TS13

EM3598 RADIO BOARD TECHNICAL SPECIFICATION

Technical specifications for the EM3598 Radio Board with SE2432L FEM will be provided in this document:

- Design details
- RF measurement results
- Recommendations for the EM3598 Radio Board FCC compliance

New in This Revision

Initial release.

Contents

1 EM3598 Radio Board Design with FEM

To assist designers interested in using the EM35xx with external FEM, Silicon Labs developed a board design around this two-chip solution with EM3598 and SE3432L FEM from Skyworks. The EM3598 Radio Board can be connected to the Wireless STK to utilize the display, buttons and features of Expansion Boards. The EM3598 Radio Board can also be connected to the EM359x Breakout Board for use with the EM35x Development Kit. Stand-alone operation without the WSTK Motherboard is also possible (powered from USB).

The EM3598 Radio Board (BRD4601A Rev. A03) is shown in Figure 1.

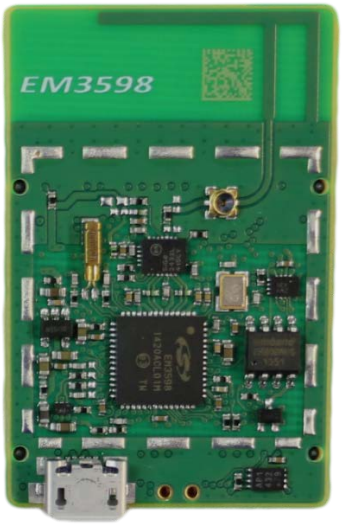


Figure 1. EM3598 Radio Board (BRD4601A Rev. A03)

The block diagram of the EM3598 Radio Board is shown in Figure 2.

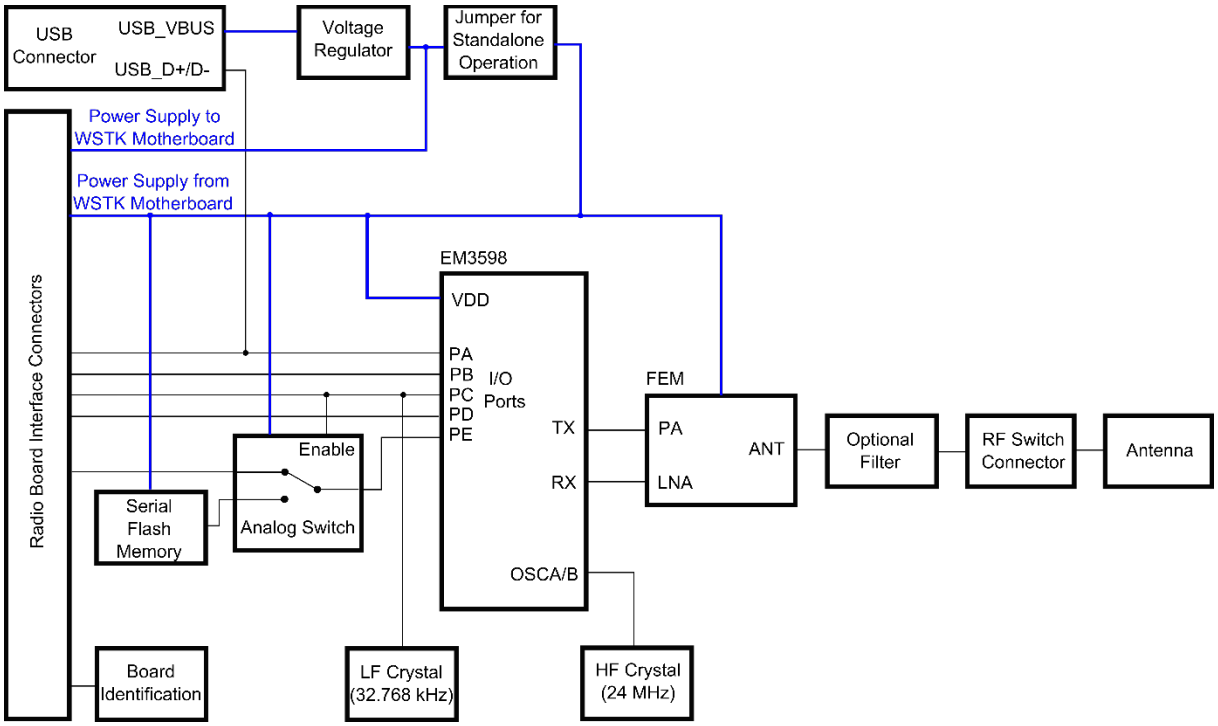


Figure 2. Block diagram of the EM3598 Radio Board

1.1 EM3598

Silicon Labs' EM3598 is a fully integrated System-on-Chip that integrates a 2.4 GHz, IEEE 802.15.4-2003-compliant transceiver, 32-bit ARM® Cortex™-M3 microprocessor, flash and RAM memory, and peripherals of use to designers of ZigBee-based systems. It has a USB 2.0-compliant full-speed (12 Mbps) device peripheral, with on-chip transceiver. Also, the EM3598 integrates two low dropout regulators to provide 1.8 V and 1.25 V power supplies. The 1V8 regulator supplies the analog and memories, and the 1V25 regulator supplies the digital core.

1.2 USB

The EM3598 Radio Board incorporates a micro USB connector. The USB power rails are routed back to the WSTK Motherboard through the Interface Connectors so the Radio Board can supply power to the WSTK Motherboard.

Normally, the power source to the Radio Board is selected by the power switch on the WSTK Motherboard. The EM3598 Radio Board has option to mount a pin header. If it is shorted the on-board USB voltage regulator powers the board without the need of the WSTK Motherboard so USB powered stand-alone operation is possible.

For additional information on EM359x USB, refer to AN740, *Using the Ember ® EM358x/EM359x USB*.

1.3 Serial Flash Memory

The EM3598 Radio Board also includes a serial flash memory (P/N: W25Q80BVSNIG (Winbond)) connected to the I/O port pins of the EM3598 through an on-board analog switch. The serial flash is used in cases where ZigBee OTA Profile application bootloader is required. For more information on the serial flash, refer to its data sheet (http://www.winbond.com/NR/rdonlyres/4D2BF674-7427-4FC8-AEF0-1A534DF74F16/0/W25Q80BV.pdf).

1.4 RF Section

Figure 3 illustrates the RF section of the typical application circuit.

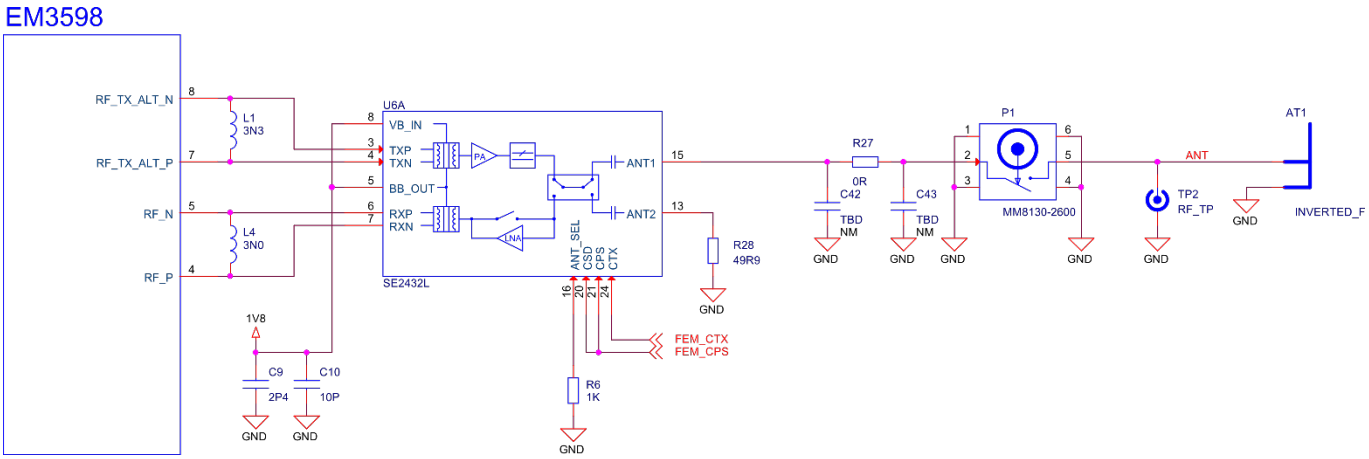


Figure 3. Schematic of the RF section of the EM3589 Radio Board (BRD4601A Rev. A03)

1.4.1 EM359x RF Ports

The EM359x's bi-directional RF port – RF_P (pin 4) and RF_N (pin 5) – provides access to a low noise amplifier (LNA) and a power amplifier (PA) through a shared differential interface. The disabled high -Z state of either the PA or the LNA allows transmitting and receiving through the shared port without the need for a conventional T/R switch.

An 'alternate' PA-only port – RF_TX_ALT_P (pin 7) and RF_TX_ALT_N (pin 8) – is also provided. This function is achieved via an additional PA. The on-chip parasitic capacitance is different between the two ports, which will alter the off-chip matching component values, L1 and L4, slightly.

1.4.2 FEM

To obtain the maximum allowable transmit power from a ZigBee system, the EM3598 Radio Board uses an external FEM: SE2432L from Skyworks.

The SE2432L contains a Power Amplifier (PA), Low Noise Amplifier (LNA), integrated balun, RX/TX Switch for RF as well as a diversity switch for use with applications that require antenna diversity. In addition, the SE2432L allows designers a unique opportunity to characterize their design both with and without an LNA. This is due to the integrated LNA bypass mode.

For more details on the FEM please refer to the datasheet:

http://www.skyworksinc.com/uploads/documents/SE2432L_201696E.pdf

The Antenna port of the SE2432L FEM presents a 50 Ohm, single-ended impedance in order to connect to standard, off-the-shelf, singled port, 2.4 GHz antennas. Silicon Labs recommends the HW designer follow any and all application notes around their antenna of choice in order to maximize efficiency and directivity.

Note: the LNA is always enabled on the EM3598 Radio Board.

1.4.3 Optional Filter

Although the SE2432L FEM includes a filter after its power amplifier, depending on the power level of the fundamental and the harmonic spurs of the input signal (and the used antenna), the suppression provided by the built-in filter might be insufficient. In that case additional filtering should be added.

The EM3598 Radio Board (BRD4601A Rev. A03) board includes the option to mount additional filtering after the output of the FEM. By default the filter is not mounted (the series component is bypassed by a 0 Ohm resistor).

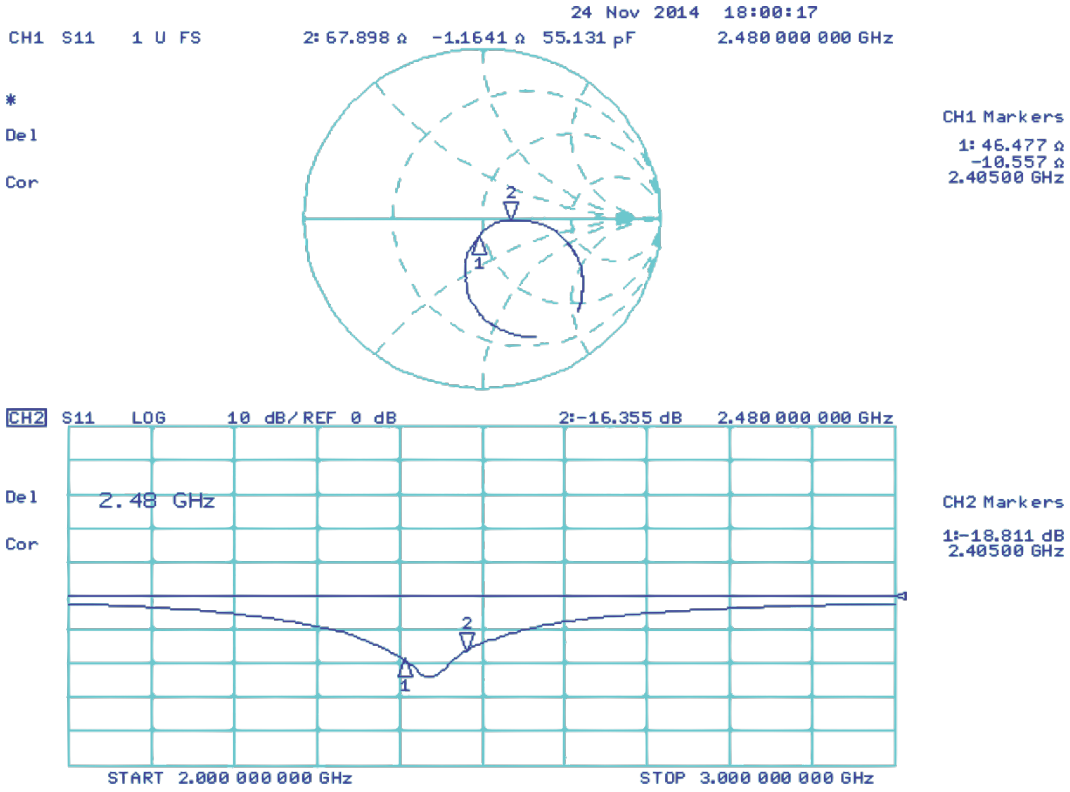
1.4.4 RF Test Connector

To assist with manufacturing test of the printed circuit assemblies, Silicon Labs added an RF switch connector (P/N: MM8130-2600 (Murata)). The RF switch connector allows an external 50 Ohm RF cable (e.g. P/N: MXHS83QE3000 (Murata)) to be connected during design verification testing. With the external RF cable connected to the RF switch connector, the antenna is isolated from the RF test measurement which provides for an accurate and repeatable RF Test. When the cable is not connected, the RF switch connector allows the antenna to be connected to the EM3598 RF path.

The RF switch connector is in stock, low cost, and low loss. However, if a designer does not want to incur the extra cost, you can add the footprint for the RF switch connector along with two resistors to select the connector during prototyping phase and not populate when in higher volume manufacturing.

1.4.5 Antenna of the EM3598 Radio Board

The EM3598 Radio Board incorporates a printed inverted-F antenna (IFA) tuned to have close to 50 Ohm impedance in the 2.4 GHz band (see Figure 4).



Marker	Freq. [MHz]	Impedance	Reflection (S11)
1	2405	6.5-j10.6 Ohm	-18.8 dB
2	2480	67.9-j1.2 Ohm	-16.4 dB

Figure 4. Impedance and reflection of the on-board printed IFA

2 EM3598 Configurations

The EM3598 on the EM3598 Radio Board can be set to different RF frequency channels as well as different power levels. When using Ember NodeTest Application on the board, the frequency channels and output power levels can be configured through a command line interface (see AN710, *Bringing up Custom Devices for the EM35x SoC Platform* for uploading and running NodeTest).

In order to configure the output power, the setTXPower command can be used. Table 1 demonstrates the setTXPower command and the power levels. Note that these are the typical expected power output levels based on the performance of the EM3598 IC and the SE2432L FEM.

Table 1: List of TX output powers when using SetTxPower

SetTxPower [signed hexadecimal]	Output Power of EM3598 (dBm)	Output Power of SE2432L FEM (dBm)
SetTxPower 9	+3	Not recommended
SetTxPower 8	+8	Not recommended
SetTxPower 7	+7	Not recommended
SetTxPower 6	+6	Not recommended
SetTxPower 5	+5	Not recommended
SetTxPower 4	+4	Not recommended
SetTxPower 3	+3	Not recommended
SetTxPower 2	+2	Not recommended
SetTxPower 1	+1	Not recommended
SetTxPower 0	0	Not recommended
SetTxPower -1	-1	Not recommended
SetTxPower -2	-2	Not recommended
SetTxPower -3	-3	Not recommended
SetTxPower -4	-4	Not recommended
SetTxPower -5	-5	+19.5
SetTxPower -6	-6	+19.0
SetTxPower -7	-7	+18
SetTxPower -8	-8	+17
SetTxPower -9	-9	+16
SetTxPower -a	-11	+14.5
SetTxPower -b	-11	+14.5
SetTxPower -c	-12	+13
SetTxPower -d	-14	+11
SetTxPower -e	-14	+11
SetTxPower -f	-17	+8
SetTxPower -10	-17	+8
SetTxPower -11	-17	+8
SetTxPower -12	-20	+4.5
SetTxPower -13	-20	+4.5

SetTxPower [signed hexadecimal]	Output Power of EM3598 (dBm)	Output Power of SE2432L FEM (dBm)
SetTxPower -14	-20	+4.5
SetTxPower -15	-26	-1.5
SetTxPower -16	-26	-1.5
SetTxPower -17	-26	-1.5

Note: setting power level above -5 dBm is not recommended due to the increasing nonlinear effects in the FEM causing increased harmonic levels.

To change the channel, the setChannel command can be used (assuming NodeTest application is on the device). Table 2 lists the valid parameters to be used with setChannel command.

Table 2. List of setChannel values for EM35xx

setChannel (decimal)	Center Frequency (GHz)	radioChannel (decimal)	Center Frequency (GHz)
11	2.405	19	2.445
12	2.410	20	2.450
13	2.415	21	2.455
14	2.420	22	2.460
15	2.425	23	2.465
16	2.430	24	2.470
17	2.435	25	2.475
18	2.440	26	2.480

3 Mechanical Details

The EM3598 Radio Board (BRD4601A Rev. A03) is illustrated in Figure 5 (top view) and Figure 6 (bottom view).

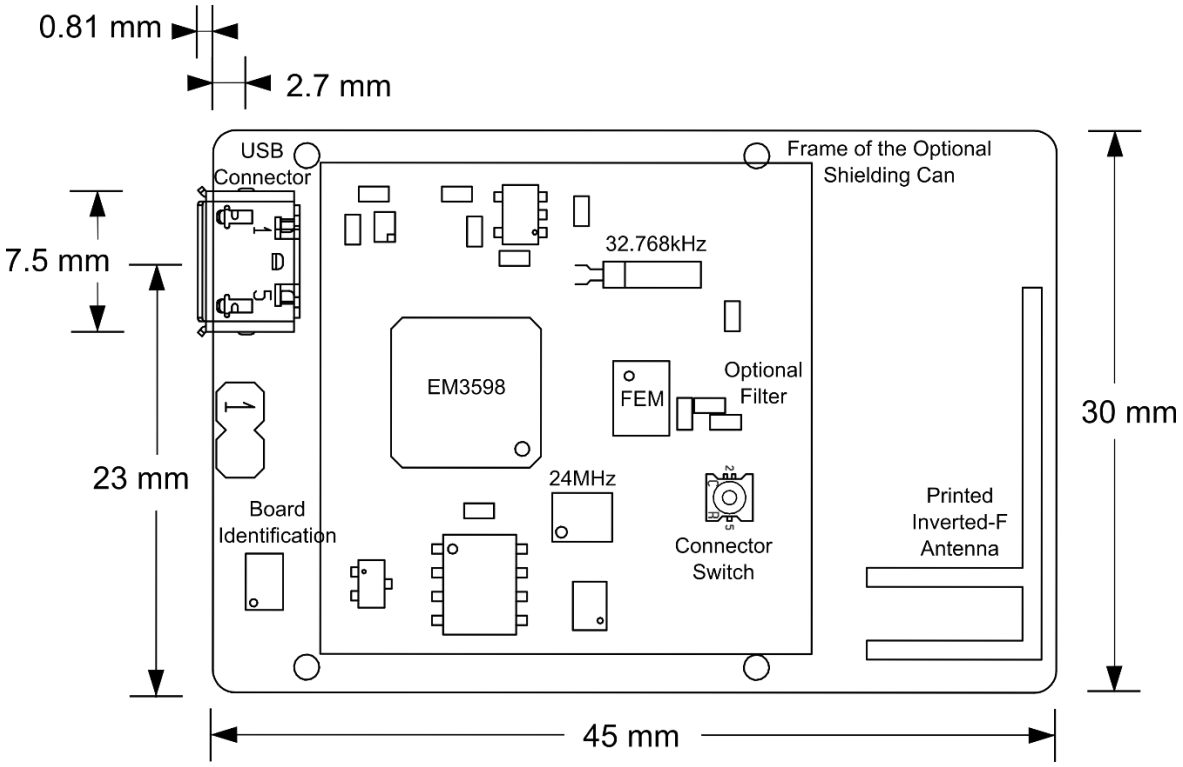


Figure 5. EM3598 Radio Board (BRD4601A Rev. A03) top view

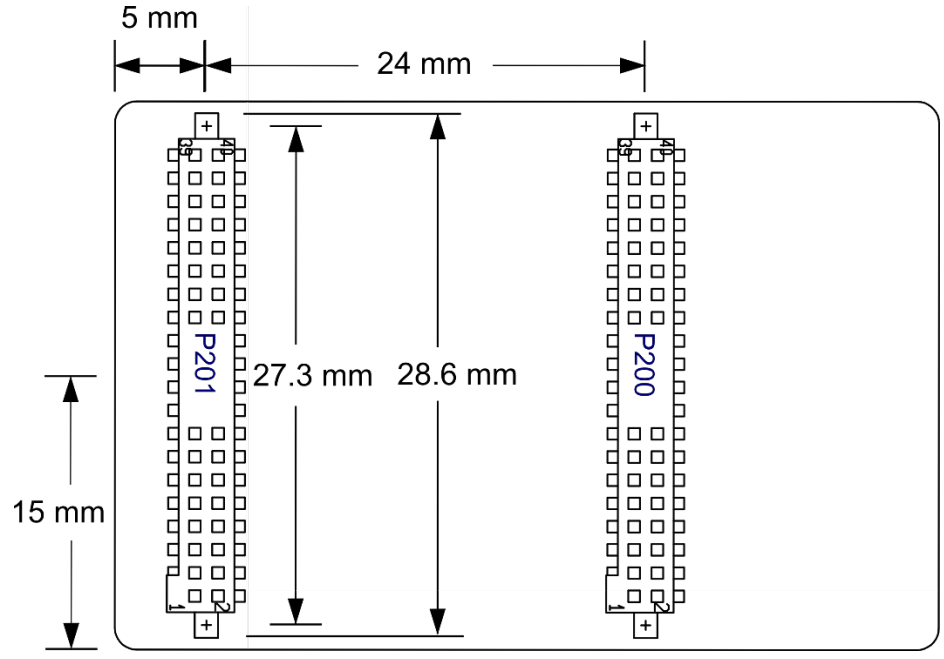


Figure 6. EM3598 Radio Board (BRD4601A Rev. A03) bottom view

3.1 EM3598 Radio Board Interface Connector

Two dual-row, 0.05” pitch polarized connectors (P/N: SFC-120-T2-L-D-A-K-TR (Samtec)) make up the EM3598 Radio Board interface to the WSTK Motherboard. The board-to-board connector scheme allows access to all EM3598 GPIO as well as nRESET and the JCLK signals. The connector is illustrated in Figure 6.

Table 3 describes the pinout and signal names on the connector.

For more information on the alternate functions of the GPIO connector, refer to the *EM359x Data Sheet*.

Table 3, Pinout and Signal Names of the Interface Connectors

Pin #	Signal Name	Direction[1]	Description
P200.1	3V3	Power	3.3 V power rail
P200.2	GND	Power	Ground connection
P200.3	NC	-	Not connected
P200.4	SENSOR_ENABLE	I/O	Pulled up to VBRD. (Humidity & temp. sensor on WSTK Motherboard is always on.)
P200.5	NC	-	Not connected
P200.6	NC	-	Not connected
P200.7	NC	-	Not connected
P200.8	PC3	I/O	EM35xx GPIO
P200.9	PC2	I/O	EM35xx GPIO
P200.10	PC0	I/O	EM35xx GPIO
P200.11	PA4	I/O	EM35xx GPIO
P200.12	PA5	I/O	EM35xx GPIO (nBOOTMODE function)
P200.13	PC4	I/O	EM35xx GPIO
P200.14	SWCLK, JTCK	I/O	JTAG interface, serial clock
P200.15	PC2	I/O	EM35xx GPIO
P200.16	PC3	I/O	EM35xx GPIO
P200.17	nReset	I/O	Active low chip reset (internal pull-up on EM35xx)
P200.18	PB5	I/O	EM35xx GPIO
P200.19	PB1	I/O	EM35xx GPIO
P200.20	PB2	I/O	EM35xx GPIO
P200.21	PB3	I/O	EM35xx GPIO
P200.22	PB4	I/O	EM35xx GPIO
P200.23	PA6	I/O	EM35xx GPIO
P200.24	PA7	I/O	EM35xx GPIO
P200.25	PB6	I/O	EM35xx GPIO
P200.26	PB7	I/O	EM35xx GPIO
P200.27	PD3	I/O	EM35xx GPIO
P200.28	PE2 (Through analog switch)	I/O	EM35xx GPIO
P200.29	PE0 (Through analog switch)	I/O	EM35xx GPIO
P200.30	PD4	I/O	EM35xx GPIO
P200.31	PE1 (Through analog switch)	I/O	EM35xx GPIO

[1] with respect to the EM3598 Radio Board

Pin #	Signal Name	Direction[1]	Description
P200.32	PA4	I/O	EM35xx GPIO
P200.33	PA5	I/O	EM35xx GPIO
P200.34	NC	-	Not connected
P200.35	USB_VBUS	Power	Power supply from USB
P200.36	USB_VREG	Power	Regulated USB power supply
P200.37	5V	Power	5 V power rail
P200.38	GND	Power	Ground connection
P200.39	BOARD_ID_SCL	I/O	Board Identification, Serial clock
P200.40	BOARD_ID_SDA	I/O	Board Identification, Serial Data
P201.1	GND	Power	Ground connection
P201.2	WMCU_IN	Power	MCU Power Supply
P201.3	PB3	I/O	EM35xx GPIO
P201.4	PE0 (Through analog switch)	I/O	EM35xx GPIO
P201.5	PB4	I/O	EM35xx GPIO
P201.6	PE1 (Through analog switch)	I/O	EM35xx GPIO
P201.7	PA6	I/O	EM35xx GPIO
P201.8	PE2 (Through analog switch)	I/O	EM35xx GPIO
P201.9	PA7	I/O	EM35xx GPIO
P201.10	PE3 (Through analog switch)	I/O	EM35xx GPIO
P201.11	PC1	I/O	EM35xx GPIO
P201.12	PB1	I/O	EM35xx GPIO
P201.13	PB6	I/O	EM35xx GPIO
P201.14	PB2	I/O	EM35xx GPIO
P201.15	PD2	I/O	EM35xx GPIO
P201.16	PD1	I/O	EM35xx GPIO
P201.11	PC1	I/O	EM35xx GPIO
P201.12	PB1	I/O	EM35xx GPIO
P201.13	PB6	I/O	EM35xx GPIO
P201.14	PB2	I/O	EM35xx GPIO
P201.15	PD2	I/O	EM35xx GPIO
P201.16	PD1	I/O	EM35xx GPIO
P201.17	NC (option to connect to PA0)	-	NC
P201.18	NC (option to connect to PA1)	-	NC
P201.19	PA2	I/O	EM35xx GPIO
P201.20	PA3	I/O	EM35xx GPIO
P201.21	PB5	I/O	EM35xx GPIO
P201.22	PB7	I/O	EM35xx GPIO
P201.23	PC4	I/O	EM35xx GPIO
P201.24	PC6	I/O	EM35xx GPIO
P201.25	PC7	I/O	EM35xx GPIO

[1] with respect to the EM3598 Radio Board

Pin #	Signal Name	Direction[1]	Description
P201.26	PD3	I/O	EM35xx GPIO
P201.27	PD4	I/O	EM35xx GPIO
P201.28	PB0	I/O	EM35xx GPIO
P201.29	PC5	I/O	EM35xx GPIO
P201.30	NC	-	Not connected
P201.31	NC	-	Not connected
P201.32	NC	-	Not connected
P201.33	NC	-	Not connected
P201.34	NC	-	Not connected
P201.35	NC	-	Not connected
P201.36	NC	-	Not connected
P201.37	NC	-	Not connected
P201.38	NC	-	Not connected
P201.39	GND	Power	Ground connection
P201.40	VRF_IN	Power	Radio Power Supply

[1] with respect to the EM3598 Radio Board

4 EMC Compliance

Compliance of the fundamental and harmonic levels is tested against the two most common standards:

- FCC 15.247
- ETSI EN 300-328

4.1 Harmonic limits

FCC 15.35 allows for a duty-cycle relaxation to the regulatory limits for spurious frequencies above 1 GHz. For EmberZNet PRO, the relaxation is 3.6 dB.

FCC 15.205 defines 'restricted bands' where harmonics/spurs must meet the levels set out in FCC 15.209. This is defined as -41.2 dBm (in EIRP) up to 12.5 GHz. This applies to the 2nd, 3rd, and 5th harmonics, but not the 4th harmonic. For spurs outside the restricted bands FCC 15.247 specifies -20 dBc spur limit.

However the ETSI EN 300 440-1 requires spurious emissions to be less than -30 dBm (in ERP), 1 GHz~24 GHz, so this becomes the default limit for the 4th harmonic.

Generally, if the FCC limits are met it is extremely unlikely that harmonics to 24 GHz would fail the ETSI requirements, so harmonics above the 5th will not be considered here.

The overall requirements is shown in Table 4.

Table 4. Harmonic power limits

Harmonic	Frequency	Limit
2nd	4810~4960MHz	≤-37.6 dBm
3rd	7215~7440MHz	≤-37.6 dBm
4th	9620~9920MHz	≤-30 dBm
5th	12025~12400MHz	≤-37.6 dBm

The ETSI limits are applied both for conducted and radiated measurements.

The FCC restricted band limits are radiated limits only. Besides that, Silicon Labs applies those to the conducted spectrum i.e. it is assumed that in case of a custom board an antenna is used which has 0 dB gain at the fundamental and the harmonic frequencies. In that theoretical case, based on the conducted measurement, the compliance with the radiated limits can be estimated.

Note: in practice used antennas usually have > 0 dB gain at the fundamental and < 0 dB gain at the harmonic frequencies so if the conducted levels are compliant with the regulation limits with small margin (e.g., < 1 dB), it is likely that reduction of the fundamental power will be required and/or the margin on the harmonics radiated by the antenna will be higher.

Unfortunately, in most cases, the PCB radiation (from traces or and/or components) is stronger so using shielding, applying larger duty cycle correction or additional fundamental power reduction could be necessary.

5 Output Power Measurements

5.1 Measurement setup

The EM3598 Radio Board (BRD4601A Rev. A03) was attached to a WSTK Motherboard (BRD4001 Rev. A02) and its transmitter was operated in continuous carrier transmission mode.

5.2 Conducted Power Measurements

In case of the conducted measurements the output power was measured through a short coax cable connected directly to the output of the FEM, the connector switch was disconnected.

Note: In case of measuring through the on-board connector switch, depending on the used measuring cable, the measured power levels can differ from the ones measured directly at the FEM output.

A typical output spectrum measured with short coax cable at the output of the FEM (the connector switch was disconnected) is shown in Figure 7, the same output spectrum measured through the on-board connector switch and a UFL cable (P/N: MXHS83QE3000 (Murata)) is shown in Figure 8. As it can be observed by measuring through UFL cable the fundamental is attenuated but the harmonics are slightly amplified (by the FEM due to the reflection of the fundamental power from the connector switch).

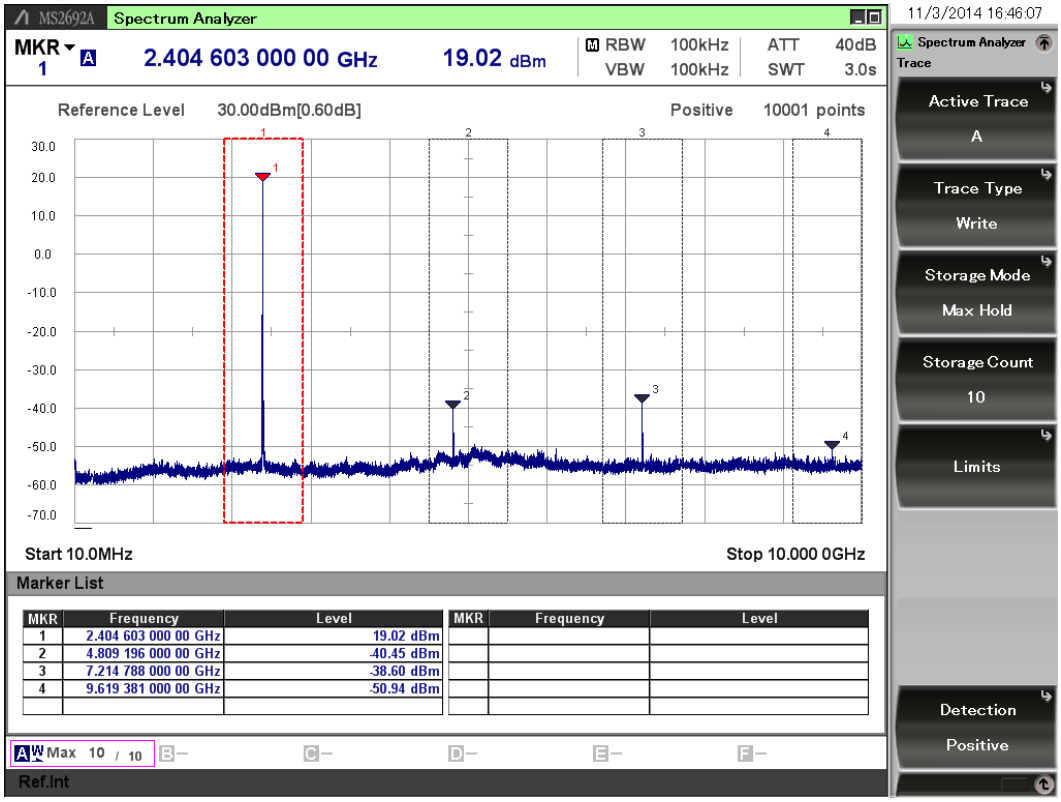


Figure 7. Typical output spectrum of the EM3589 Radio Board (BRD4601A Rev. A03) with setTxPower -5 at 3.3 V; measured through short coax cable directly at the FEM output

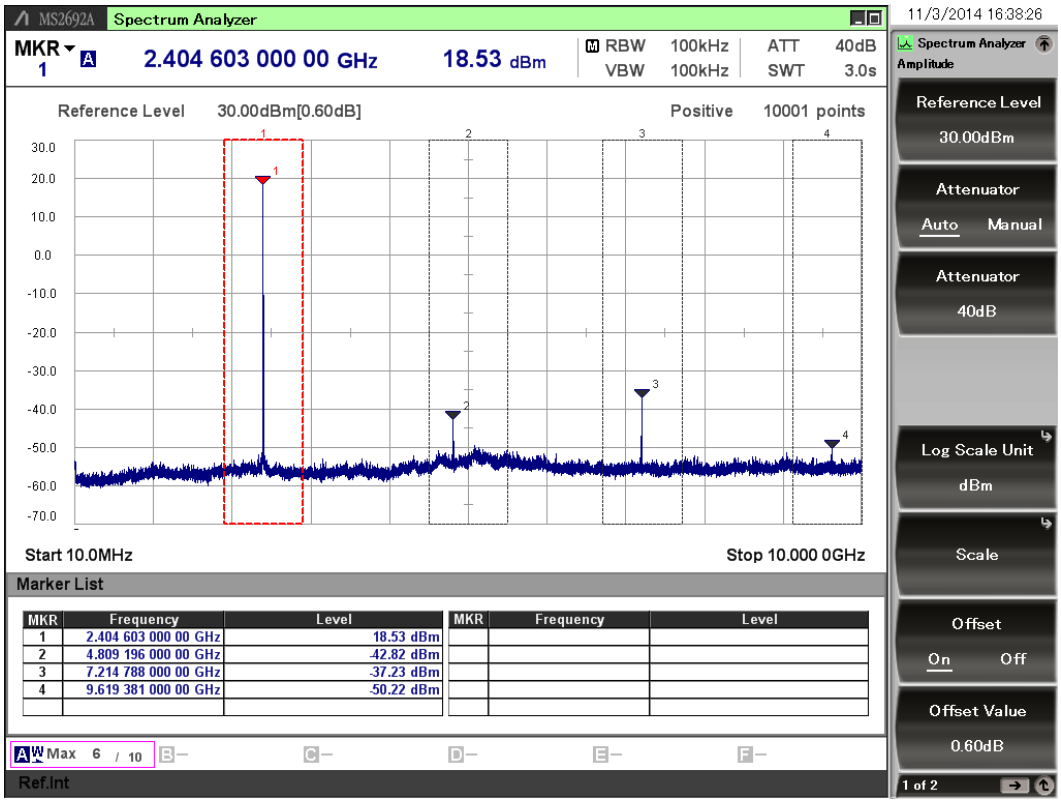


Figure 8. Typical output spectrum of the EM3598 Radio Board (BRD4601A Rev. A03) with setTxPower -5 at 3.3 V; measured through the on-board connector switch and UFL cable

The measured conducted powers are shown in Table 5. The values were measured through a short coax cable connected directly to the output of the FEM (the connector switch was disconnected).

Table 5. Results of the conducted power measurements

	Measured conducted power in [dBm]					Applied limit in EIRP [dBm]
setTxPower	**-9**	**-8**	**-7**	**-6**	**-5**	
Fundamental	**+16.0**	**+17.2**	**+18.2**	**+19.1**	**+19.5**	**+21**
2nd	**-45.7**	**-44.2**	**-42.9**	**-42.0**	**-41.3**	**-37.6***
3rd	**-48.4**	**-46.0**	**-43.2**	**-40.1**	**-37.2**	**-37.6***
4th	**-52.6**	**-51.1**	**-50.1**	**-47.5**	**-45.4**	**-30****
5th	**-59.4**	**-56.9**	**-54.1**	**-50.5**	**-49.8**	**-37.6***

* FCC 15.247 restricted band limit with 3.6 dB duty-cycle relaxation based on the EmberZNet PRO

** ETSI EN 300 440-1 limit

5.3 Radiated Power Measurements

During radiated measurements the IFA antenna on the EM3598 Radio Board was used as the transmitter antenna (the output of the FEM was connected to the antenna input by the mounted connector switch).

The power supply for the board were two AA batteries (3V). The batteries were connected to the WSTK Motherboard through its External Power Supply connector with minimal wire length to minimize the wire radiation.

The DUT was rotated in 360 degree with horizontal and vertical reference antenna polarizations in the XY, XZ and YZ cuts (see Figure 9).

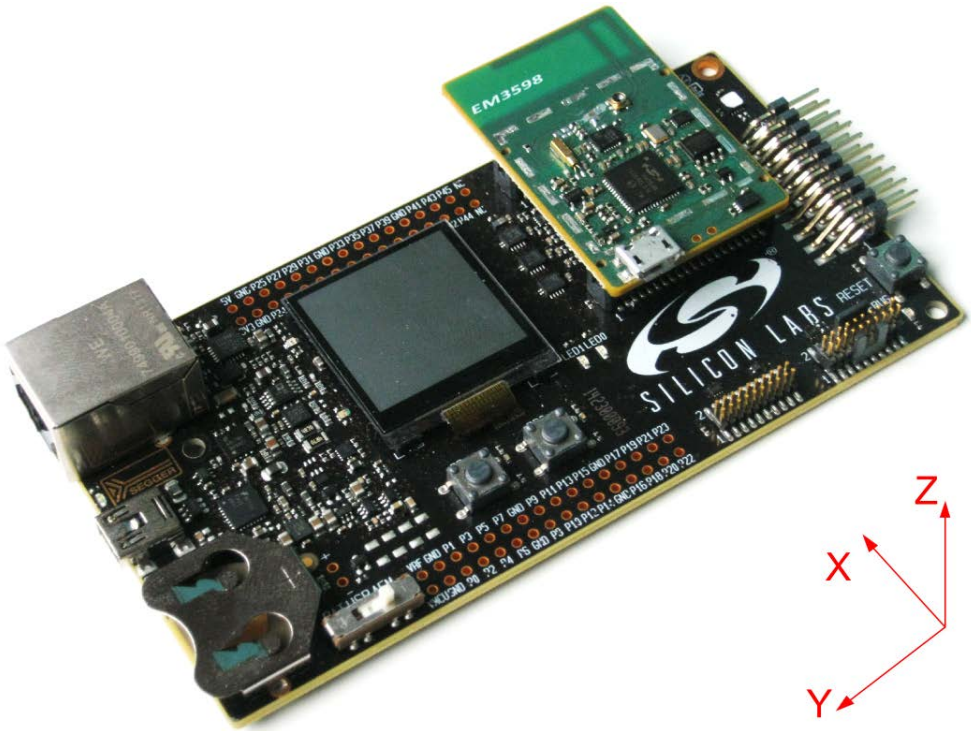


Figure 9. DUT: EM3958 Radio Board with Wireless Motherboard

The measured radiated powers with different power settings are shown in Table 6.

Table 6. Results of the radiated power measurements; without shielding

	Measured radiated power in EIRP [dBm]					Applied limit in EIRP [dBm]
setTxPower	**-9**	**-8**	**-7**	**-6**	**-5**	
Fundamental	**+18.3**	**+19.4**	**+20.3**	**+21.2**	**+22.1**	**+21**
2nd	**-39.1**	**-38.6**	**-37.7**	**-37.3**	**-36.5**	**-37.6***
3rd	**-46.3**	**-44.1**	**-41.6**	**-37.1**	**-33.9**	**-37.6***
4th	**-43.8**	**-40.8**	**-40.0**	**-36.9**	**-36.9**	**-30****
5th	**<-47.0**	**<-47.0**	**<-47.0**	**<-47.0**	**-45.8**	**-37.6***

* FCC 15.247 restricted band limit with 3.6 dB duty-cycle relaxation based on the EmberZNet PRO

** ETSI EN 300 440-1 limit

Comparing the conducted and the radiated powers one can notice that e.g. in case of the 'setTxPower -5' state the fundamental power at the output of the FEM is only ~19.5 dBm, the radiated power is higher by ~2.5 dB. This is due to the fact that the applied IFA antenna has 2~3 dB gain at the fundamental frequency.

Unfortunately the harmonic levels are higher compared to the levels expected based on the conducted measurements. Investigations showed that this increase is due to the PCB radiations so the radiated power measurements was performed on the same board but with a shielding can (P/N: 97-2002 (Laird Tech.)) mounted. As it can be observed the shielding improves the radiated levels by ~2-4 dB. The rest of the radiation is produced by the board connector pins.

The measured radiated powers with mounted shielding can with different power settings are shown in Table 7.

Table 7. Results of the Radiated Power Measurements ith Shielding

	Measured radiated power in EIRP [dBm]					Applied limit in EIRP [dBm]
setTxPower	**-9**	**-8**	**-7**	**-6**	**-5**	
Fundamental	**+18.7**	**+19.5**	**+20.7**	**+21.5**	**+21.8**	**+21**
2nd	**-43.3**	**-41.7**	**-41.2**	**-40.3**	**-40.4**	**-37.6***
3rd	**-46.5**	**-45.5**	**-44.4**	**-39.3**	**-37.2**	**-37.6***
4th	**-46.3**	**-44.6**	**-43.7**	**-42.7**	**-42.7**	**-30****
5th	**<-47.0**	**<-47.0**	**<-47.0**	**<-47.0**	**-46.1**	**-37.6***

* FCC 15.247 restricted band limit with 3.6 dB duty-cycle relaxation based on the EmberZNet PRO

** ETSI EN 300 440-1 limit

Also one can notice that the fundamental is a bit stronger with shielding since the shielding can slightly increases the effective ground area for the antenna.

Note: the measurement results presented in this document were recorded in an unlicensed antenna chamber. Also the radiated power levels may change depending on the actual application (PCB size, used antenna etc.) therefore the absolute levels and margins of the final application is recommended to be verified in a licensed EMC testhouse!

6 EMC Compliance Recommendations

6.1 Recommendations for FCC Compliance

In order to be compliant with the FCC 15.247 fundamental limit (+21 dBm) it is recommended to use the EM3598 Radio Board (BRD4601A Rev. A03) with the 'setTxPower -7' setting. With that the output power of the FEM is reduced to +18 dBm but thanks to the +2~3 dB gain of the on-board printed inverted-F antenna the radiated power will be around +20 dBm, just below the limit by less than 1 dB margin.

Thanks to the allowed duty-cycle relaxation, which is 3.6 dB in case of the EmberZNet PRO, the 2nd harmonic is marginally compliant, the 3rd harmonic is compliant with small margin. Further harmonics, even the ones falling into a restricted band are compliant with larger margin. For further improvement without the reduction of the fundamental power mounting a shielding can is advised.

6.2 Recommendations for ETSI Compliance

The limit based on ETSI EN 300 440-1 for the fundamental is +20 dBm so compared to FCC additional 1 dB reduction of the fundamental is required for the radiated compliance [i.e., the 'setTxPower -8' setting is recommended for the EM3598 Radio Board (BRD4601A Rev. A03)]. With that the harmonics are below the limit with large margin.

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