WIRELESS & SENSING PRODUCTS

Application Note: Adaptive Matching and Configuration for Multiband Operation

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1. Introduction

Both the SX1261 and SX1262 low-power sub-GHz LoRa RF transceivers cover a wide frequency range, extending from 150 MHz up to 960 MHz.

Although the circuit itself covers this frequency range continuously, traditional circuit designs typically require several impedance-matching networks which, in turn, require multiple reference designs to meet both acceptable RF performance (in line with published specifications) and the specific requirements of various regulatory regimes to ensure compliance.

This Application Note describes a method in which the RF performance of a circuit can be configured by firmware to allow a single **Bill Of Materials** (BOM) to be implemented for both ITU Regions 1 and 2. This enables coverage over the frequency range 860 – 930 MHz, **with particular reference to the ETSI EN 300 220-1, CFR 47 Part 15 and ISED / ISDE RSS-247 regulatory requirements**. This firmware configurability will demonstrate the flexibility of the SX1261 and SX1262 transmitter architecture.

It should be noted that the techniques described can be readily adapted for other frequency bands and regulatory domains.

The advantages of a firmware-configurable approach are:

- To provide a single design which may be adopted in multiple regions
- To enable an application to be used in multiple regions through a single hardware BOM
- Simplified logistical and support requirements

The Application Note further describes a switchless reference design, which takes advantage of the flexibility of the transceiver architecture to implement a reference design without the requirement for a switch between the antenna and the transmitter and receiver paths.

2. Transmitter Architecture

A simplified block diagram of the power amplifier (PA) architecture is illustrated in Figure 1, below.

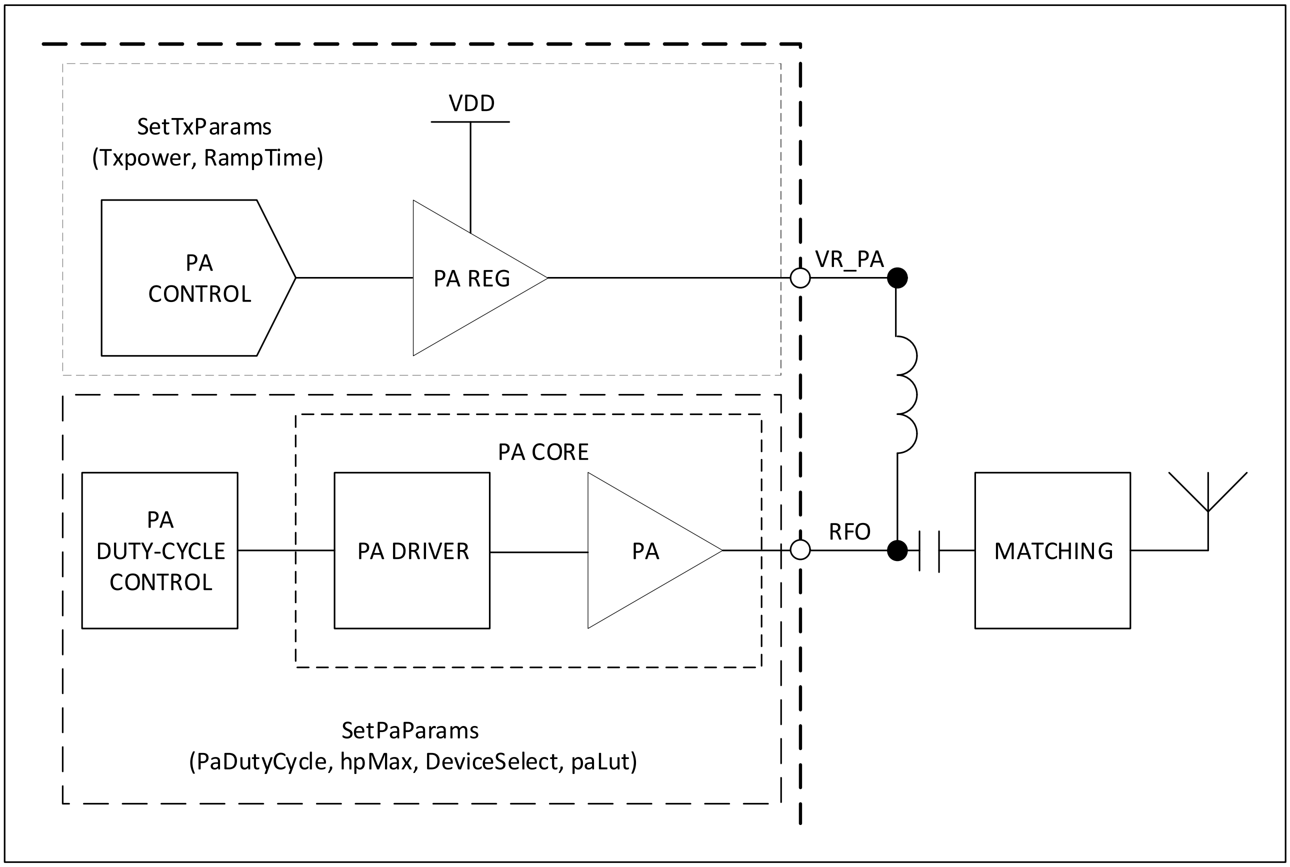


Figure 1: Simplified Transmitter Architecture

The PA architecture of the SX1261 and SX1262 is flexible by design, and capable of delivering a wide output power range without sacrificing efficiency. This architecture, shown above, uses three configurable parameters to control the output power, **TxPower**, **PaDutyCycle** and **hpMax**.

Both the output power and current consumption increase with an increase in any one of the above parameters. However, the behavior of the overall efficiency and the harmonic levels vary differently depending on which parameter is used to control functionality, as described in the following sections.

2.1 TxPower

Configuration of the **TxPower** parameter sets the voltage supply of the PA (VR_PA). For the purposes of the examples considered by this application note, **TxPower** is configured to a maximum, which sets VR_PA to a maximum and maximizes the efficiency of the circuit. However, as is also demonstrated, the configured **TxPower** can be adapted to provide for a degree of fine-tuning, as required. Further information relating to configured output power as a function of VR_PA can be found in Section 4.4 of the datasheet [1].

2.2 PaDutyCycle

The **PaDutyCycle** parameter controls the duty cycle of the PA driver stage, which is equivalent to controlling the conduction angle of a class C amplifier. It will be demonstrated that both output power and current consumption increase with higher duty cycles. Therefore, it is recommended that the **PaDutyCycle** should be kept as low as possible to maximize efficiency. Note that the relative amplitude of odd and even harmonics are a function **PaDutyCycle**.

The valid range of **PaDutyCycle** for SX1262 is 0 to 4 (for **hpMax** 0 to 7) or 0 to 7 for (**hpMax** = 0 to 4) and 0 to 7 for SX1261 for synthesized frequencies greater than 400 MHz.

2.3 hpMax

The third parameter, **hpMax**, configures the number of stages in the high power amplifier (HPA) block. As the number of stages increase so do the output power and current consumption. In addition, it should be noted that harmonic emissions similarly increase with increasing output power. For maximum efficiency, **hpMax** should be configured to the lowest possible value required to achieve the desired output power. Note that the balance of configured **PaDutyCycle** and **hpMax** parameters will be both circuit and application dependent.

The valid range of **hpMax** is 0 to 7. Above this upper limit, degradation to the SX1262 PA structure may occur. Note the SX1261 low-power amplifier LPA block is similar to that of the HPA stage of the SX1262. However, there is no additional configuration of this stage and **hpMax** should be set to "0" for the SX1261.

3. Transmitter Configuration and Optimization

Sections 11.1 and 13.1.14 of the SX126x datasheet describe the optimal configuration of the PaConfig parameters for given "narrow-band" or region-specific cases.

The configuration of the transmitter architecture is defined by the following:

- Radio.SetTxParams (**TxPower**, RampTime)
- Radio.Set PaConfig (**PaDutyCycle**, **hpMax**, DeviceSelect, paLut)

As described in Section 2, the transceiver is configured for maximum output power to maximize both VR_PA and efficiency. RampTime is selected to ensure any transient or switching spectrum complies with regulatory requirements.

The recommended range of both TxParams and PaConfig variables for operation over the frequency range 863 – 928 MHz is tabulated below in Table 1.

Parameter	Range	
	SX1261	SX1262
TxPower (dBm)	-17 to +14	-9 to +22
RampTime (μs)	10 to 3400	
PaDutyCycle	0 to 7	0 to 4
hpMax	1	0 to 7
DeviceSelect	1	0
paLut	1	

Table 1: TX and PA Configuration Variables

To observe the effect on the emissions spectrum and current consumption, as a function of the configuration of both **hpMax** and **PaDutyCycle** parameters, a representative SX1262 switched reference design, pcb_e428v03a and as illustrated in Figure 15, is configured to operate over the frequency range from 860 MHz to 935 MHz, with **TxPower** configured to +22 dBm.

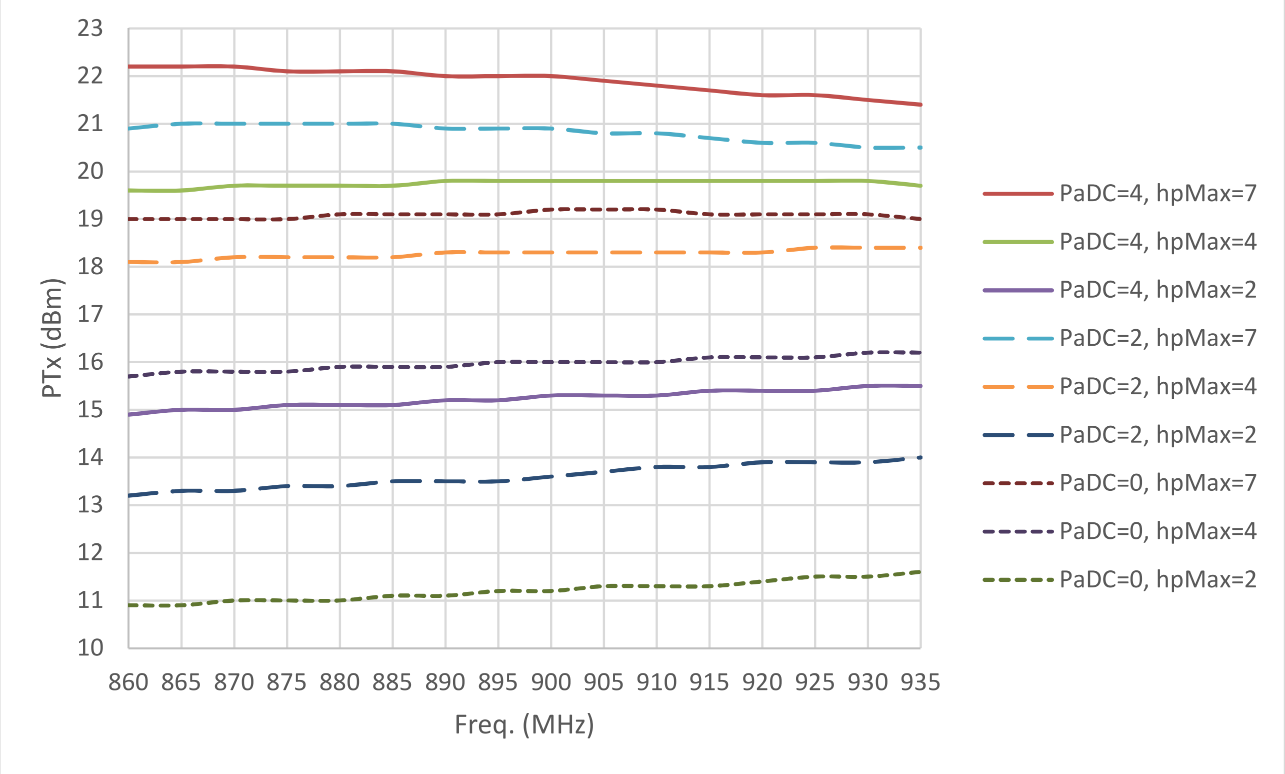


Figure 2: Fundamental Tx Output Power as a Function of PaDutyCycle and hpMax

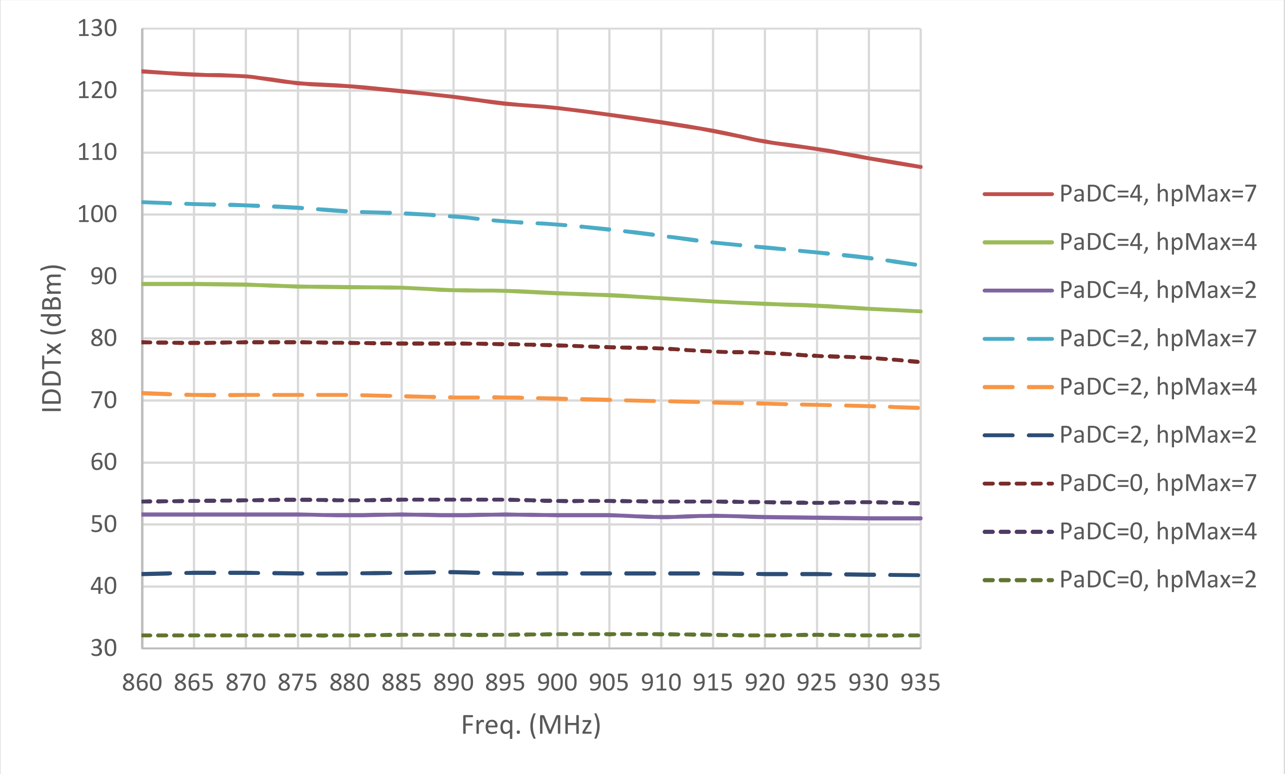


Figure 3: IDDTx as a Function of PaDutyCycle and hpMax

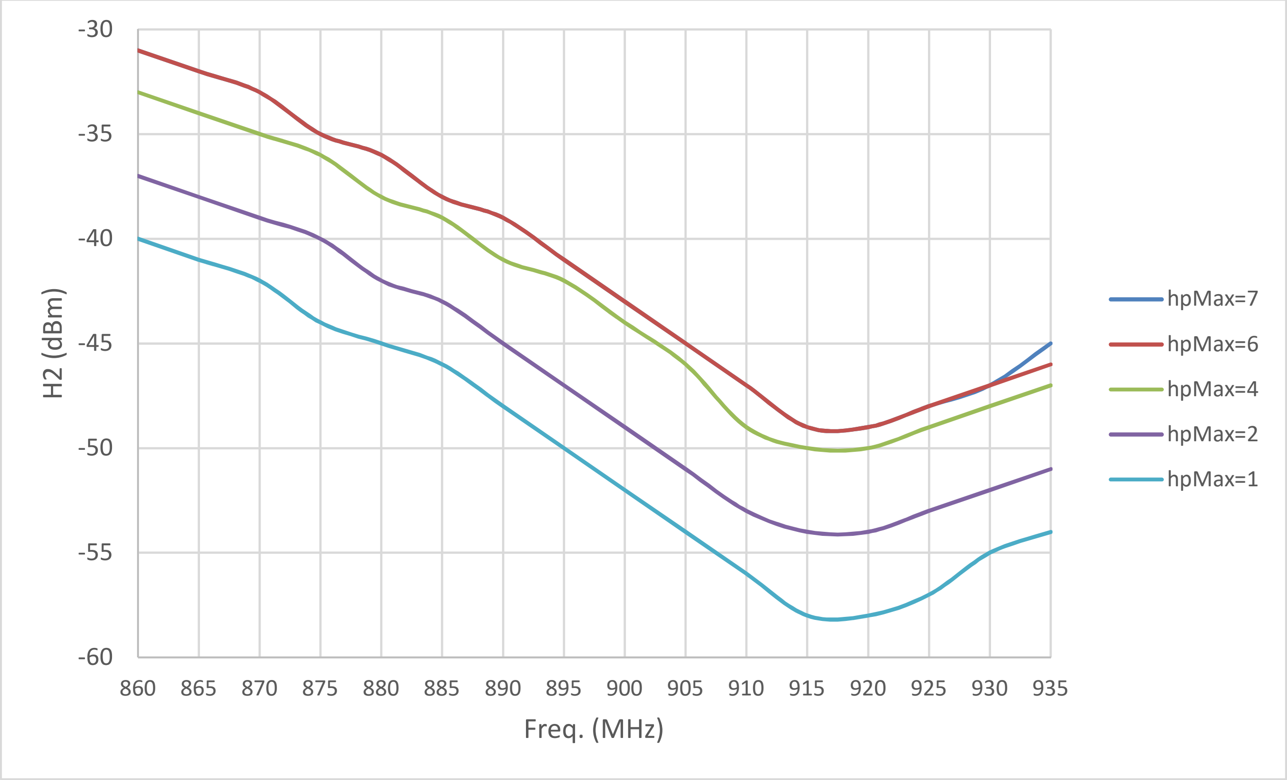


Figure 4: Second Harmonic Emissions as a Function of hpMax for PaDutyCycle = 2

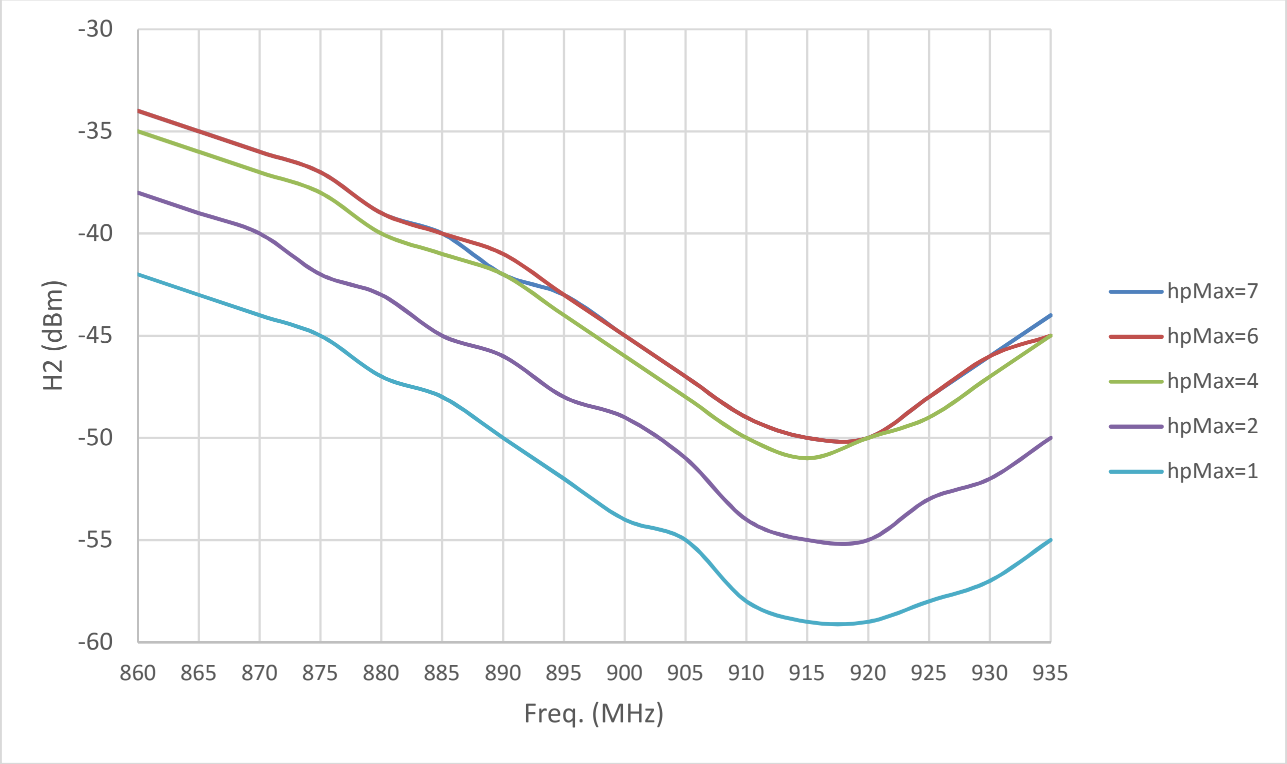


Figure 5: Second Harmonic Emissions as a Function of hpMax for PaDutyCycle = 4

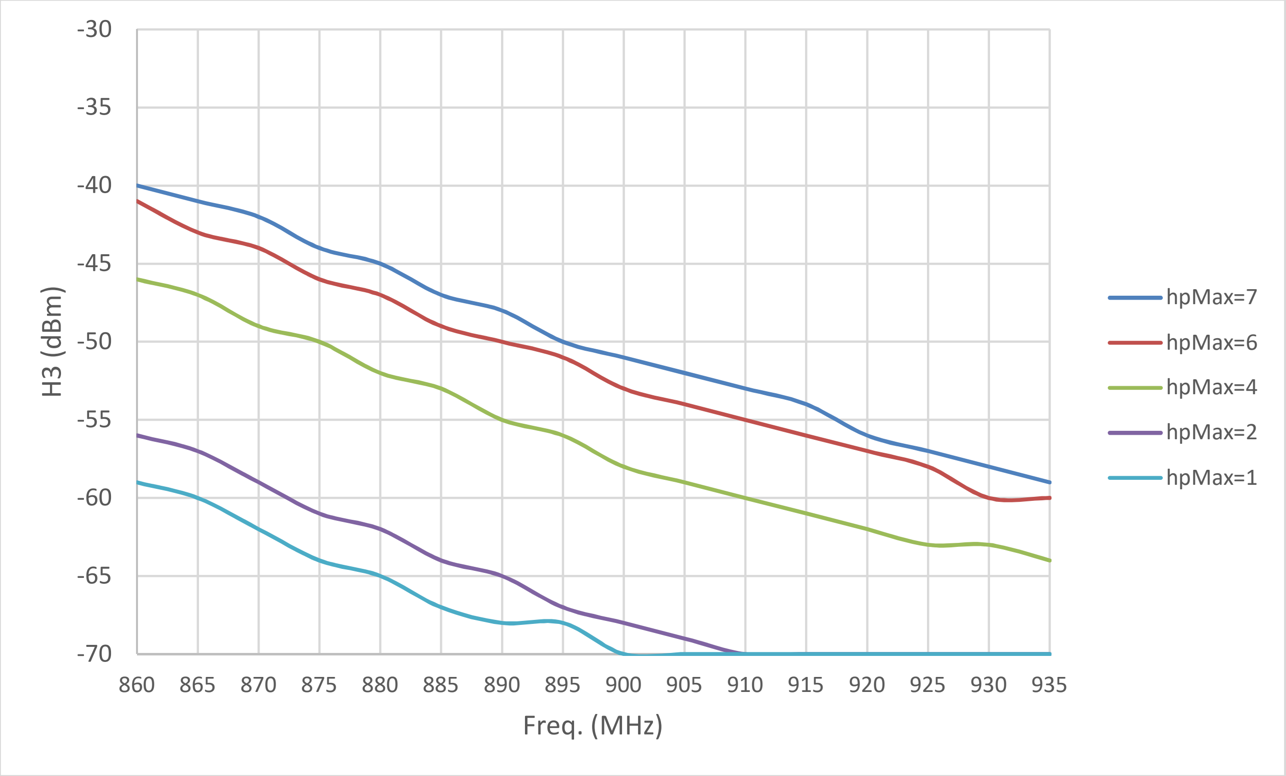


Figure 6: Third Harmonic Emissions as a Function of hpMax for PaDutyCycle = 2

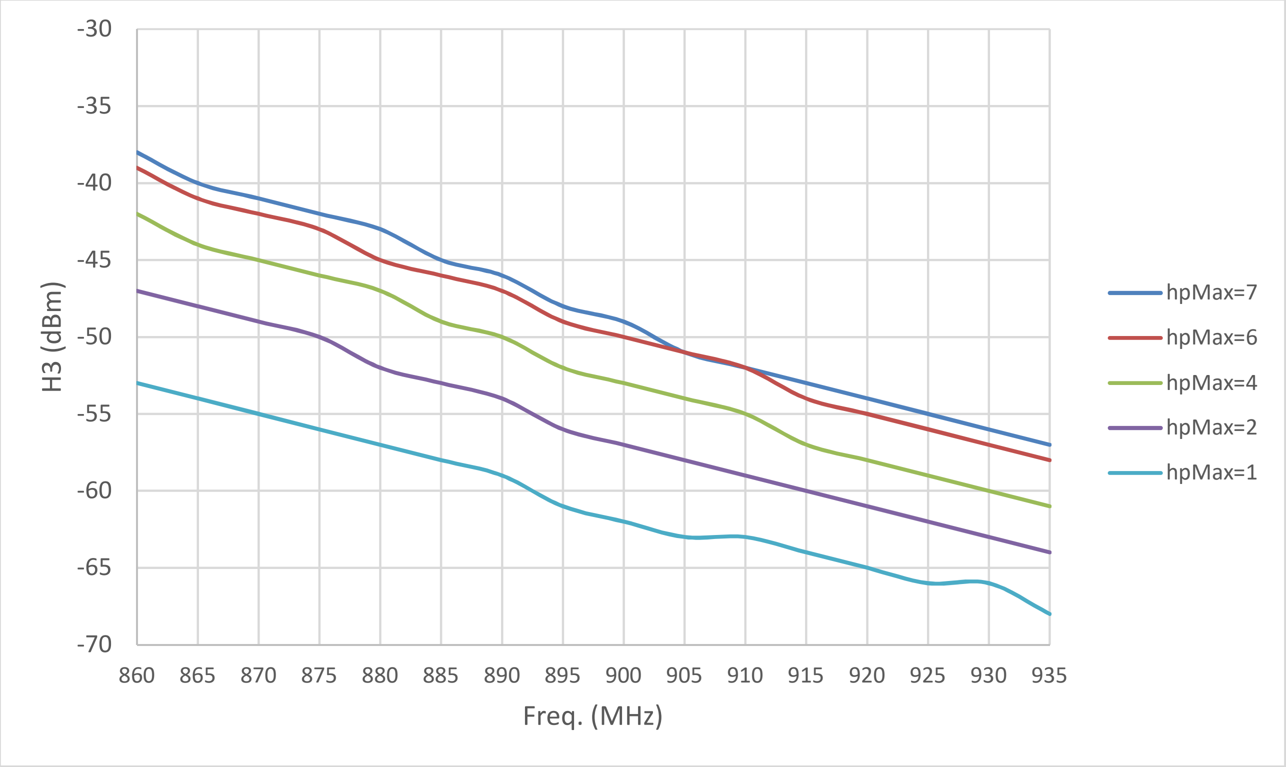


Figure 7: Third Harmonic Emissions as a Function of hpMax for PaDutyCycle = 4

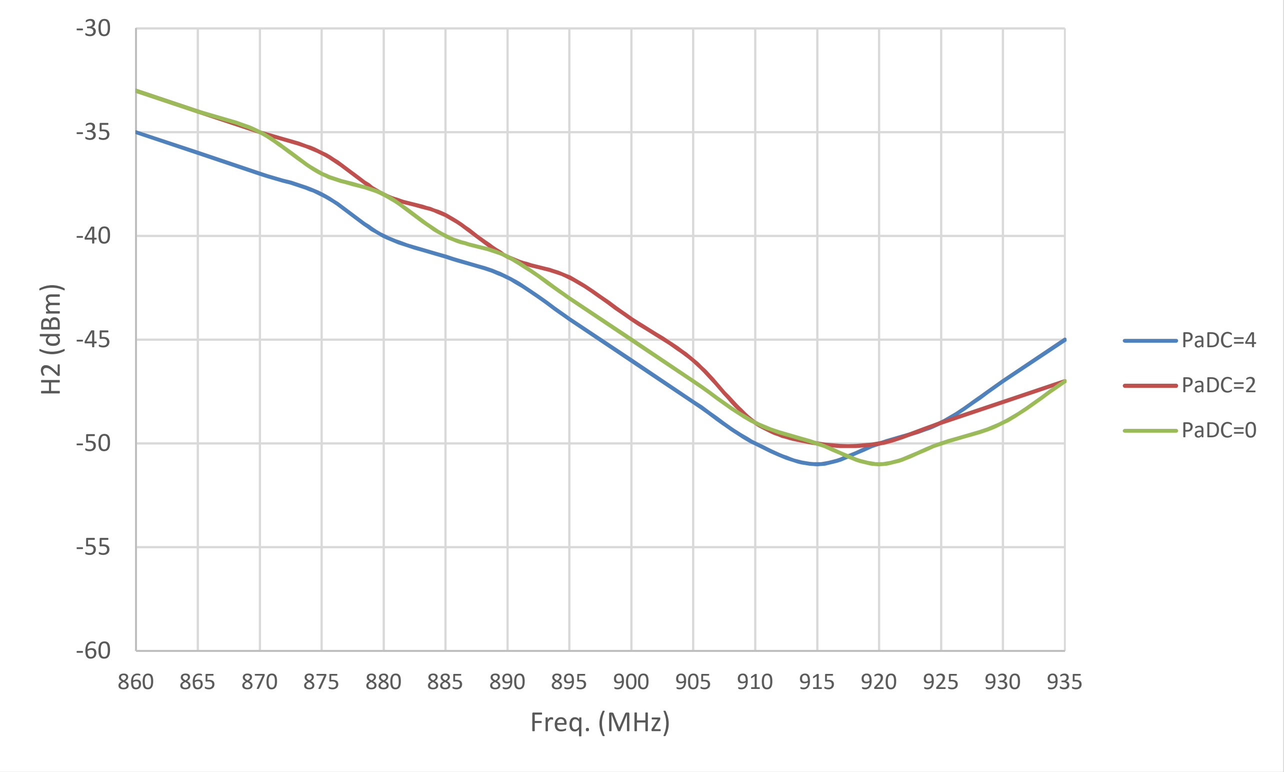


Figure 8: Second Harmonic Emissions as a Function of PaDutyCycle for hpMax = 4

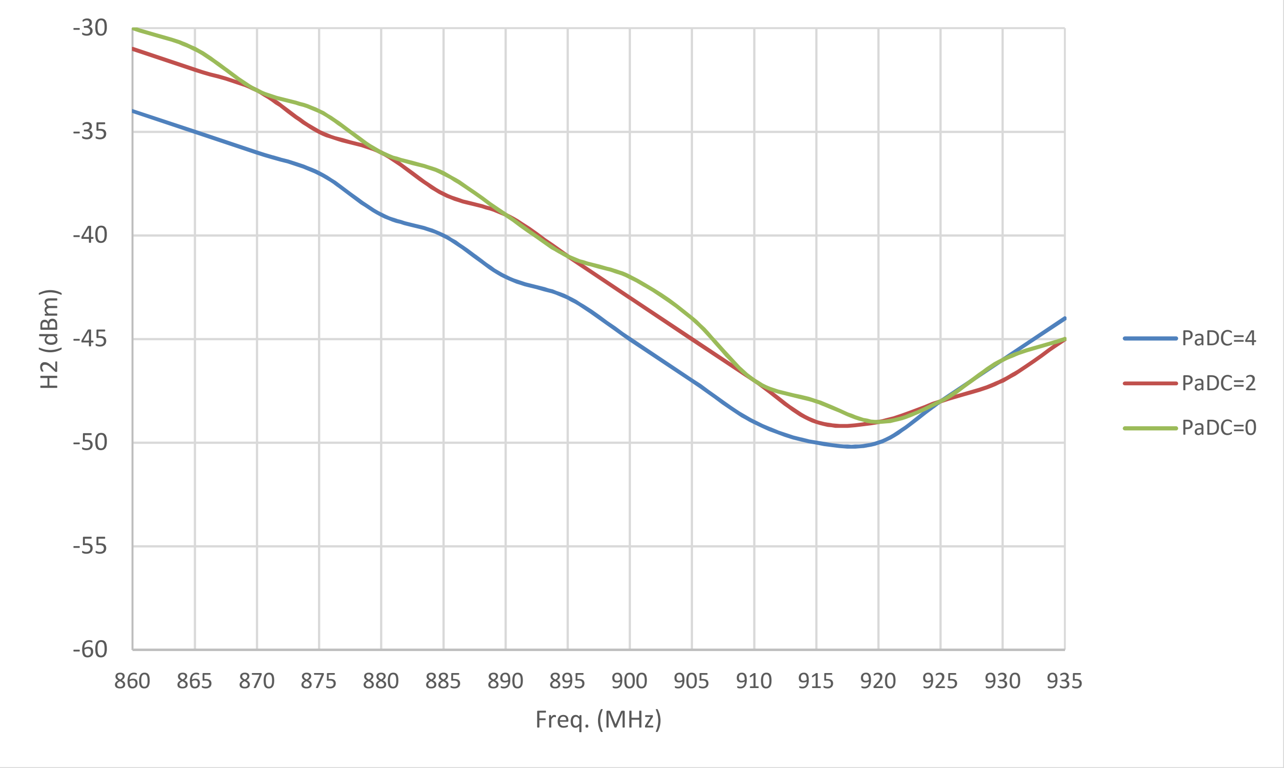


Figure 9: Second Harmonic Emissions as a Function of PaDutyCycle for hpMax = 7

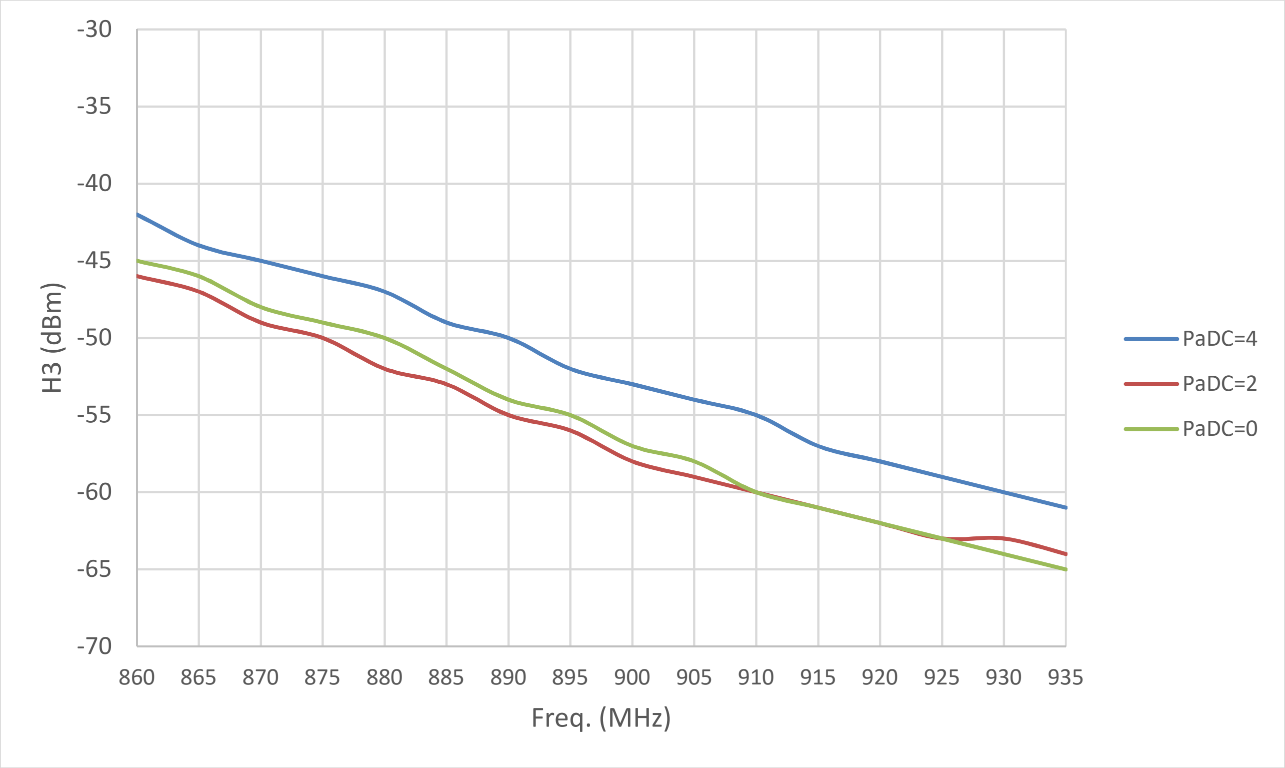


Figure 10: Third Harmonic Emissions as a Function of PaDutyCycle for hpMax = 4

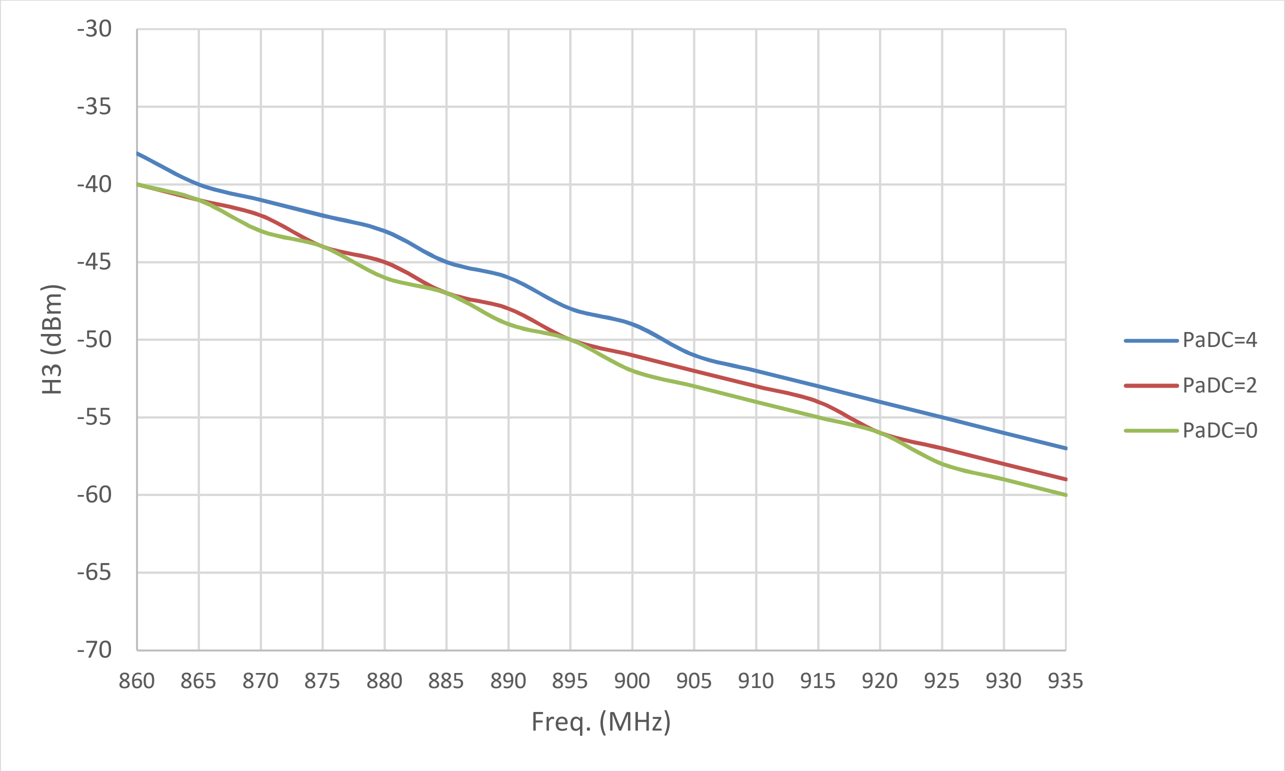


Figure 11: Third Harmonic Emissions as a Function of PaDutyCycle for hpMax = 7

From the results illustrated above, it can be observed that for a fixed **TXPower**, configuration of both **PaDutyCycle** and **hpMax** parameters can be used to modify the emissions signature and, as will be demonstrated, the efficiency of both SX1262 and SX1261.

Maximum indicated fundamental output power, PTx, is obtained for the maximum configured values of **PaDutyCycle** and **hpMax**. In general, increasing **hpMax** increases the output power and all harmonics. On the other hand, the behavior of the individual harmonic components is a function of **PaDutyCycle** configured.

Note that for the case where **PaDutyCycle** is set to zero, this particular configuration will result in the lowest transmitter output power and transmit mode current consumption. However, it does not result in maximum efficiency and relative to the fundamental wanted emission, will lead to the highest relative harmonic emission levels.

It should also be noted that the load impedance presented by the matching network at the RFO port and the characteristics of the matching network will also exert an influence upon the measured parameters.

As this Application Note will show, through a combination of hardware BOM and firmware configuration both SX1262 and SX1261 can adapted to meet both regulatory and application requirements over a wide frequency range that encompasses both the Americas and European regions.

4. Receiver Architecture

A simplified block diagram of the differential receiver architecture is illustrated in Figure 12.

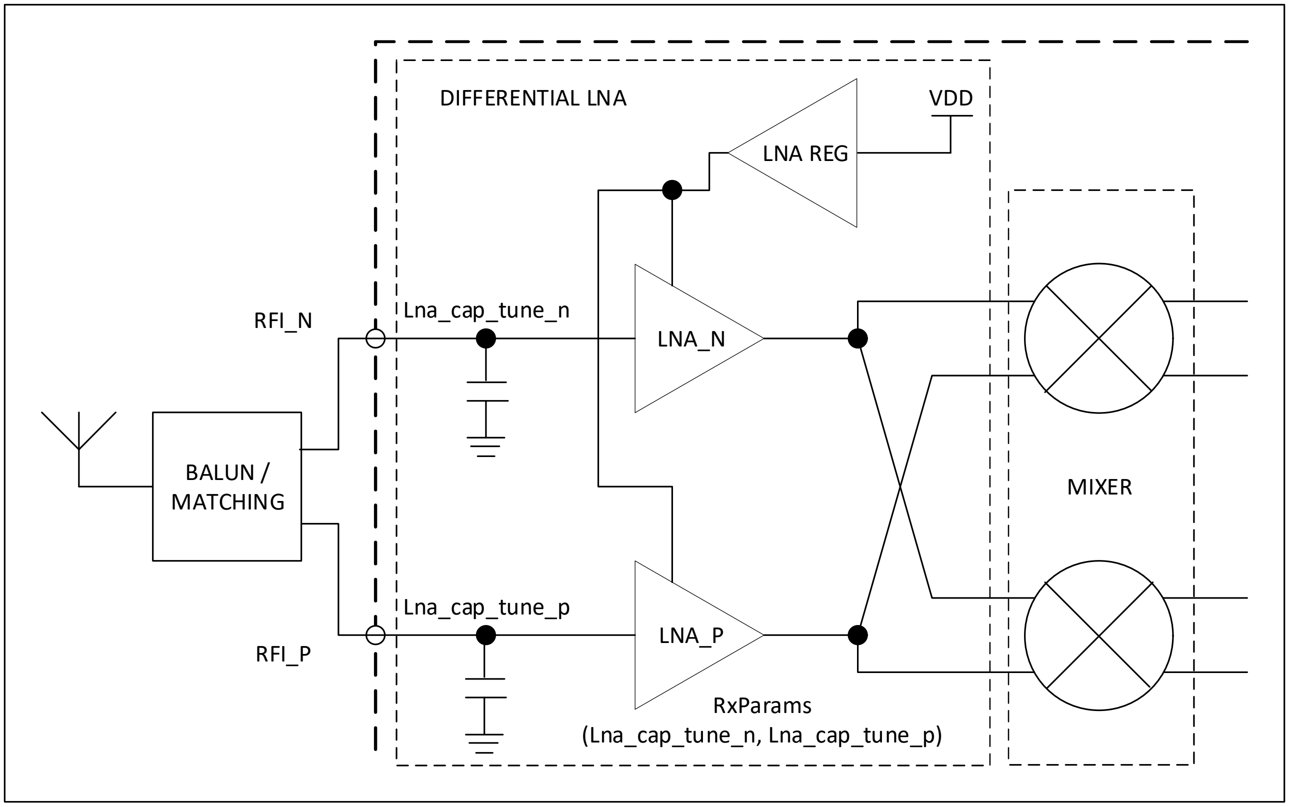


Figure 12: Simplified SX126x Receiver Front-End Architecture

The balun and matching circuit of the SX1261 and SX1262 reference designs provides for a broadband optimum match between the differential input structure of LNA and the single-ended nominal 50 ohm impedance of either the RF switch or antenna feed-point. However, for some applications the topology and routing of this network may require additional matching network optimization.

As an alternative to hardware optimization, it is possible to "tune" the input impedance of the LNA and thus the effective capacitive loading at the ports, through independently configuring the input shunt capacitances. These are identified in the figure above as **lna_cap_tune_n** (accessible at bits [3:0] at address 0x08E3) and **lna_cap_tune_p** (accessible at bits [7:4] at address 0x08E4) and both can be varied over a typ. 0.8pF range in increments of 50fF per LSB.

The default value of lna_cap_tune is 0100b, equivalent to an additional 0.2 pF loading across each port.

5. Receiver Configuration and Optimization

Section 9.6 of the SX126x datasheet describes the optimal configuration of the receiver parameters. As documented in Section 4 of this Application Note, the input capacitive loading of the differential LNA inputs can be configured to accommodate either a non-optimal implementation of the receiver matching network or where modification to the BOM may influence the performance of the transmitter circuit, as will be discussed in Section 7.2.

To observe the effects of changing the configuration of the capacitive loading at each port a simple packet error rate (PER) measurement is performed at the frequencies of interest for each possible configuration of **lna_cap_tune_n** and **lna_cap_tune_p** in turn.

This process will reveal a range of values of **lna_cap_tune_n** and **lna_cap_tune_p** over which an optimized sensitivity level is indicated, subject to the granularity provided by the PER measurement. It is recommended that the identified range be verified on a number of devices to ensure the component tolerances of the external matching network are taken into consideration.

6. Transmitter Adaptive Match Design Methodology

In this section, a method illustrating how both the PA configuration and hardware matching networks can be optimized to provide a broadband response capable of satisfying the relevant regulatory requirements of both European and North American regulations over a frequency range from 863 - 928 MHz with a single hardware BOM.

Again, this will be achieved by simply reconfiguring the on-chip amplifier stage to compensate for variation in the characteristics presented to the TX port by the RF matching network over the frequency range of interest, using the methodology described in Section 3.

This approach can also be used to assist in compensating for the characteristics of a particular matching network or layout topology. However, it is not a substitute for good RF design practices.

Semtech has developed an adaptive match reference design, which does not require a T/R switch (pcb_e460v01a). However, this Application Note will also consider the further analysis of the switched design introduced in Section 3.

Note that for the description of the adaptive match design methodology, the Application Note defines two additional parameters, η_{SX}, the efficiency of the entire radio circuit and η_{PA}, the efficiency of the PA circuit. These additional parameters may be considered when deciding upon the optimum configuration for power-constrained or battery-operated applications.

$$\eta_{SX} = \left(\frac{RF\ Output\ Power}{DC\ Input\ Power}\right) * 100\% = \left(\frac{10^{\left(\frac{PTX(dBm)}{10}\right)}}{VDD\_RADIO * IDDTX}\right) * 100\%$$

$$\eta_{PA} = \left(\frac{RF\ Output\ Power}{PA\ DC\ Power}\right) * 100\% = \left(\frac{10^{\left(\frac{PTX(dBm)}{10}\right)}}{VR\_PA * IDDTX}\right) * 100\%$$

6.1 Switchless Reference Design

The schematic of the switchless reference design is illustrated in Figure 13:

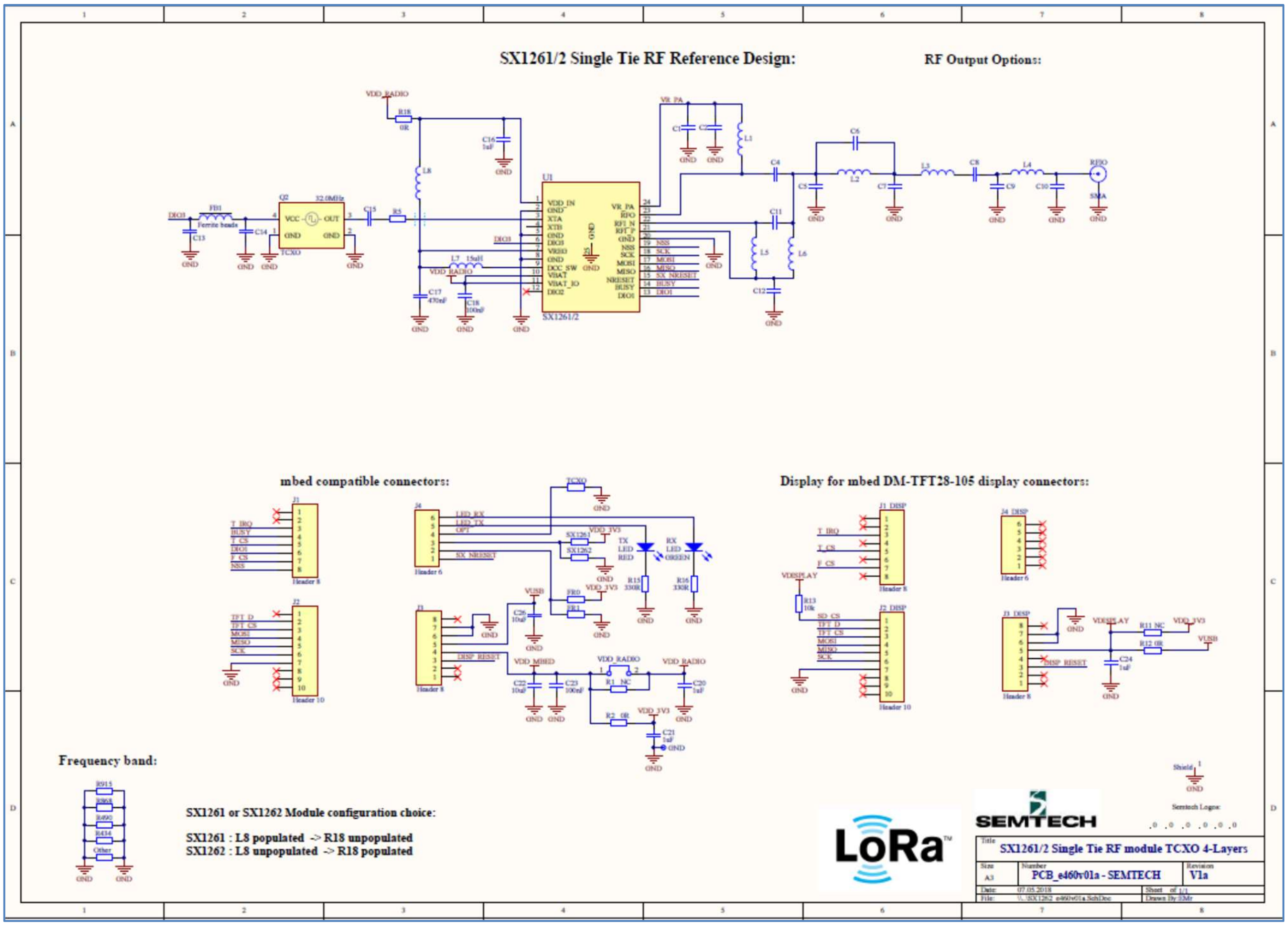
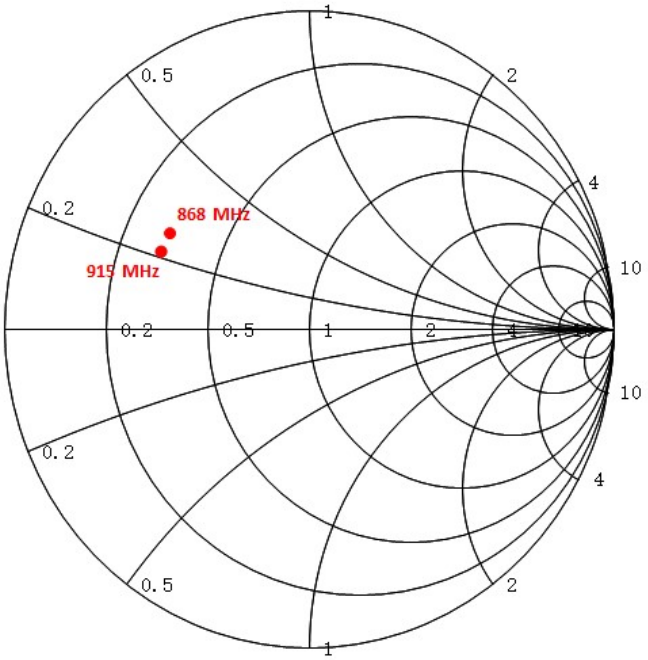


Figure 13: SX126x Switchless Reference Design

From the schematic diagram, it can be observed that the receiver (RFI) and transmitter (RFO) ports are connected at the junction of C4, C11, C5.

The receiver matching network is a classic lumped-element balun formed by C11, C12, L6 (L5 is DNP), while for the transmitter circuit, the matching network is a cascaded low-pass filter topology with the addition of a harmonic trap formed by C6 in parallel with L2.

To match the TX, a cascaded low-pass filter stage is developed from the nominal 50 Ohm port of the antenna back to the optimum load impedance (Zopt or S_{22}*) of the RFO port for +22 dBm operation at the frequencies of interest. As illustrated in Figure 14, the optimum load impedance at both 868 MHz and 915 MHz are similar and either point may be selected.



Freq. (MHz)	Zopt (R+jX) (Ω)
868	16.1 + j13.5
915	15.5 + j10.8

Figure 14: SX1262 Tx Zopt (+22 dBm)

With the receiver network isolated from the transmitter, the low-pass matching network is developed. During this process, C6 is not populated and a value of L2 in the range 3.0 nH – 3.3 nH is selected. With the match optimized, L2 is set in the range typically 0.75 – 0.8 of that initially selected above, and C6 is selected to ensure good rejection of H2 in the 863 – 870 MHz band, while not significantly degrading the H3 response when operating in the 902 – 928 MHz band.

Finally, we populate the receiver matching network. The component values of the BOM should be used.

Since this matching network will “pull” the matching network impedance presented to the transmitter circuit, fine-tuning of the transmitter matching network may be required.

The BOM for the TX and RX matching networks is as documented below:

RefDes	Value	Description	Manufacturer
C1	47nF	Multilayer Ceramic Capacitor X7R ±1%, 16V	Murata
C2	47pF	Multilayer ceramic capacitors C0G ±5%, 50V	Murata
C4	47pF	Multilayer ceramic capacitors C0G ±5%, 50V	Murata
C5	DNP		
C6	3.0pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C7	5.6pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C8	47pF	Multilayer ceramic capacitors C0G ±5%, 50V	Murata
C9	5.6pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C10	3.3pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C11	4.0pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C12	3.9pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
L1	4.7nH	Wirewound inductor ±5%	Murata
L2	2.7nH	Wirewound inductor ±0.2nH%	Murata
L3	2.7nH	Wirewound inductor ±0.2nH%	Murata
L4	8.2nH	Wirewound inductor ±2%	Murata
L5	9.5nH	Wirewound inductor ±2%	Murata
L6	DNP		

Table 2: Switchless Reference Design BOM

Adaptive matching configuration of the PA is then implemented to fine-tune the response of the SX1262 to meet the requirements for the particular application.

As an example, the application scenarios described below are considered:

1. Operation as a default LoRaWAN channel operating in Band h1.4 of Annex 1 of ERC 70-03[2] at 868.3 MHz with an approximate ERP of 25 mW (+14 dBm)
2. Operation as a LoRaWAN channel operating in Band h1.7 of Annex 1 of ERC 70-03 at 869.525 MHz with an approximate ERP of 158 mW (+22 dBm)
3. Operation as a LoRaWAN channel operating under the auspicious of CFR 47 Part 15.247 with an approximate output power of +22 dBm

First, consider the case for operating at 868.3 MHz with a nominal output power of +14 dBm as documented below in Table 3.

Introducing PaConfig parameter annotation (m; n) to denote the configuration setting for **PaDutyCycle** and **hpMax** values respectively, the results indicate that PaConfig parameters (0; 3), (2; 2), (3; 2) (4; 2) set a fundamental output power of approximately +14 dBm. Configuration PaConfig(2; 2) provides for the lowest current consumption and good harmonic balance, while configuration PaConfig(3; 2) indicates the conditions for maximum efficiency.

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)						η_{PA} (%)	η_{SX} (%)
				PTx	H2	H3	H4	H5	H6		
0	1	19.5	3.10	5.7	-44	≤ -70	≤ -70	≤ -70	≤ -70	6.13	5.76
0	2	31.8	3.11	11.0	-43	≤ -70	≤ -70	≤ -70	≤ -70	12.73	12.00
0	3	43.4	3.12	14.0	-42	≤ -70	≤ -70	≤ -70	≤ -70	18.38	17.38
0	7	75.5	3.14	18.7	-39	-61	≤ -70	≤ -70	-66	31.27	29.75
…	…	…	…	…	…	…	…	…	…	…	…
1	1	22.2	3.10	7.2	-45	≤ -70	≤ -70	≤ -70	≤ -70	7.57	7.11
1	2	36.9	3.11	12.4	-43	≤ -70	≤ -70	≤ -70	≤ -70	15.14	14.27
1	3	50.3	3.12	15.3	-42	-67	≤ -70	≤ -70	≤ -70	21.59	20.41
1	4	61.5	3.13	17.1	-41	-63	≤ -70	≤ -70	-66	26.64	25.27
…	…	…	…	…	…	…	…	…	…	…	…
1	7	85.0	3.14	19.6	-40	-60	≤ -70	≤ -70	-66	34.17	32.51
2	1	24.9	3.10	8.3	-46	≤ -70	≤ -70	≤ -70	≤ -70	8.76	8.23
2	2	41.8	3.12	13.5	-44	-67	≤ -70	≤ -70	≤ -70	17.17	16.23
2	3	57.3	3.13	16.3	-43	-64	≤ -70	≤ -70	≤ -70	23.78	22.56
…	…	…	…	…	…	…	…	…	…	…	…
2	7	95.5	3.14	20.4	-42	-57	≤ -70	≤ -70	-66	36.57	34.79
3	1	46.8	3.12	14.3	-46	-66	≤ -70	≤ -70	≤ -70	9.79	9.20
3	2	46.8	3.12	14.3	-46	-66	≤ -70	≤ -70	≤ -70	18.43	17.43
…	…	…	…	…	…	…	…	…	…	…	…
3	7	107.9	3.16	21.2	-47	-56	≤ -70	≤ -70	-65	38.66	37.02
4	1	32.0	3.11	9.9	-48	-68	≤ -70	≤ -70	≤ -70	9.86	9.30
4	2	54.1	3.12	14.9	-49	-62	≤ -70	≤ -70	≤ -70	18.31	17.31
…	…	…	…	…	…	…	…	…	…	…	…
4	7	123.4	3.17	21.8	-56	-55	≤ -70	≤ -70	-62	38.51	37.00

Table 3: SX1262 Tx Characteristics as a Function of PaConfig (868.3 MHz; +14 dBm - Switchless)

In the second application scenario, operating at 869.525 MHz with a nominal output power of +22 dBm is required and the same process can be repeated, as shown in Table 4.

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)						η_{PA} (%)	η_{SX} (%)
				PTx	H2	H3	H4	H5	H6		
3	7	107.8	3.16	21.1	-47	-56	≤ -70	≤ -70	-63	37.82	36.21
4	7	121.4	3.17	21.7	-55	-55	≤ -70	≤ -70	-61	38.43	36.92

Table 4: SX1262 Tx Characteristics as a Function of PaConfig (869.525 MHz; +22 dBm - Switchless)

Configuration (4; 7) indicates the condition for both maximum output power and efficiency, consistent with the default configuration noted in the SX126x datasheet.

Finally, consider operating within ITU region 2, with a LoRaWAN uplink channel operating at 902.3 MHz and an output power of nominally +22 dBm.

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										η_{PA} (%)	η_{SX} (%)
				PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
2	7	98.5	3.15	20.3	-39	≤ -70	≤ -70	≤ -70	-64	-53	-65	-66	-57	34.53	32.96
3	7	111.2	3.16	21.0	-42	≤ -70	≤ -70	≤ -70	-62	-53	-63	-67	-56	35.83	34.31
4	6	116.7	3.16	21.1	-41	-69	≤ -70	≤ -70	-61	-53	-64	-68	-56	34.93	33.45
4	7	124.9	3.17	21.6	-39	-69	≤ -70	≤ -70	-61	-52	-64	-66	-56	36.51	35.07

Table 5: SX1262 Tx Characteristics as a Function of PaConfig (902.3 MHz; +22 dBm - Switchless)

Again, configuration PaConfig(4; 7) indicates the condition for both maximum output power and efficiency. In addition, good harmonic rejection of both H2 (non-restricted band emission) and H3 (restricted band spurious emission) is obtained.

Implementing the same PA configuration at both 914.9 MHz and 927.5 MHz yields similar results, enabling the same parameter configuration values for the 26 MHz of available spectrum, as shown in Table 8.

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										η_{PA} (%)	η_{SX} (%)
				PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
2	7	98.8	3.15	20.2	-39	≤ -70	≤ -70	≤ -70	-63	-55	-64	-67	-56	33.34	31.82
3	7	111.6	3.16	20.9	-39	≤ -70	≤ -70	≤ -70	-62	-55	-63	-67	-56	34.89	33.41
4	7	125.6	3.17	21.5	-36	≤ -70	≤ -70	≤ -70	-61	-53	-64	-66	-55	35.48	34.08

Table 6: SX1262 Tx Characteristics as a Function of PaConfig (914.9 MHz; +22 dBm - Switchless)

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										η_{PA} (%)	η_{SX} (%)
				PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
2	7	99.4	3.15	20.1	-38	≤ -70	≤ -70	≤ -70	-62	-57	-65	-68	-56	32.68	31.20
3	7	112.2	3.16	20.8	-37	≤ -70	≤ -70	≤ -70	-61	-56	-64	-69	-56	33.91	32.47
4	7	125.3	3.17	21.5	-35	≤ -70	≤ -70	≤ -70	-61	-55	-66	-69	-56	35.92	33.93

Table 7: SX1262 Tx Characteristics as a Function of PaConfig (927.5 MHz; +22 dBm - Switchless)

Table 10 shows an application where, for a particular mode of operation, the SX1262 TX is implemented as a pre-driver for an external PA or Front End Module (FEM) where an output power of nominally +13.5 to +14 dBm is required, so as to ensure the optimum operating conditions for this external device.

PaDC	hpMax	TXCfg (dBm)	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										η_{PA} (%)	η_{SX} (%)
					PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
0	3	22	45.5	3.12	13.7	-37	≤ -70	≤ -70	≤ -70	≤ -70	-60	≤ -70	≤ -70	-63	16.51	15.61
3	2	22	48.9	3.12	13.9	-44	≤ -70	≤ -70	≤ -70	≤ -70	-61	-69	≤ -70	-66	16.09	15.21
1	3	21	52.2	2.78	14.0	-40	≤ -70	≤ -70	≤ -70	-67	-60	≤ -70	≤ -70	-63	17.31	14.58
4	2	21	53.5	2.78	13.6	-47	≤ -70	≤ -70	≤ -70	≤ -70	-61	≤ -70	≤ -70	-64	15.40	12.98
2	3	20	58.6	2.49	13.9	-39	≤ -70	≤ -70	≤ -70	-69	-63	≤ -70	≤ -70	-62	16.82	12.69

Table 8: SX1262 Tx Characteristics as a Function of Tx and PaConfig (914.9 MHz; +14 dBm - Switchless)

With **TxPower** configured to maximize VR_PA, **PaConfig** configurations PaConfig(0; 3) and PaConfig(3; 2) meet the design brief and are consistent with the settings obtained for operation in the 863 – 870 MHz band. However, we see that by configuring the **TxPower** setting in tandem with **PaConfig**, a degree of fine-tuning can also be achieved, enabling further trade-off of the SX1262 operating characteristics.

To demonstrate the versatility of the reference design, the SX1262 is replaced with SX1261, while the BOM remains unmodified. **TxPower** is configured to +14 dBm for maximum efficiency and as previously noted, **hpMax** is set to 0. Again, operation in both the European and North American frequency bands is required.

Operation at 868.3 MHz is considered first, as tabulated below in Table 9.

PaDC	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)						η_{PA} (%)	η_{SX} (%)
			PTx	H2	H3	H4	H5	H6		
1	17.4	1.36	10.4	-42	-66	≤ -70	≤ -70	≤ -70	45.80	18.88
2	19.9	1.37	11.5	-43	≤ -70	≤ -70	≤ -70	≤ -70	51.93	21.56
3	22.7	1.37	12.6	-44	-62	≤ -70	≤ -70	≤ -70	57.84	24.01
4	25.8	1.38	13.4	-47	-61	≤ -70	≤ -70	≤ -70	61.45	25.70
5	29.1	1.38	14.2	-52	-59	≤ -70	≤ -70	≤ -70	65.20	27.26
6	32.9	1.38	14.8	-59	-58	≤ -70	≤ -70	≤ -70	66.21	27.69
7	36.6	1.39	15.2	-50	-58	≤ -70	≤ -70	≤ -70	65.09	27.42

Table 9: SX1261 Tx Characteristics as a Function of PaConfig (868.3 MHz; +14 dBm - Switchless)

Table 10 indicates the configuration parameters for operation at 902.3 MHz:

PaDC	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										η_{PA} (%)	η_{SX} (%)
			PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
1	16.8	1.36	9.8	-40	≤ -70	≤ -70	≤ -70	≤ -70	-62	≤ -70	≤ -70	-62	41.80	17.23
2	19.2	1.37	11.0	-41	≤ -70	≤ -70	≤ -70	≤ -70	-63	≤ -70	≤ -70	-64	47.86	19.87
3	21.9	1.37	12.1	-43	≤ -70	≤ -70	≤ -70	≤ -70	-60	≤ -70	≤ -70	≤ -70	54.05	22.44
4	24.8	1.38	13.0	-45	≤ -70	≤ -70	≤ -70	≤ -70	-59	≤ -70	≤ -70	-63	58.30	24.38
5	28.1	1.38	13.8	-51	-64	≤ -70	≤ -70	-64	-63	≤ -70	≤ -70	≤ -70	61.86	25.87
6	31.7	1.38	14.5	-57	-63	≤ -70	≤ -70	≤ -70	-64	-64	≤ -70	≤ -70	63.84	26.69
7	35.1	1.39	15.0	-48	-64	≤ -70	≤ -70	≤ -70	-61	≤ -70	≤ -70	≤ -70	64.37	27.11

Table 10: SX1261Tx Characteristics as a Function of PaConfig (902.3 MHz; +14 dBm - Switchless)

Similarly, it can be demonstrated that the same PA configuration at both 914.9 MHz and 927.5 MHz yields similar results, again enabling the same parameter configurations to be used, as tabulated below in Table 11 and Table 12:

PaDC	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										η_{PA} (%)	η_{SX} (%)
			PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
5	27.9	1.38	13.7	-51	≤ -70	≤ -70	≤ -70	-64	≤ -70	≤ -70	≤ -70	-63	60.61	25.34
6	31.6	1.38	14.3	-54	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	-62	61.72	25.81

Table 11: SX1261 Tx Characteristics as a Function of PaConfig (914.9 MHz; +14 dBm - Switchless)

PaDC	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										η_{PA} (%)	η_{SX} (%)
			PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
5	27.9	1.38	13.7	-51	≤ -70	≤ -70	≤ -70	-64	≤ -70	≤ -70	≤ -70	-63	60.61	25.34
6	31.6	1.38	14.3	-54	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	-62	61.72	25.81

Table 12: SX1261 Tx Characteristics as a Function of PaConfig (927.5 MHz; +14 dBm - Switchless)

6.2 T/R Switch Reference Design (pcb_e428v03a)

In the following example, we consider the existing North American SX1262MB1CAS mbed shield reference design pcb_e428v03a[3] illustrated in Figure 15, to demonstrate the versatility of the adaptive match PaConfig parameter configuration approach.

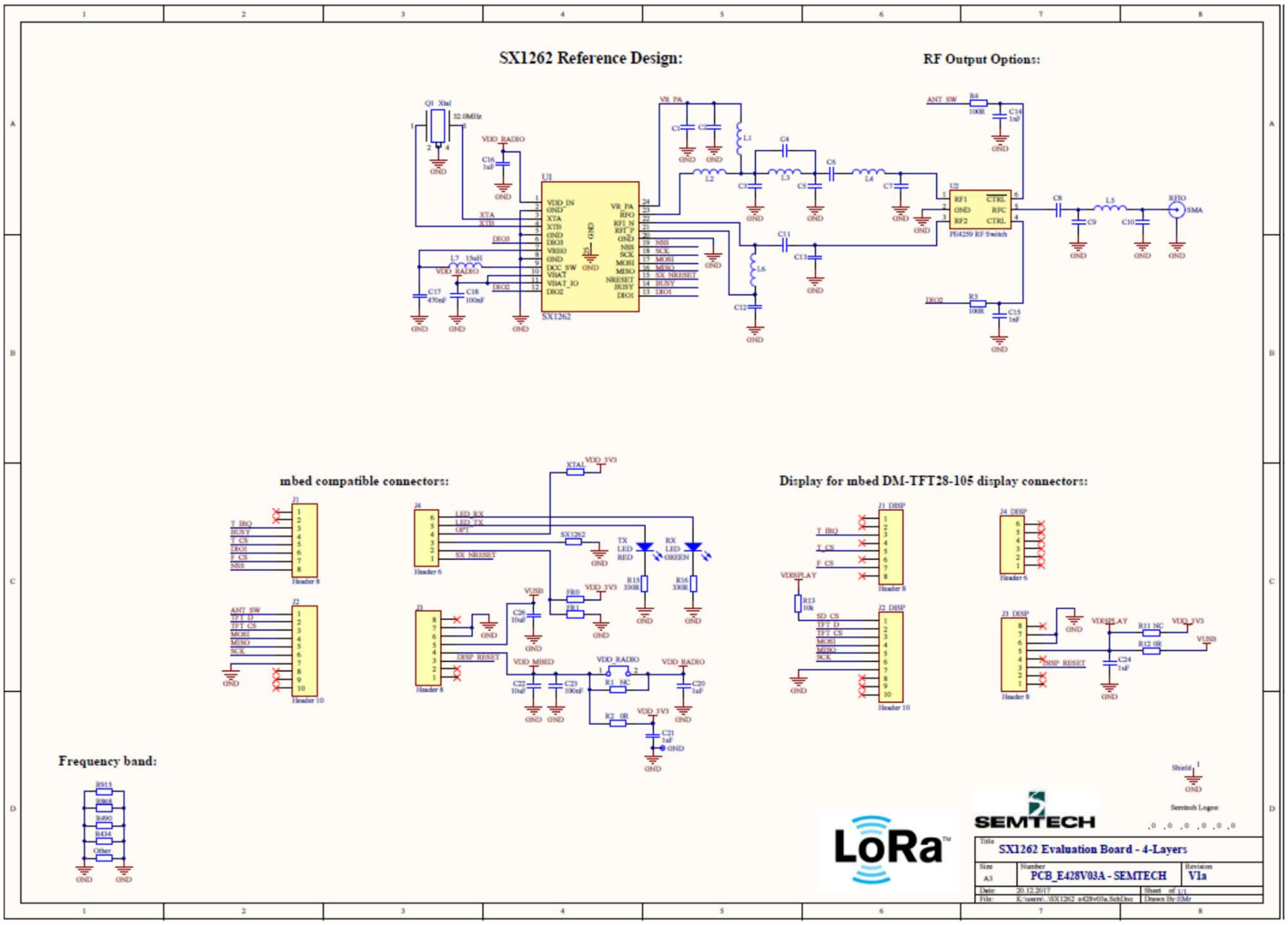


Figure 15: SX1262MB1CAS Reference Design pcb_e428v03a

As with the switchless design, configurations for three typical application scenarios will be demonstrated:

1. Operation as a default LoRaWAN channel operating at 868.3 MHz with an approximate ERP of 25 mW (+14 dBm)
2. Operation as a LoRaWAN channel operating in at 869.525 MHz with an approximate ERP of 158 mW (+22 dBm)
3. Operation as a LoRaWAN channel operating at 902.3 MHz with an approximate output power of +22 dBm

We consider the case for operation at 868.3 MHz with a nominal output power of +14 dBm (± 1 dB) as documented below in Table 13.

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)						η_{PA} (%)	η_{SX} (%)
				PTx	H2	H3	H4	H5	H6		
0	3	46.7	3.11	13.8	-39	-51	≤ -70	≤ -70	≤ -70	16.33	15.39
2	2	44.3	3.11	13.3	-41	-61	≤ -70	≤ -70	≤ -70	15.45	14.56
3	2	49.1	3.11	14.1	-41	-54	≤ -70	≤ -70	≤ -70	16.91	15.94

Table 13: SX1262 Tx Characteristics as a Function of PaConfig (868.3 MHz; +14 dBm - Switched)

From the results shown in Table 16, it can again be noted that PaConfig parameters (0; 3), (2; 2), (3; 2) result in the required indicated fundamental output power. Configuration PaConfig(2; 2) provides for the lowest current consumption and good harmonic balance, while configuration PaConfig(3; 2) indicates the conditions for maximum efficiency.

In the second application scenario, operation at 869.525 MHz with a nominal output power of +22 dBm is tabulated below in Table 14.

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)						η_{PA} (%)	η_{SX} (%)
				PTx	H2	H3	H4	H5	H6		
3	7	116.4	3.16	21.6	-36	-44	≤ -70	≤ -70	≤ -70	39.30	37.63
4	7	127.0	3.16	22.1	-38	-43	≤ -70	≤ -70	≤ -70	40.79	39.06

Table 14: SX1262 Tx Characteristics as a Function of PaConfig (869.525 MHz; +22 dBm - Switched)

Again, configuration PaConfig(4; 7) indicates the condition for both maximum output power and efficiency, consistent with the default configuration noted in the datasheet.

If operation at +14 dBm is required, the configurations highlighted previously in Table 13 apply:

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)						ηPA (%)	ηSX (%)
				PTx	H2	H3	H4	H5	H6		
0	3	46.6	3.11	13.9	-39	-51	≤ -70	≤ -70	≤ -70	16.74	15.78
2	2	44.3	3.10	13.3	-41	-60	≤ -70	≤ -70	≤ -70	15.57	14.62
3	2	49.1	3.11	14.1	-42	-54	≤ -70	≤ -70	≤ -70	16.99	16.01

Table 15: SX1262 Tx Characteristics as a Function of PaConfig (869.525 MHz; +14 dBm - Switched)

Finally, we consider operation within ITU region 2, and consider a LoRaWAN uplink channel operating at 914.9 MHz with an output power of nominally +22 dBm.

PaDC	hpMax	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										ηPA (%)	ηSX (%)
				PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
3	7	110.1	3.16	21.4	-49	-54	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	39.68	37.99
4	7	118.2	3.15	21.8	-49	-52	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	40.65	38.80

Table 16: SX1262 Tx Characteristics as a Function of PaConfig (902.3 MHz; +22 dBm - Switched)

As gain, configuration PaConfig(4; 7) indicates the condition for both maximum output power and efficiency, and can be applied to any LoRaWAN channel configured for operation in the 902 – 928 MHz band.

Similarly, the SX1262 can again be replaced by SX1261, while the published BOM remains unmodified:

Freq. (MHz)	PaDC	IDDTx (mA)	VR_PA (V)	TX Output Power (dBm)										ηPA (%)	ηSX (%)
				PTx	H2	H3	H4	H5	H6	H7	H8	H9	H10		
868.3	4	25.1	1.38	12.9	-46	-62	≤ -70	≤ -70	≤ -70					56.29	23.54
902.3	6	31.4	1.38	13.8	-55	-65	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	55.36	23.15
914.9	6	30.8	1.38	13.7	-53	-67	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	55.15	23.06
927.5	6	30.7	1.38	13.5	-52	-67	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	≤ -70	52.84	22.10

Table 17: SX1261 Tx Characteristics as a Function of PaConfig and Frequency (+14 dBm - Switched)

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The BOM for the TX and RX matching networks is shown below:

RefDes	Value	Description	Manufacturer
C1	47nF	Multilayer Ceramic Capacitor X7R ±1%, 16V	Murata
C2	47pF	Multilayer ceramic capacitors C0G ±5%, 50V	Murata
C4	3.0pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C5	5.6pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C6	39pF	Multilayer ceramic capacitors C0G ±5%, 50V	Murata
C7	1.8pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C8	39pF	Multilayer ceramic capacitors C0G ±5%, 50V	Murata
C9	3.3pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C10	3.3pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C11	2.4pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
C12	1.8pF	Multilayer ceramic capacitors C0G ±0.1pF, 50V	Murata
L1	4.7nH	Wirewound inductor ±2%	Murata
L2	0R	Resistor	Any
L3	2.5nH	Wirewound inductor ±0.2nH%	Murata
L4	4.7nH	Wirewound inductor ±2%	Murata
L5	9.1nH	Wirewound inductor ±2%	Murata
L6	15nH	Wirewound inductor ±2%	Murata

Table 18: Switched Reference Design pcb_e428v03a BOM

6.3 Design Considerations

As documented in this Application Note the transmitter matching network is a cascaded low-pass filter topology with the addition of a harmonic trap formed by C6, L2 (Switchless design) or C4, L3 (Switched design). The harmonic trap is required to attenuate the H2 component while operating in Europe and H3 in North America. As such "fine-tuning" of the network may be required in terms of both hardware BOM and FW configurations depending upon the PCB layout, stack definition, layer separation and both component series and tolerance.

7. Receiver Adaptive Match Design Methodology

As described in Section 5, a PER measurement is performed at the frequencies of interest for each possible configuration of **lna_cap_tune_n** and **lna_cap_tune_p** in turn.

The receiver under test is placed in a shielded RF enclosure and the PER, as a function of lna_cap_tune, is measured with a suitably modulated signal conducted at the antenna port.

A 10% PER metric is used as an indication of the receiver sensitivity, since this provides for a more repeatable threshold level than 1% PER. The minimum number of packets transmitted for each measurement is 1000 to ensure that a minimum of 100 packets received in error (10% of the total transmitted) can be used as an indication of the sensitivity level.

Note that this process will reveal a range of values of **lna_cap_tune_n** and **lna_cap_tune_p** over which an optimized sensitivity level is indicated, subject to the granularity provided by the PER measurement. It is recommended that the identified range be verified on a number of devices to ensure the component tolerances of the external matching network are taken into consideration.

In the examples below, we consider an application intended to operate over both European and North American ISM bands over a frequency range from 863 - 928 MHz with a single hardware BOM. For each possible configuration of lna_cap_tune the resultant PER was validated with a 64 byte packet at CR = 4/5 with payload CRC enabled at BW = 125 kHz, SF =7.

7.1 T/R Switch Reference Design (pcb_e428v03a)

As illustrated in Figure 15, the transmitter and receiver networks of the SX1262MB1CAS mbed shield reference design are isolated by the T/R switch and thus either the receiver hardware matching network or the port configuration can be optimized independently of the transmitter circuit, as summarized below in Table 19.

lna_cap_tune		10% PER Sensitivity Threshold (dBm) at Test Frequency (MHz)				
n	p	863.3	869.525	902.3	914.9	927.5
0x4	0x4	-126	-126	-126	-126	-126
0x0	0x0	-126	-126	-126	-126	-126
0x0	0x8	-126	-126	-126	-126	-126
0x0	0xF	-126	-126	-126	-126	-126
0x4	0x0	-126	-126	-126	-126	-126
0x4	0x8	-126	-126	-126	-126	-126
0x4	0xF	-126	-126	-126	-126	-126
0x8	0x0	-126	-126	-126	-125	-126
0x8	0x8	-126	-126	-125	-125	-125
0x8	0xF	-126	-126	-125	-125	-125
0xB	0x0	-126	-126	-125	-125	-125
0xB	0x8	-126	-126	-125	-125	-125
0xB	0xF	-126	-126	-125	-125	-125
0xF	0x0	-126	-126	-125	-125	-125
0xF	0x8	-126	-126	-125	-125	-125
0xF	0xF	-126	-126	-125	-125	-125

Table 19: 10% PER Threshold as a Function of lna_cap_tune (T/R Switch Design)

From the results obtained it can be observed that for value pairs of **lna_cap_tune_n** from 0x0 to 0x04 and **lna_cap_tune_p** from 0x0 to 0xF, a 10% sensitivity threshold of at least -126 dBm is obtained over the entire frequency band of interest. It should be noted that the indicated sensitivity in the European ISM band is insensitive to the values of lna_cap_tune configured.

Above these configured values (i.e. port loading capacitance increases), there is a small degradation in indicated PER, although it should be noted that by comparing the indicated PER value for at the sensitivity threshold, the degradation is less than < 1 dB when the indicated PER value at the sensitivity threshold is taken into consideration.

7.2 Switchless Reference Design (pcb_e460v02a)

As illustrated in Figure 13, the transmitter and receiver networks of the switchless reference design are part of the same matching network. With the transmit circuit previously optimized, optimization of receiver performance can be purely implemented through firmware configuration as summarized below in Table 20.

lna_cap_tune		**10% PER Sensitivity Threshold (dBm) at Test Frequency (MHz)**				
n	**p**	**863.3**	**869.525**	**902.3**	**914.9**	**927.5**
0x4	0x4	-125	-125	-125	-125	-126
0x0	0x0	-125	-125	-125	-125	-126
0x0	0x8	-125	-125	-125	-125	-126
0x0	0xF	-125	-125	-125	-125	-126
0x4	0x0	-125	-125	-125	-125	-126
0x4	0x8	-125	-125	-126	-126	-126
0x4	0xF	-125	-126	-126	-126	-126
0x8	0x0	-125	-125	-125	-125	-126
0x8	0x8	-125	-126	-126	-126	-126
0x8	0xB	-125	-126	-126	-126	-126
0x8	0xF	-126	-126	-126	-126	-126
0xB	0x0	-125	-126	-126	-126	-126
0xB	0x8	-125	-126	-126	-126	-126
0xB	0xB	-125	-126	-126	-126	-126
0xB	0xF	-125	-126	-126	-126	-126
0xF	0x0	-125	-125	-125	-125	-126
0xF	0x8	-126	-126	-126	-126	-126
0xF	0xF	-126	-126	-126	-126	-126

Table 20: 10% PER Threshold as a Function of lna_cap_tune (Switchless Design)

From the results obtained, it can be observed that for value pairs of **lna_cap_tune_n** 0xF and **lna_cap_tune_p** 0x8 - 0xF, a 10% PER sensitivity threshold of at least -126 dBm is obtained over the entire frequency band of interest.

Again it should be noted that by comparing the indicated PER value for at the sensitivity threshold over the range of possible lna_cap_tune combinations, the indicated sensitivity degradation is less than < 1 dB.

Due to the Q-factor associated with the matching network and the associated component tolerances it is recommend that if firmware configuration is implemented that values of lna_cap_tune are selected from a mid-position over a contiguous range of values that provide the required sensitivity level.

8. Conclusions

This Application Note demonstrates that both the transmitter PA and receiver input capacitance configuration of both SX1261 and SX1262 can be manipulated by firmware to provide additional tools to assist the RF design process.

The Application Note also describes a lower-cost reference design that does not require a T/R switch and which can be utilized for both SX1261 and SX1262 designs. It describes a methodology for designing a common hardware BOM covering the frequency range and differing transmit output power requirements of the 863 to 928 MHz using the adaptive matching techniques described.

Finally, this Application Note demonstrates that these techniques can be applied to existing circuit designs that incorporate a switch between antenna and the transmitter and receiver ports.

9. References

[1] SX1261/2 Datasheet
(https://semtech.my.salesforce.com/sfc/p/E0000000JelG/a/2R000000HT76/7Nka9W5WgugoZe.xwIHJy6ebj1hW8UJ.USO_Pt2CLLo)

[2] ERC Recommendation 70-03
(https://www.ecodocdb.dk/download/25c41779-cd6e/Rec7003e.pdf)

[3] SX1262MB2CAS mbed Shield
(https://semtech.my.salesforce.com/sfc/p/#E0000000JelG/a/2R000000HUOY/lGqG.OI20XwWPrKbxw0lH5gk_8AtnuoEAIpsqOm5AJU)

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