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RFM95/96/97/98(W) - Low Power Long Range Transceiver Module V1.0

GENERAL DESCRIPTION

The RFM95/96/97/98(W) transceivers feature the LoRa™ long range modem that provides ultra-long range spread spectrum communication and high interference immunity whilst minimising current consumption.

Using Hope RF's patented LoRa™ modulation technique RFM95/96/97/98(W) can achieve a sensitivity of over -148dBm using a low cost crystal and bill of materials. The high sensitivity combined with the integrated +20 dBm power amplifier yields industry leading link budget making it optimal for any application requiring range or robustness. LoRa™ also provides significant advantages in both blocking and selectivity over conventional modulation techniques, solving the traditional design compromise between range, interference immunity and energy consumption.

These devices also support high performance (G)FSK modes for systems including WMBus, IEEE802.15.4g. The RFM95/96/97/98(W) deliver exceptional phase noise, selectivity, receiver linearity and IIP3 for significantly lower current consumption than competing devices.

RFM95/96/97/98(W)

KEY PRODUCT FEATURES

- LoRa™ Modem.
- 168 dB maximum link budget.
- +20 dBm - 100 mW constant RF output vs. V supply.
- +14 dBm high efficiency PA.
- Programmable bit rate up to 300 kbps.
- High sensitivity: down to -148 dBm.
- Bullet-proof front end: IIP3 = -12.5 dBm.
- Excellent blocking immunity.
- Low RX current of 10.3 mA, 200 nA register retention.
- Fully integrated synthesizer with a resolution of 61 Hz.
- FSK, GFSK, MSK, GMSK, LoRa™ and OOK modulation.
- Built-in bit synchronizer for clock recovery.
- Preamble detection.
- 127 dB Dynamic Range RSSI.
- Automatic RF Sense and CAD with ultra-fast AFC.
- Packet engine up to 256 bytes with CRC.
- Built-in temperature sensor and low battery indicator.
- Modue Size：16*16mm

APPLICATIONS

- Automated Meter Reading.
- Home and Building Automation.
- Wireless Alarm and Security Systems.
- Industrial Monitoring and Control
- Long range Irrigation Systems

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1. General Description

The RFM95/96/97/98(W) incorporates the LoRa™ spread spectrum modem which is capable of achieving significantly longer range than existing systems based on FSK or OOK modulation. With this new modulation scheme sensitivities 8 dB better than FSK can be achieved with a low-cost, low-tolerance, crystal reference. This increase in link budget provides much longer range and robustness without the need for external amplification. LoRa™ also provides significant advances in selectivity and blocking performance, further improving communication reliability. For maximum flexibility the user may decide on the spread spectrum modulation bandwidth (BW), spreading factor (SF) and error correction rate (CR). Another benefit of the spread modulation is that each spreading factor is orthogonal - thus multiple transmitted signals can occupy the same channel without interfering. This also permits simple coexistence with existing FSK based systems. Standard GFSK, FSK, OOK, and GMSK modulation is also provided to allow compatibility with existing systems or standards such as wireless MBUS and IEEE 802.15.4g.

The RFM97 offers bandwidth options ranging from 7.8 kHz to 500 kHz with spreading factors ranging from 6 to 12, and covering all available frequency bands. The RFM97 offers the same bandwidth and frequency band options with spreading factors from 6 to 9. The RFM98 offers bandwidths and spreading factor options, but only covers the lower UHF bands.

1.1. Simplified Block Diagram

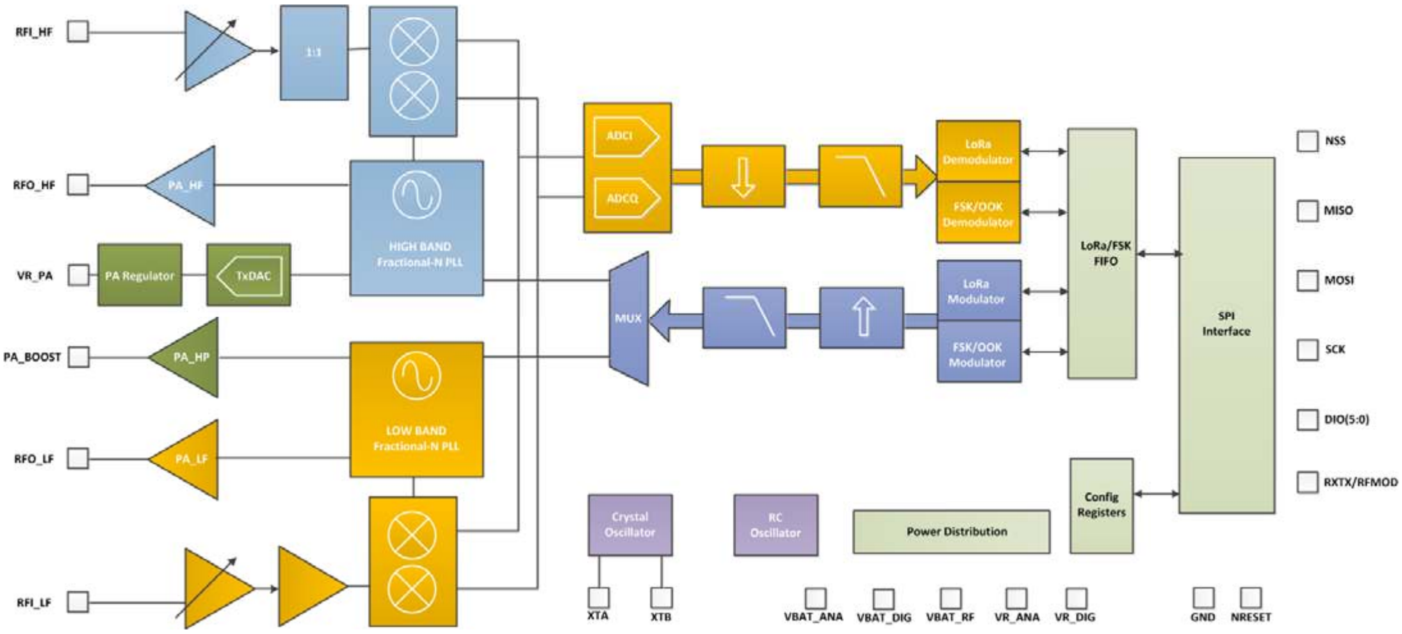

Figure 1. Block Diagram

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1.2. Product Versions

The features of the three product variants are detailed in the following table.

Table 48 RFM95/96/97/98(W) Device Variants and Key Parameters

Part Number	Frequency Range	Spreading Factor	Bandwidth	Effective Bitrate	Est. Sensitivity
RFM95W	868/915 MHz	6 - 12	7.8 - 500 kHz	.018 - 37.5 kbps	-111 to -148 dBm
RFM97W	868/915 MHz	6 - 9	7.8 - 500 kHz	0.11 - 37.5 kbps	-111 to -139 dBm
RFM96W/RFM98W	433/470MHz	6- 12	7.8 - 500 kHz	.018 - 37.5 kbps	-111 to -148 dBm

1.3. Pin Diagram

The following diagram shows the pin arrangement , top view.

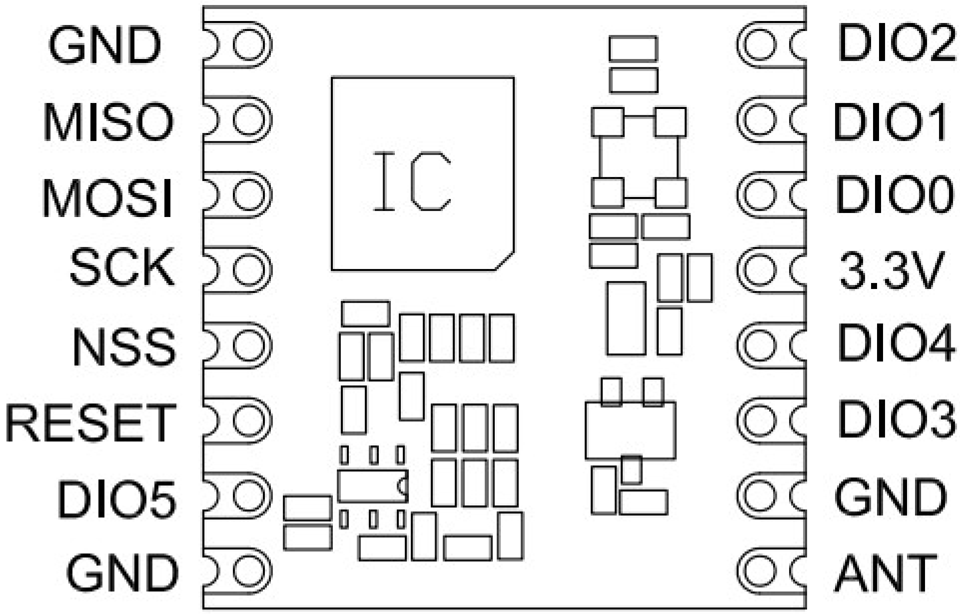

Figure 2. Pin Diagrams

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1.4. Pin Description

Number	Name	Type	Description Description Stand Alone Mode
1	GND	-	Ground
2	MISO	I	SPI Data output
3	MOSI	O	SPI Data input
4	SCK	I	SPI Clock input
5	NSS	I	SPI Chip select input
6	RESET	I/O	Reset trigger input
7	DIO5	I/O	Digital I/O, software configured
8	GND	-	Ground
9	ANT	-	RF signal output/input.
10	GND	-	Ground
11	DIO3	I/O	Digital I/O, software configured
12	DIO4	I/O	Digital I/O, software configured
13	3.3V	-	Supply voltage
14	DIO0	I/O	Digital I/O, software configured
15	DIO1	I/O	Digital I/O, software configured
16	DIO2	I/O	Digital I/O, software configured

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2. Electrical Characteristics

2.1. ESD Notice

The RFM95/96/97/98(W) is a high performance radio frequency device. It satisfies:

- Class 2 of the JEDEC standard JESD22-A114-B (Human Body Model) on all pins.
- Class III of the JEDEC standard JESD22-C101C (Charged Device Model) on all pins

It should thus be handled with all the necessary ESD precautions to avoid any permanent damage.

2.2. Absolute Maximum Ratings

Stresses above the values listed below may cause permanent device failure. Exposure to absolute maximum ratings for extended periods may affect device reliability.

Table 49 Absolute Maximum Ratings

Symbol	Description	Min	Max	Unit
VDDmr	Supply Voltage	-0.5	3.9	V
Tmr	Temperature	-55	+115	° C
Tj	Junction temperature	-	+125	° C
Pmr	RF Input Level	-	+10	dBm

Note Specific ratings apply to +20 dBm operation (see Section 5.4.3).

2.3. Operating Range

Table 50 Operating Range

Symbol	Description	Min	Max	Unit
VDDop	Supply voltage	1.8	3.7	V
Top	Operational temperature range	-20	+70	°C
Clop	Load capacitance on digital ports	-	25	pF
ML	RF Input Level	-	+10	dBm

Note A specific supply voltage range applies to +20 dBm operation (see Section 5.4.3).

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2.4. Chip Specification

The tables below give the electrical specifications of the transceiver under the following conditions: Supply voltage VDD=3.3 V, temperature = 25 °C, *FXOSC* = 32 MHz, F_{RF} = 169/434/868/915 MHz (see specific indication), Pout = +13dBm, 2-level FSK modulation without pre-filtering, FDA = 5 kHz, Bit Rate = 4.8 kb/s and terminated in a matched 50 Ohm impedance, shared Rx and Tx path matching., unless otherwise specified.

2.4.1. Power Consumption

Table 51 Power Consumption Specification

Symbol	Description	Conditions	Min	Typ	Max	Unit
IDDSL	Supply current in Sleep mode		-	0.2	1	uA
IDDIDLE	Supply current in Idle mode	RC oscillator enabled	-	1.5	-	uA
IDDST	Supply current in Standby mode	Crystal oscillator enabled	-	1.6	1.8	mA
IDDFS	Supply current in Synthesizer mode	FSRx	-	5.8	-	mA
IDDR	Supply current in Receive mode	*LnaBoost* Off, higher bands *LnaBoost* On, higher bands Lower bands	- - -	10.8 11.5 12.1	- - -	mA
IDDT	Supply current in Transmit mode with impedance matching	RFOP = +20 dBm, on PA_BOOST RFOP = +17 dBm, on PA_BOOST RFOP = +13 dBm, on RFO_LF/HF pin RFOP = + 7 dBm, on RFO_LF/HF pin	- - - -	120 87 29 20	- - - -	mA mA mA mA

2.4.2. Frequency Synthesis

Table 52 Frequency Synthesizer Specification

Symbol	Description	Conditions	Min	Typ	Max	Unit
FR	Synthesizer frequency range	Programmable	137 410 862	- - -	175 525 1020	MHz
FXOSC	Crystal oscillator frequency		-	32	-	MHz
TS_OSC	Crystal oscillator wake-up time		-	250	-	us
TS_FS	Frequency synthesizer wake-up time to PllLock signal	From Standby mode	-	60	-	us
TS_HOP	Frequency synthesizer hop time at most 10 kHz away from the target frequency	200 kHz step 1 MHz step 5 MHz step 7 MHz step 12 MHz step 20 MHz step 25 MHz step	- - - - - - -	20 20 50 50 50 50 50	- - - - - - -	us us us us us us us
FSTEP	Frequency synthesizer step	FSTEP = FXOSC/2^{19}	-	61.0	-	Hz

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FRC	RC Oscillator frequency	After calibration	-	62.5	-	kHz
BRF	Bit rate, FSK	Programmable values (1)	1.2	-	300	kbps
BRO	Bit rate, OOK	Programmable	1.2	-	32.768	kbps
BRA	Bit Rate Accuracy	ABS(wanted BR - available BR)	-	-	250	ppm
FDA	Frequency deviation, FSK (1)	Programmable FDA + BRF/2 =< 250 kHz	0.6	-	200	kHz

Note For Maximum Bit rate the maximum modulation index is 0.5.

2.4.3. FSK/OOK Mode Receiver

All receiver tests are performed with RxBw = 10 kHz (Single Side Bandwidth) as programmed in *RegRxBw*, receiving a PN15 sequence. Sensitivities are reported for a 0.1% BER (with Bit Synchronizer enabled), unless otherwise specified. Blocking tests are performed with an unmodulated interferer. The wanted signal power for the Blocking Immunity, ACR, IIP2, IIP3 and AMR tests is set 3 dB above the receiver sensitivity level.

Table 53 FSK/OOK Receiver Specification

Symbol	Description	Conditions	Min	Typ	Max	Unit
RFS_F_LF	Direct tie of RFI and RFO pins, shared Rx, Tx paths FSK sensitivity, highest LNA gain. Lower frequency bands	FDA = 5 kHz, BR = 1.2 kb/s FDA = 5 kHz, BR = 4.8 kb/s FDA = 40 kHz, BR = 38.4 kb/s* FDA = 20 kHz, BR = 38.4 kb/s** FDA = 62.5 kHz, BR = 250 kb/s***	- - - - -	-121 -117 -107 -108 -95	- - - - -	dBm dBm dBm dBm dBm
	Split RF paths, the RF switch insertion loss is not accounted for. Lower frequency bands	FDA = 5 kHz, BR = 1.2 kb/s FDA = 5 kHz, BR = 4.8 kb/s FDA = 40 kHz, BR = 38.4 kb/s* FDA = 20 kHz, BR = 38.4 kb/s** FDA = 62.5 kHz, BR = 250 kb/s***	- - - - -	-123 -119 -109 -110 -97	- - - - -	dBm dBm dBm dBm dBm
RFS_F_HF	Direct tie of RFI and RFO pins, shared Rx, Tx paths FSK sensitivity, highest LNA gain. Higher frequency bands	FDA = 5 kHz, BR = 1.2 kb/s FDA = 5 kHz, BR = 4.8 kb/s FDA = 40 kHz, BR = 38.4 kb/s* FDA = 20 kHz, BR = 38.4 kb/s** FDA = 62.5 kHz, BR = 250 kb/s***	- - - - -	-119 -115 -105 -105 -92	- - - - -	dBm dBm dBm dBm dBm
	Split RF paths, LnaBoost is turned on, the RF switch insertion loss is not accounted for. Higher frequency bands	FDA = 5 kHz, BR = 1.2 kb/s FDA = 5 kHz, BR = 4.8 kb/s FDA = 40 kHz, BR = 38.4 kb/s* FDA = 20 kHz, BR = 38.4 kb/s** FDA = 62.5 kHz, BR = 250 kb/s***	- - - - -	-123 -119 -109 -109 -96	- - - - -	dBm dBm dBm dBm dBm
RFS_O	OOK sensitivity, highest LNA gain shared Rx, Tx paths	BR = 4.8 kb/s BR = 32 kb/s	- -	-117 -108	- -	dBm dBm
CCR	Co-Channel Rejection		-	-9	-	dB

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ACR	Adjacent Channel Rejection	FDA = 5 kHz, BR=4.8kb/s Offset = +/- 25 kHz or +/- 50kHz 169MHz Band 434 MHz Band 8-900 MHz Band	- - -	59 56 50	- - -	dB dB dB
BI_HF	Blocking Immunity, higher bands	Offset = +/- 1 MHz Offset = +/- 2 MHz Offset = +/- 10 MHz	- - -	71 76 84	- - -	dB dB dB
BI_LF	Blocking Immunity, lower bands	Offset = +/- 1 MHz Offset = +/- 2 MHz Offset = +/- 10 MHz	- - -	71 72 78	- - -	dB dB dB
IIP2	2nd order Input Intercept Point Unwanted tones are 20 MHz above the LO	Highest LNA gain	-	+55	-	dBm
IIP3_HF	3rd order Input Intercept point Unwanted tones are 1MHz and 1.995 MHz above the LO	Higher bands Highest LNA gain G1 LNA gain G2, 4dB sensitivity hit	- -	-12.5 -8.5	- -	dBm dBm
IIP3_LF	3rd order Input Intercept point Unwanted tones are 1MHz and 1.995 MHz above the LO	Lower bands Highest LNA gain G1 LNA gain G2, 2.5dB sensitivity hit	- -	-22 -16	- -	dBm dBm
BW_SSB	Single Side channel filter BW	Programmable	2.7	-	250	kHz
IMR	Image Rejection	Wanted signal 3dB over sensitivity BER=0.1%	-	48	-	dB
IMA	Image Attenuation		-	57	-	dB
DR_RSSI	RSSI Dynamic Range	AGC enabled Min Max	- -	-127 0	- -	dBm dBm

* *RxBw = 83 kHz (Single Side Bandwidth)*

** *RxBw = 50 kHz (Single Side Bandwidth)*

*** *RxBw = 250 kHz (Single Side Bandwidth)*

2.4.4. FSK/OOK Mode Transmitter

Table 54 Transmitter Specification

Symbol	Description	Conditions	Min	Typ	Max	Unit
RF_OP	RF output power in 50 ohms on RFO pin (High efficiency PA).	Programmable with steps Max Min	+11 -	+14 -1	- -	dBm dBm
ΔRF_OP_V	RF output power stability on RFO pin versus voltage supply.	VDD = 2.5 V to 3.3 V VDD = 1.8 V to 3.7 V	- -	3 8	- -	dB dB
RF_OPH	RF output power in 50 ohms, on PA_BOOST pin (Regulated PA).	Programmable with 1dB steps Max Min	- -	+17 +2	- -	dBm dBm

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RF_OPH_MAX	Max RF output power, on PA_BOOST pin	High power mode	-	+20	-	dBm
ΔRF_OPH_V	RF output power stability on PA_-BOOST pin versus voltage supply.	VDD = 2.4 V to 3.7 V	-	+/-1	-	dB
ΔRF_T	RF output power stability versus temperature on PA_BOOST pin.	From T = -40 °C to +85 °C	-	+/-1	-	dB
PHN	Transmitter Phase Noise	169 MHz band 10kHz Offset 50kHz Offset 400kHz Offset 1MHz Offset	- - - -	-118 -118 -128 -132	- - - -	dBc/Hz
		433 MHz band 10kHz Offset 50kHz Offset 400kHz Offset 1MHz Offset	- - - -	-109 -109 -121 -128	- - - -	dBc/Hz
		868/915 MHz band 10kHz Offset 50kHz Offset 400kHz Offset 1MHz Offset	- - - -	-103 -103 -115 -122	- - - -	dBc/Hz
ACP	Transmitter adjacent channel power (measured at 25 kHz offset)	BT=1. Measurement conditions as defined by EN 300 220-1 V2.3.1	-	-	-37	dBm
TS_TR	Transmitter wake up time, to the first rising edge of DCLK	Frequency Synthesizer enabled, *PaR-amp* = 10us, BR = 4.8 kb/s	-	120	-	us

2.4.5. Electrical specification for Lora™ modulation

The table below gives the electrical specifications for the transceiver operating with Lora™ modulation. Following conditions apply unless otherwise specified:

- Supply voltage = 3.3 V.
- Temperature = 25° C.
- f_{XOSC} = 32 MHz.
- Lower bands: 169 MHz and 433 MHz, higher bands: 868 and 915 MHz
- bandwidth (BW) = 125 kHz.
- Spreading Factor (SF) = 12.
- Error Correction Code (EC) = 4/6.
- Packet Error Rate (PER)= 1%
- CRC on payload enabled.
- Output power = 13 dBm in transmission.
- Payload length = 64 bytes.
- Preamble Length = 12 symbols (programmed register *PreambleLength=8*)
- With matched impedances

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Table 55 LoRa Receiver Specification.

Symbol	Description	Conditions	Min.	Typ	Max	Unit
IDDR_L	Supply current in receiver Lora^{TM} mode, LnaBoost off	Lower Bands, Lower BW Lower Bands, BW = 125 kHz Lower Bands, BW = 250 kHz Lower Bands, BW = 500 kHz	- - - -	TBC 11.5 12.4 13.8	- - - -	mA mA mA mA
		Higher Bands, Lower BW Higher Bands, BW = 125 kHz Higher Bands, BW = 250 kHz Higher Bands, BW = 500 kHz	- - - -	TBC 10.3 11.1 12.6	- - - -	mA mA mA mA
IDDT_L	Supply current in transmitter mode	RFOP = 13 dBm RFOP = 7 dBm	- -	28 20	- -	mA mA
IDDT_H_L	Supply current in transmitter mode with an external impedance transformation	Using PA_BOOST pin RFOP = 17 dBm	-	90	-	mA
BI_L	Blocking immunity, FRF=868 MHz CW interferer	offset = +/- 1 MHz offset = +/- 2 MHz offset = +/- 10 MHz	-	TBC TBC TBC		dB dB dB
IIP3_L_HF	3rd order Input Intercept point Unwanted tones are 1MHz and 1.995 MHz above the LO	Higher bands Highest LNA gain G1 LNA gain G2, 4dB sensitivity hit	- -	-12.5 -8.5	- -	dBm dBm
IIP3_L_LF	3rd order Input Intercept point Unwanted tones are 1MHz and 1.995 MHz above the LO	Lower bands Highest LNA gain G1 LNA gain G2, 2.5dB sensitivity hit	- -	-22 -16	- -	dBm dBm
IIP2_L	2nd order input intercept point, highest LNA gain, FRF=868 MHz, CW interferer.	F1 = FRF + 20 MHz F2 = FRF+ 20 MHz + Δf	-	+55	-	dBm
BR_L	Bit rate, Long-Range Mode	From SF6, BW=500kHz to SF12, BW=7.8kHz	0.018	-	37.5	kbps
RFS_L10	RF sensitivity, Long-Range Mode, highest LNA gain, LNA boost for higher bands, using split Rx/Tx path 10.4 kHz bandwidth	SF = 6 SF = 7 SF = 8 SF = 9 SF = 10 SF = 11 SF = 12	- - - - - - -	TBC -134 TBC TBC TBC TBC TBC	- - - - - - -	dBm dBm dBm dBm dBm dBm dBm
RFS_L62	RF sensitivity, Long-Range Mode, highest LNA gain, LNA boost for higher bands, using split Rx/Tx path 62.5 kHz bandwidth	SF = 6 SF = 7 SF = 8 SF = 9 SF = 10 SF = 11 SF = 12	- - - - - - -	-121 -126 -129 -132 -135 -137 -139	- - - - - - -	dBm dBm dBm dBm dBm dBm dBm

Table 56. Electrical specifications: Lora^{TM} *mode*

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Symbol	Description	Conditions	Min.	Typ	Max	Unit
RFS_L125	RF sensitivity, Long-Range Mode, highest LNA gain, LNA boost for higher bands, using split Rx/Tx path 125 kHz bandwidth	SF = 6 SF = 7 SF = 8 SF = 9 SF = 10 SF = 11 SF = 12	- - - - - - -	-118 -123 -126 -129 -132 -133 -136	- - - - - - -	dBm dBm dBm dBm dBm dBm dBm
RFS_L250	RF sensitivity, Long-Range Mode, highest LNA gain, LNA boost for higher bands, using split Rx/Tx path 250 kHz bandwidth	SF = 6 SF = 7 SF = 8 SF = 9 SF = 10 SF = 11 SF = 12	- - - - - - -	-115 -120 -123 -125 -128 -130 -133	- - - - - - -	dBm dBm dBm dBm dBm dBm dBm
RFS_L500	RF sensitivity, Long-Range Mode, highest LNA gain, LNA boost for higher bands, using split Rx/Tx path 500 kHz bandwidth	SF = 6 SF = 7 SF = 8 SF = 9 SF = 10 SF = 11 SF = 12	- - - - - - -	-111 -116 -119 -122 -125 TBC TBC	- - - - - - -	dBm dBm dBm dBm dBm dBm dBm
CCR_LCW	Co-channel rejection Single CW tone = Sens +6 dB 1% PER	SF = 7 SF = 8 SF = 9 SF = 10 SF = 11 SF = 12	- - - - - -	5 9.5 12 14.4 17 19.5	- - - - - -	dB dB dB dB dB dB
CCR_LL	Co-channel rejection	Interferer is a LoRa^{TM} signal using same BW and same SF. Pw = Sensitivity + 3 dB		-6		dB
ACR_LCW	Adjacent channel rejection	Interferer is 1.5*BW_L from the wanted signal center frequency 1% PER, Single CW tone = Sens + 3 dB SF = 7 SF = 12	 - -	 60 72	 - -	 dB dB
IMR_LCW	Image rejection after calibration.	1% PER, Single CW tone = Sens +3 dB	-	66	-	dB
FERR_L	Maximum tolerated frequency offset between transmitter and receiver, no sensitivity degradation, SF6 thru 9	BW_L = 10.4 kHz BW_L = 62.5 kHz BW_L = 125 kHz BW_L = 250 kHz BW_L = 500 kHz	-2.5 -15 -30 -60 -120	- - - - -	2.5 15 30 60 120	kHz kHz kHz kHz kHz
	Maximum tolerated frequency offset between transmitter and receiver, no sensitivity degradation, SF10 thru 11	SF = 12 SF = 11 SF = 10	-50 -100 -200	- - -	50 100 200	ppm ppm ppm

Table 56. Electrical specifications: Lora^{TM} *mode*

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2.4.6. Digital Specification

Conditions: Temp = 25° C, VDD = 3.3 V, FXOSC = 32 MHz, unless otherwise specified.

Table 57 Digital Specification

Symbol	Description	Conditions	Min	Typ	Max	Unit
V_{IH}	Digital input level high		0.8	-	-	VDD
V_{IL}	Digital input level low		-	-	0.2	VDD
V_{OH}	Digital output level high	Imax = 1 mA	0.9	-	-	VDD
V_{OL}	Digital output level low	Imax = -1 mA	-	-	0.1	VDD
F_{SCK}	SCK frequency		-	-	10	MHz
t_{ch}	SCK high time		50	-	-	ns
t_{cl}	SCK low time		50	-	-	ns
t_{rise}	SCK rise time		-	5	-	ns
t_{fall}	SCK fall time		-	5	-	ns
t_{setup}	MOSI setup time	From MOSI change to SCK rising edge.	30	-	-	ns
t_{hold}	MOSI hold time	From SCK rising edge to MOSI change.	20	-	-	ns
t_{nsetup}	NSS setup time	From NSS falling edge to SCK rising edge.	30	-	-	ns
t_{nhold}	NSS hold time	From SCK falling edge to NSS rising edge, normal mode.	100	-	-	ns
t_{nhigh}	NSS high time between SPI accesses		20	-	-	ns
T_DATA	DATA hold and setup time		250	-	-	ns

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3. RFM95/96/97/98(W) Features

This section gives a high-level overview of the functionality of the RFM95/96/97/98(W) low-power, highly integrated transceiver. The following figure shows a simplified block diagram of the RFM95/96/97/98(W).

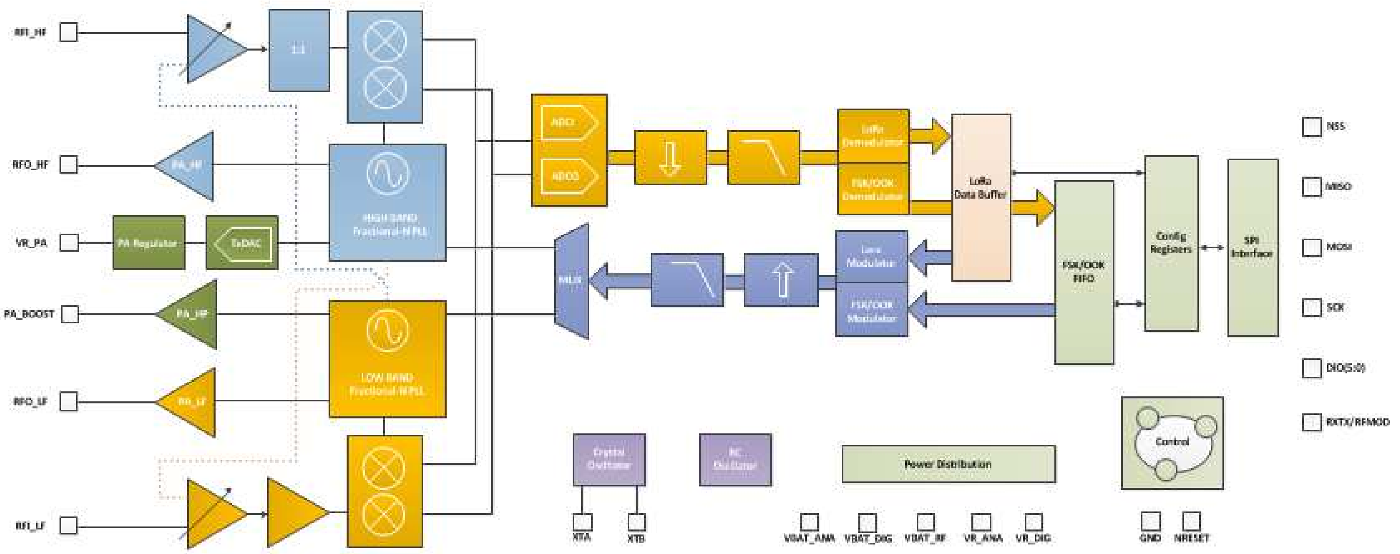

Figure 3. RFM95/96/97/98(W) Block Schematic Diagram

RFM95/96/97/98(W) is a half-duplex, low-IF transceiver. Here the received RF signal is first amplified by the LNA. The LNA inputs are single ended to minimise the external BoM and for ease of design. Following the LNA inputs, the conversion to differential is made to improve the second order linearity and harmonic rejection. The signal is then down-converted to in- phase and quadrature (I&Q) components at the intermediate frequency (IF) by the mixer stage. A pair of sigma delta ADCs then perform data conversion, with all subsequent signal processing and demodulation performed in the digital domain. The digital state machine also controls the automatic frequency correction (AFC), received signal strength indicator (RSSI) and automatic gain control (AGC). It also features the higher-level packet and protocol level functionality of the top level sequencer (TLS).

The frequency synthesisers generate the local oscillator (LO) frequency for both receiver and transmitter, one covering the lower UHF bands (up to 525 MHz), and the other one covering the upper UHF bands (from 860 MHz). The PLLs are optimized for user-transparent low lock time and fast auto-calibrating operation. In transmission, frequency modulation is performed digitally within the PLL bandwidth. The PLL also features optional pre-filtering of the bit stream to improve spectral purity.

RFM95/96/97/98(W) feature three distinct RF power amplifiers. Two of those, connected to RFO_LF and RFO_HF, can deliver up to +14 dBm, are unregulated for high power efficiency and can be connected directly to their respective RF receiver inputs via a pair of passive components to form a single antenna port high efficiency transceiver. The third PA, connected to the PA_BOOST pin and can deliver up to +20 dBm via a dedicated matching network. Unlike the high efficiency PAs, this high- stability PA covers all frequency bands that the frequency synthesizer addresses.

RFM95/96/97/98(W) also include two timing references, an RC oscillator and a 32 MHz crystal oscillator.

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All major parameters of the RF front end and digital state machine are fully configurable via an SPI interface which gives access to RFM95/96/97/98(W)'s configuration registers. This includes a mode auto sequencer that oversees the transition and calibration of the RFM95/96/97/98(W) between intermediate modes of operation in the fastest time possible.

The RFM95/96/97/98(W) are equipped with both standard FSK and long range spread spectrum (LoRa™) modems. Depending upon the mode selected either conventional OOK or FSK modulation may be employed or the LoRa™ spread spectrum modem.

3.1. LoRa™ Modem

The LoRa™ modem uses a proprietary spread spectrum modulation technique. This modulation, in contrast to legacy modulation techniques, permits an increase in link budget and increased immunity to in-band interference. At the same time the frequency tolerance requirement of the crystal reference oscillator is relaxed - allowing a performance increase for a reduction in system cost. For a fuller description of the design trade-offs and operation of the RFM95/96/97/98(W) please consult Section 4.1 of the datasheet.

3.2. FSK/OOK Modem

In FSK/OOK mode the RFM95/96/97/98(W) supports standard modulation techniques including OOK, FSK, GFSK, MSK and GMSK. The RFM95/96/97/98(W) is especially suited to narrow band communication thanks the low-IF architecture employed and the built-in AFC functionality. For full information on the FSK/OOK modem please consult Section 4.2 of this document.

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4. RFM95/96/97/98(W) Digital Electronics

4.1. The LoRa^{TM} Modem

The LoRa^{TM} modem uses spread spectrum modulation and forward error correction techniques to increase the range and robustness of radio communication links compared to traditional FSK or OOK based modulation. Examples of the performance improvement possible, for several possible settings, are summarised in the table below. Here the spreading factor and error correction rate are design variables that allow the designer to optimise the trade-off between occupied bandwidth, data rate, link budget improvement and immunity to interference.

Table 58 Example LoRa^{TM} Modem Performances

Bandwidth (kHz)	Spreading Factor	Coding rate	Nominal Rb (bps)	Sensitivity indication (dBm)	Frequency Reference
10.4	6	4/5	782	TBC	TCXO
	12	4/5	24	TBC	
20.8	6	4/5	1562	TBC	
	12	4/5	49	TBC	
62.5	6	4/5	4688	-121	XTAL
	12	4/5	146	-139	
125	6	4/5	9380	-118	
	12	4/5	293	-136	

For European operation the range of crystal tolerances acceptable for each sub-band (of the ERC 70-03) is given in the specifications table. For US based operation a frequency hopping mode is available that automates both the LoRa^{TM} spread spectrum and frequency hopping spread spectrum processes.

Another important facet of the LoRa^{TM} modem is its increased immunity to interference. The LoRa^{TM} modem is capable of co-channel GMSK rejection of up to 25 dB. This immunity to interference permits the simple coexistence of LoRa^{TM} modulated systems either in bands of heavy spectral usage or in hybrid communication networks that use LoRa^{TM} to extend range when legacy modulation schemes fail.

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4.1.1. Link Design Using the LoRa™ Modem

4.1.1.1. Overview

The LoRa™ modem is setup as shown in the following figure. This configuration permits the simple replacement of the FSK modem with the LoRa™ modem via the configuration register setting *RegOpMode.* This change can be performed on the fly (in Sleep operating mode) thus permitting the use of both standard FSK or OOK in conjunction with the long range capability. The LoRa™ modulation and demodulation process is proprietary, it uses a form of spread spectrum modulation combined with cyclic error correction coding. The combined influence of these two factors is an increase in link budget and enhanced immunity to interference.

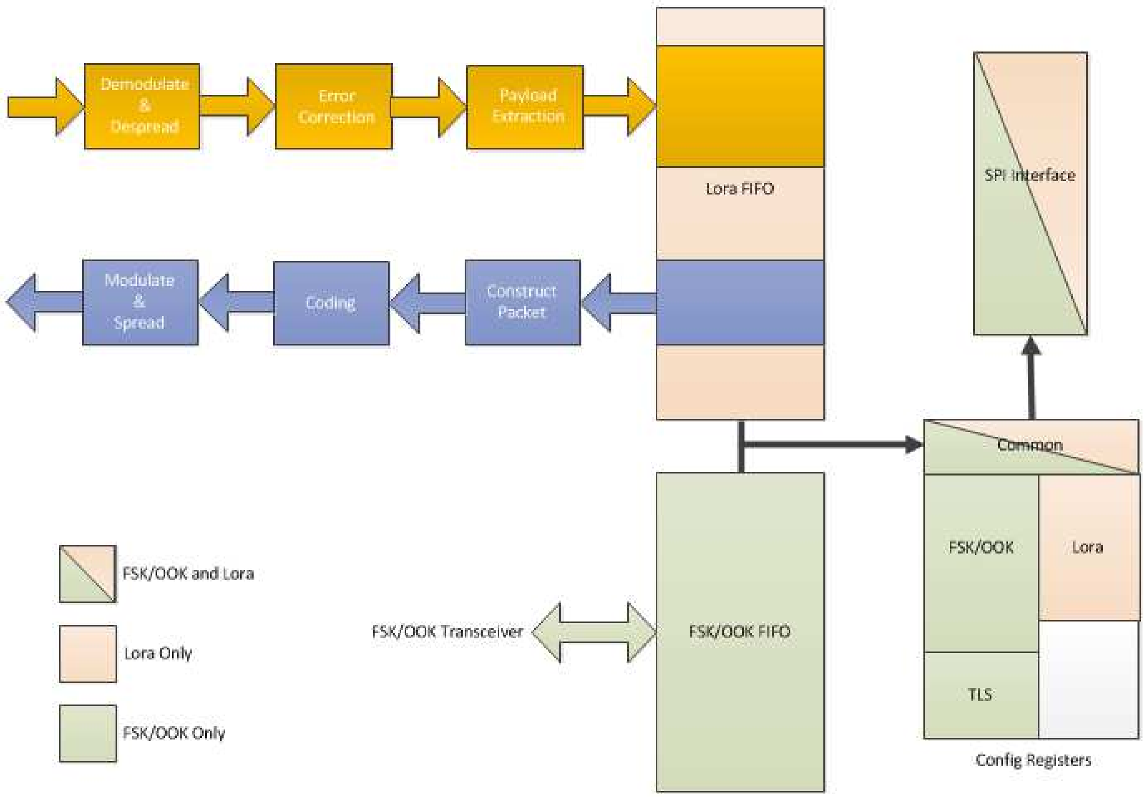

Figure 4. LoRa™ Modem Connectivity

A simplified outline of the transmit and receive processes is also shown above. Here we see that the LoRa™ modem has an independent dual port data buffer FIFO that is accessed through an SPI interface common to all modes. Upon selection of LoRa™ mode, the configuration register mapping of the RFM95/96/97/98(W) changes. For full details of this change please consult the register description of Section 6.

So that it is possible to optimise the LoRa™ modulation for a given application, access is given to the designer to three critical design parameters. Each one permitting a trade off between link budget, immunity to interference, spectral occupancy and nominal data rate. These parameters are spreading factor, modulation bandwidth and error coding rate.

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4.1.1.2. Spreading Factor

The spread spectrum LoRa™ modulation is performed by representing each bit of payload information by multiple chips of information. The rate at which the spread information is sent is referred to as the symbol rate (Rs), the ratio between the nominal symbol rate and chip rate is the spreading factor and represents the number of symbols sent per bit of information. The range of values accessible with the LoRa™ modem are shown in the following table.

Table 59 Range of Spreading Factors

SpreadingFactor **(RegModulationCfg)**	**Spreading Factor (Chips / symbol)**	**LoRa Demodulator SNR**
6	64	-5 dB
7	128	-7.5 dB
8	256	-10 dB
9	512	-12.5 dB
10	1024	-15 dB
11	2048	-17.5 dB
12	4096	-20 dB

Note that the spreading factor, *SpreadingFactor*, must be known in advance on both transmit and receive sides of the link as different spreading factors are orthogonal to each other. Note also the resulting signal to noise ratio (SNR) required at the receiver input. It is the capability to receive signals with negative SNR that increases the sensitivity, so link budget and range, of the LoRa receiver.

Spreading Factor 6

SF = 6 Is a special use case for the highest data rate transmission possible with the LoRa modem. To this end several settings must be activated in the RFM95/96/97/98(W) registers when it is in use:

- Set *SpreadingFactor* = 6 in *RegModemConfig2*
- The header must be set to Implicit mode
- Write bits 2-0 of register address 0x31 to value "0b101"
- Write register address 0x37 to value 0x0C

4.1.1.3. Coding Rate

To further improve the robustness of the link the LoRa™ modem employs cyclic error coding to perform forward error detection and correction. Such error coding incurs a transmission overhead - the resultant additional data overhead per transmission is shown in the table below.

Table 60 Cyclic Coding Overhead

CodingRate **(RegTxCfg1)**	**Cyclic Coding Rate**	**Overhead Ratio**
1	4/5	1.25
2	4/6	1.5
3	4/7	1.75
4	4/8	2

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Forward error correction is particularly efficient in improving the reliability of the link in the presence of interference. So that the coding rate (and so robustness to interference) can be changed in response to channel conditions - the coding rate can optionally be included in the packet header for use by the receiver. Please consult Section 4.1.1.6 for more information on the LoRa™ packet and header.

4.1.1.4. Signal Bandwidth

An increase in signal bandwidth permits the use of a higher effective data rate, thus reducing transmission time at the expense of reduced sensitivity improvement. There are of course regulatory constraints in most countries on the permissible occupied bandwidth. Contrary to the FSK modem which is described in terms of the single sideband bandwidth, the LoRa™ modem bandwidth refers to the double sideband bandwidth (or total channel bandwidth). The range of bandwidths relevant to most regulatory situations is given in the LoRa™ modem specifications table (see Section 2.4.5).

Bandwidth (kHz)	Spreading Factor	Coding rate	Nominal Rb (bps)
7.8	12	4/5	18
10.4	12	4/5	24
15.6	12	4/5	37
20.8	12	4/5	49
31.2	12	4/5	73
41.7	12	4/5	98
62.5	12	4/5	146
125	12	4/5	293
250	12	4/5	586
500	12	4/5	1172

Note In the lower band (169 MHz), the 250 kHz and 500 kHz bandwidths are not supported.

4.1.1.5. LoRa™ Transmission Parameter Relationship

With a knowledge of the key parameters that can be controlled by the user we define the LoRa™ symbol rate as:

$$Rs = \frac{W}{2^{SF}}$$

where BW is the programmed bandwidth and SF is the spreading factor. The transmitted signal is a constant envelope signal. Equivalently, one chip is sent per second per Hz of bandwidth.

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