase second- and third-order harmonic levels, especially in space-constrained, wearable designs.
- **Supply voltage variation:** Harmonic margin may decrease as battery voltage drops or in systems with significant voltage variation.
- **Process, voltage, and temperature variation (PVT):** System-level gain variation across the SoC and FEM can reduce harmonic margin when operating near maximum output power. In some cases, designers reduce transmit power by 1 to 1.5 dB to recover margin, albeit at the expense of link budget.

When antenna characteristics are known and additional harmonic suppression is required, a passive network can be inserted between the FEM antenna pin and the antenna. Depending on performance objectives and PCB area constraints, several filter approaches are available.

A generic filter network based on the SKY66409-11 evaluation board (EVB) is illustrated in Figure 2.

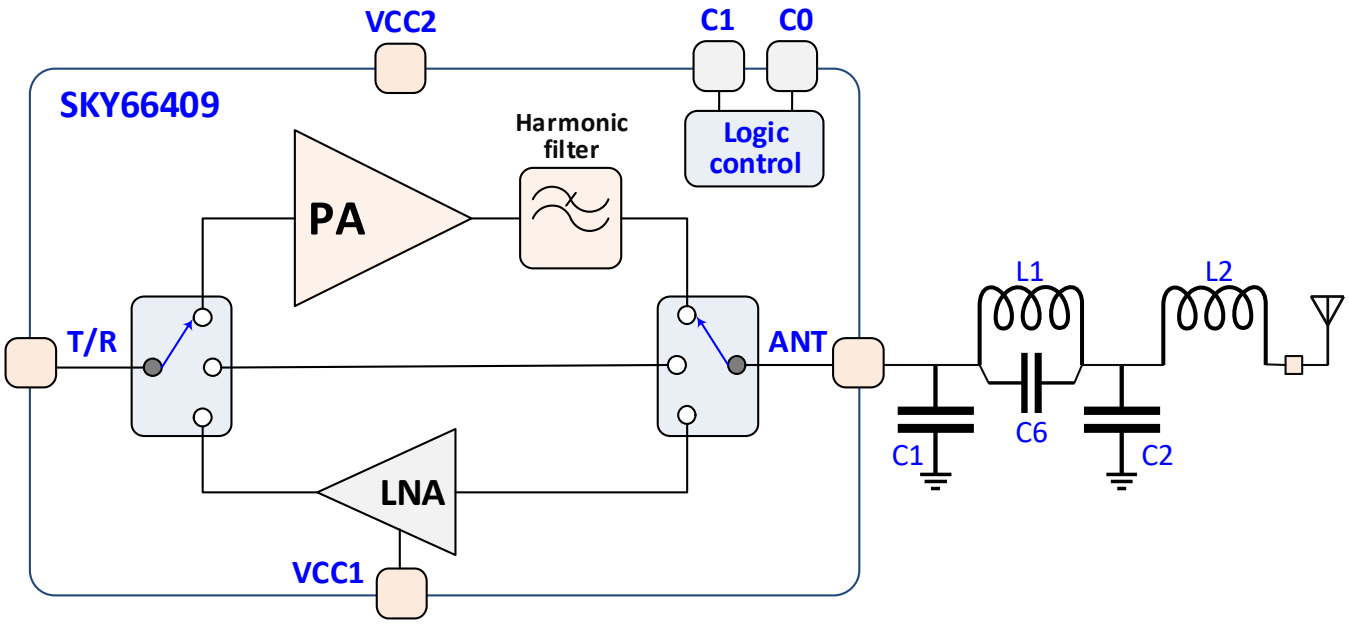
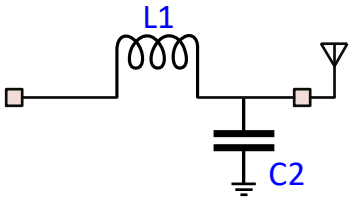
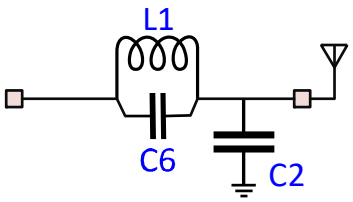
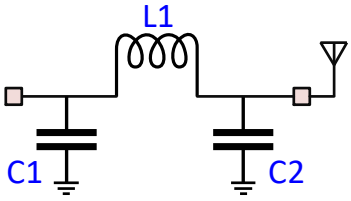
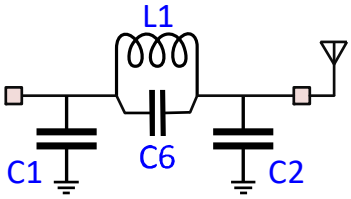
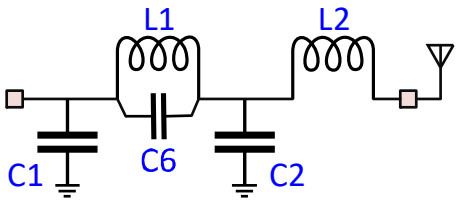


Figure 2. SKY66409-11 Block Diagram With Generic External Filter Network

No single filter topology is optimal for all applications. The choice depends on the required harmonic attenuation, available PCB area, acceptable insertion loss, and the degree of tuning flexibility needed during system optimization. Simple LC networks offer the lowest component count, while more complex networks provide additional attenuation and tuning capability. Table 2 compares several filter configurations that can be implemented using the configurable component locations provided on Skyworks EVBs.

Table 2. Various Filter Configuration Options

Filter Type	Schematic	Key Characteristics
1. Simple LC Filter		• Provides the lowest component count and smallest area • Moderate harmonic attenuation • Exhibits a relatively gentle roll-off
2. Series LC shunt harmonic trap		• Can be tuned to create a notch at a specific frequency, resulting in deep attenuation • Optimized for a narrow band
3. π filter		• Greater roll-off and harmonic rejection than a simple LC network • Additional insertion loss and more components
4. π filter with integrated harmonic trap		• Use configuration 2 if it is sufficient • In addition to configuration 2, provides additional low-pass filtering and steeper high-frequency roll-off
5. Enhanced π filter with integrated harmonic trap		• Similar in benefits to configuration 4 with improved higher-order harmonic suppression at the cost of additional components • L2 offers additional tuning flexibility for antenna matching

Design Recommendations

In most applications, the SKY664xx FEMs provide sufficient harmonic suppression without external filtering. The evaluation boards for these devices are designed for 50 Ω input and output matching and pass harmonic testing with margin. For normal 50 Ω matched conditions, the series inductor on the EVB can be replaced with a 0 Ω resistor (0R in EVB schematics), while the shunt capacitors remain unpopulated (DNP/DNI).

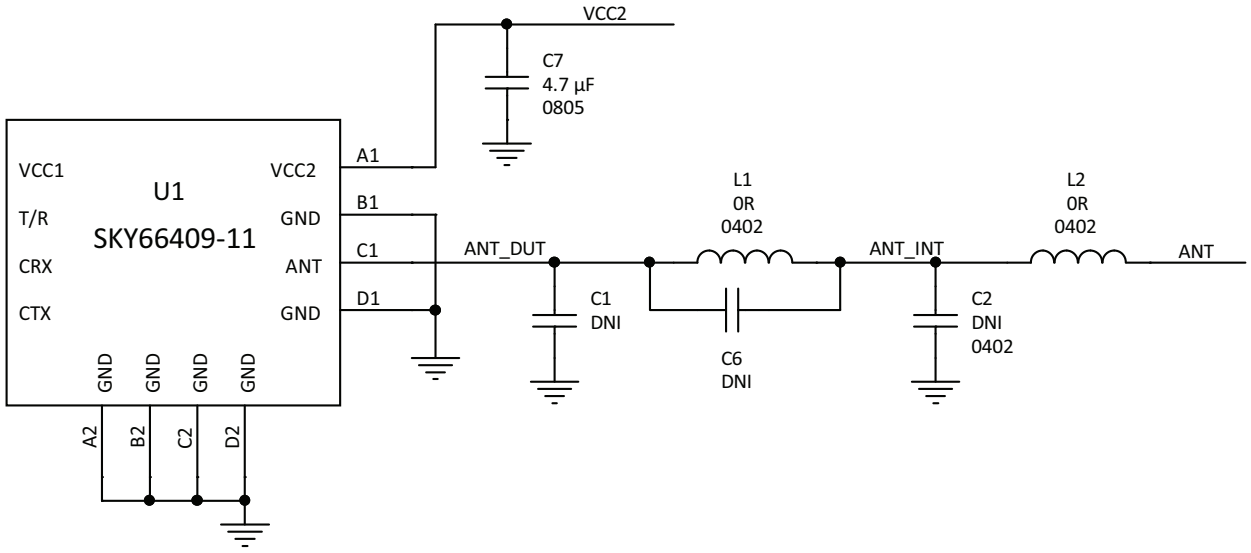


Figure 3. SKY66409-11EK1 Schematic with 0R for Normal 50 Ω Matched Conditions

However, in some applications, customers may wish to evaluate harmonic performance under non-ideal conditions such as antenna mismatch, body-loading effects, supply-voltage variation, or worst-case PVT operating conditions.

To simplify this testing, Skyworks EVBs include configurable output matching locations that can be populated with additional components to implement external filter networks. This flexible layout enables rapid evaluation of alternative filter topologies and optimization of harmonic performance without requiring a separate evaluation board.

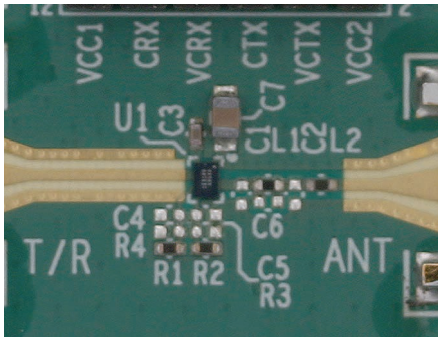


Figure 4. SKY66409-11EK1 with 0R in Place of L1 and L2 and Capacitors not Populated

Additional Resources

- Explore Skyworks portfolio of FEMs for Bluetooth® applications at https://www.skyworksinc.com/en/Technology-Standards/Bluetooth
- ETSI EN 300 328 Wideband Transmission Systems https://www.etsi.org/deliver/etsi_en/300300_300399/300328/02.02.02_60/en_300328v020202p.pdf