

Application Note:

SX126x CAD Performance

Evaluation

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1. Introduction

The use of a spread spectrum modulation technique presents challenges in determining whether the channel is already in use by a signal that may be below the noise floor of the receiver. The use of the RSSI in this situation would clearly be impracticable. To this end the channel activity detector is used to detect the presence of other LoRa® signals.

On the SX1261/2, the channel activity detection mode is designed to detect the presence of a LoRa® preamble or data symbols while the previous generations of products were only able to detect LoRa® preamble symbols.

Once in CAD mode, the SX1261/2 will perform a scan of the channel for a user-selectable duration (defined in number of symbols) and will then return with the *channelActivityDetected* Flag if LoRa® symbols have been detected during the CAD.

The parameters *cadDetPeak* and *cadDetMin* define the sensitivity of the LoRa modem when trying to correlate to actual LoRa symbols. These two settings depend on the LoRa spreading factor and bandwidth, but also depend on the number of symbols (*cadSymbolNum*) used to validate or not the presence of signal.

The test flow used to determine the combination of parameters is the following. Every 2 seconds, the DUT opens a window for CAD detection. It runs 100 times and calculates the *channelActivityDetected* percentage and the *OnRxDone* percentage, the first one representing a successful CAD, the second one a proper packet reception ensuing a positive CAD.

2. Test Procedure

2.1 Test Bench Setup

All the tests were done in conducted mode, with the signal generator connected to the DUT by a coaxial cable. A host is used to generate LoRa waveforms with different spreading factors, and control the signal generator connected to the DUT with different parameters, such as power level. The DUT performs a CAD a 100 times, and if a LoRa carrier is detected, it switches on the receive mode. At the end of the 100 loops, it notifies the host by a COM port interface how many CADs have been detected and how many packets have been received.

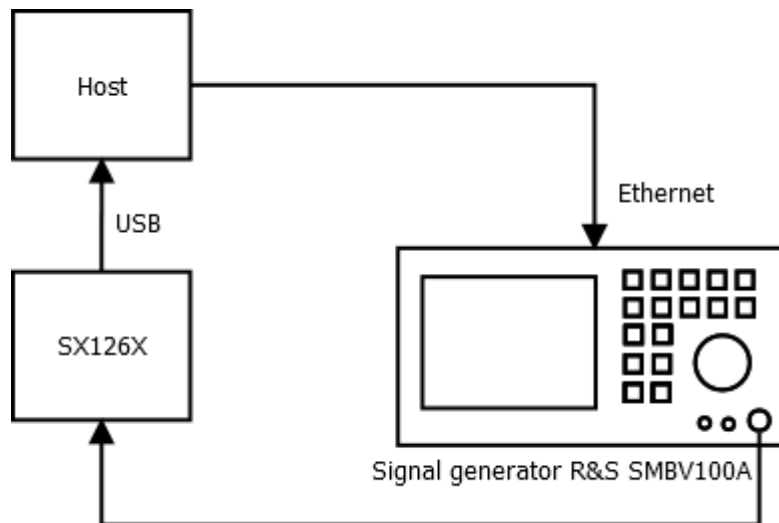


Figure 1: Test Bench Diagram

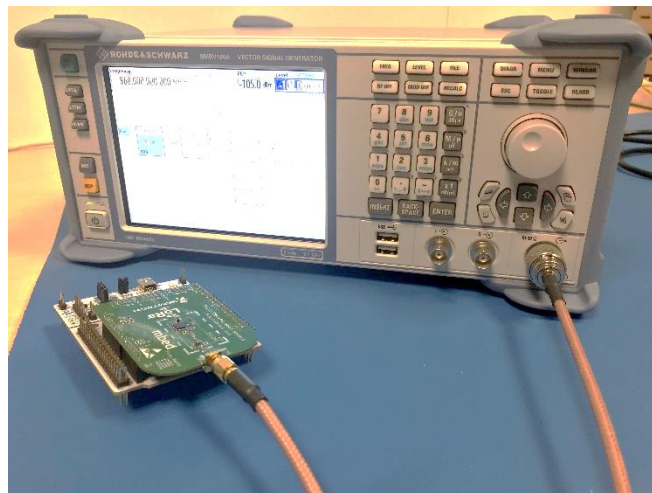


Figure 2: Test Bench Picture

2.2 Program Flow

The CAD/RX sequence on the DUT is run 100 times for each configuration. For each run, the parameters of the transmitted frame are modified. Note that the frames are sent in a row, with no down time between frames. Also, there is no synchronization between the DUT and the start of frame, meaning that the CAD evaluation may be done on Preamble or Data. Here is the program flow, DUT side.

In these tests, *cadDetMin* is fixed, all optimizations are done with *cadDetMin* = 10. There is no need to change this value.

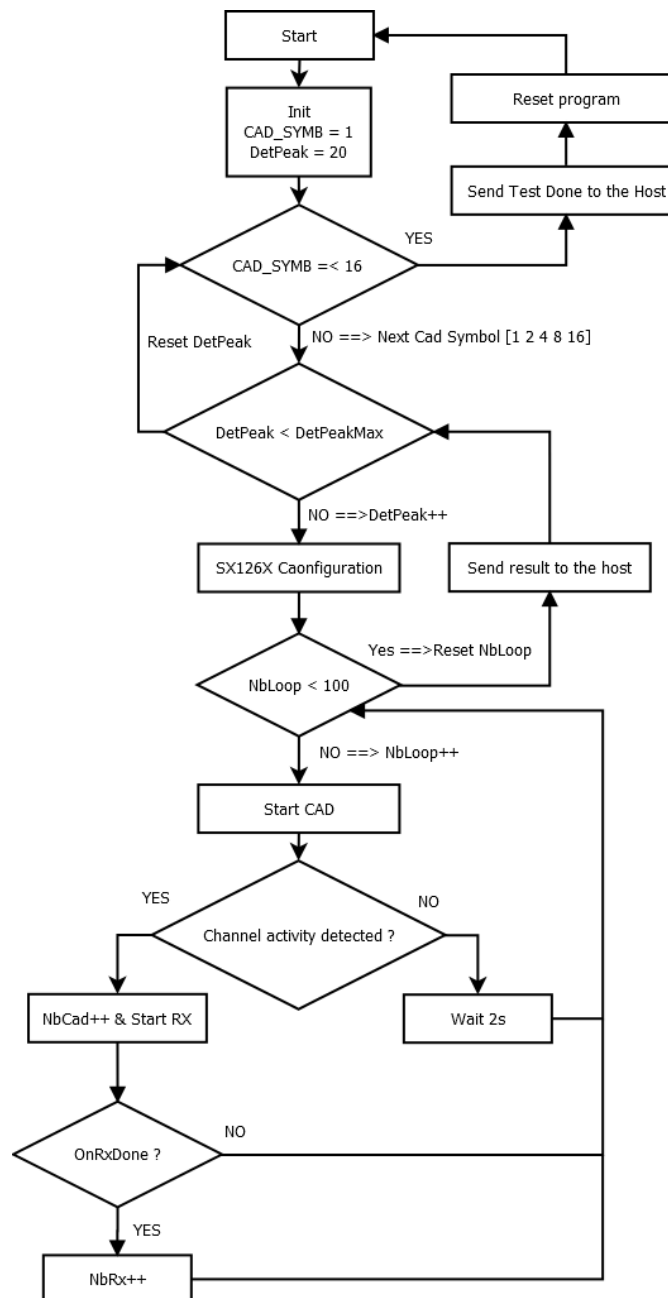


Figure 3: DUT Program Flow

And here is the test flow, on the host side:

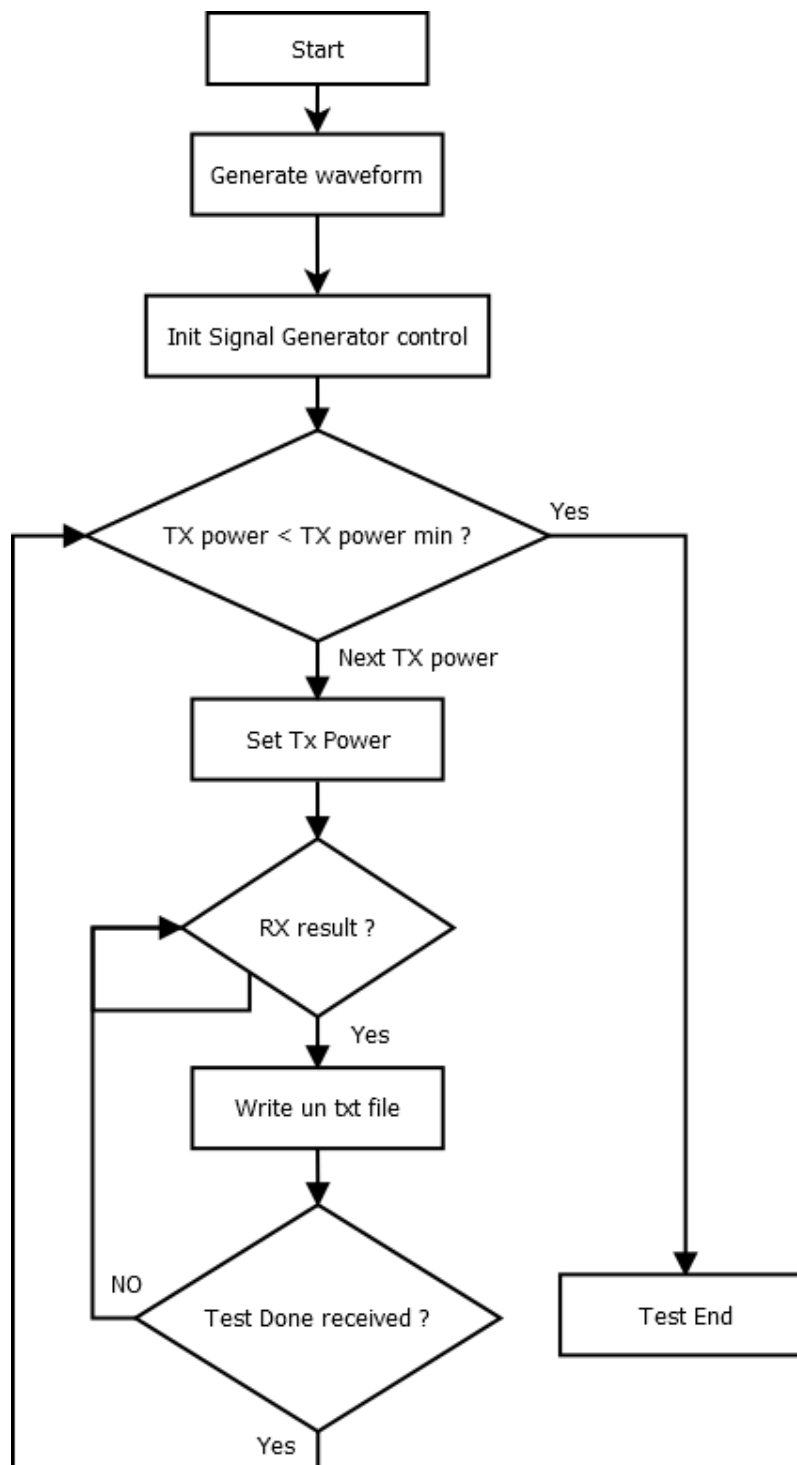


Figure 4: Host-side Program Flow

3. Firmware consideration on RxTimeout

3.1 Workaround

In order to ensure the CAD functioning, when a RX timeout occurs with a CAD scheduled just after, the radio shall be switch in sleep mode instead of standby between the both threads.

This workaround is described as following:

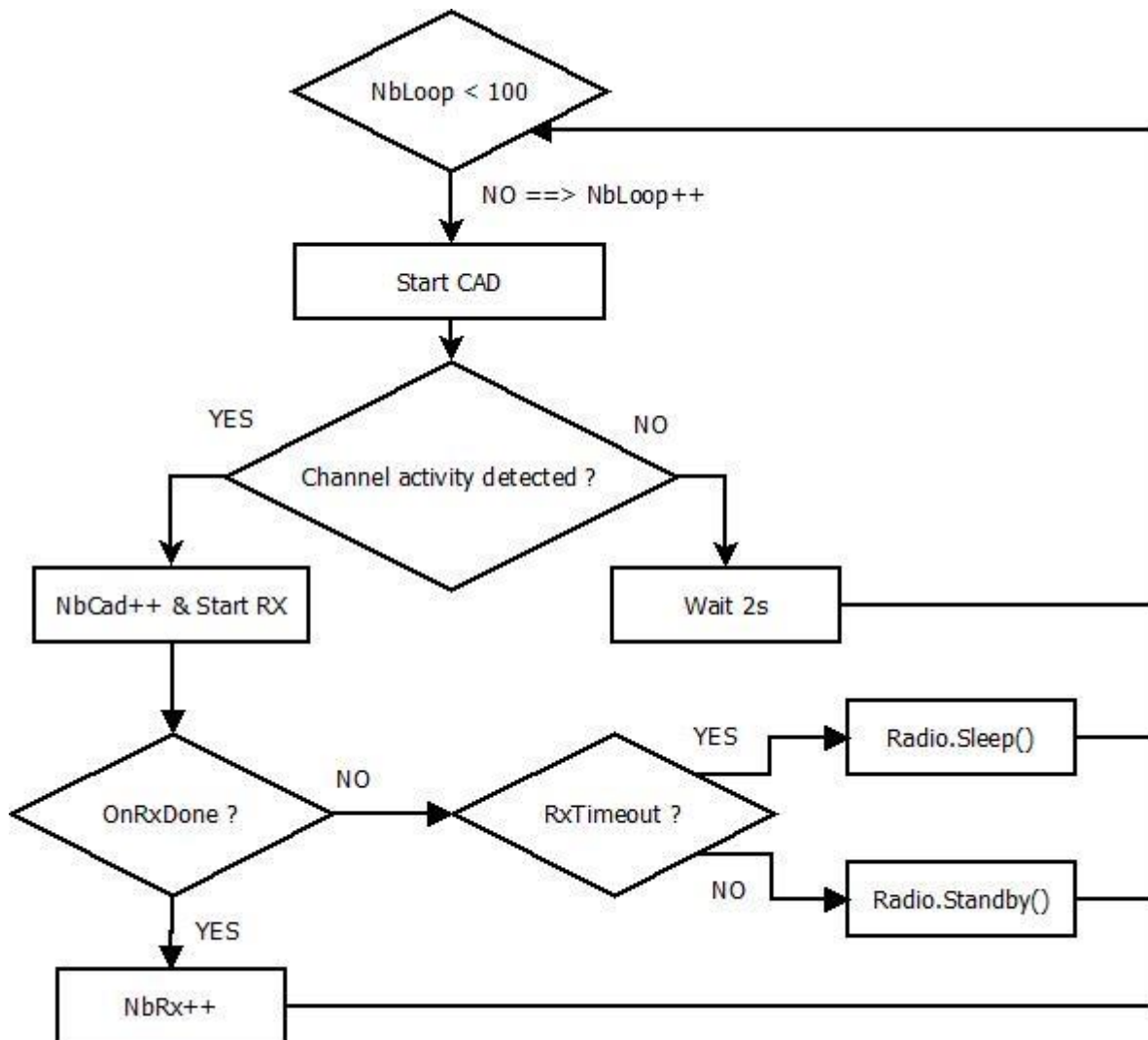


Figure 5 Firmware workaround

3.2 Energy impact

According to the SX126X datasheet the wake up timing are the following:

Transition	$T_{SW} Mode$ Typical Value [μs]
SLEEP to STBY_RC cold start (no data retention)	3500
SLEEP to STBY_RC warm start (with data retention)	340
STBY_RC to STBY_XOSC	31

Figure 6 SX126X Switching Time

Nominal case when a RX Timeout occurs:

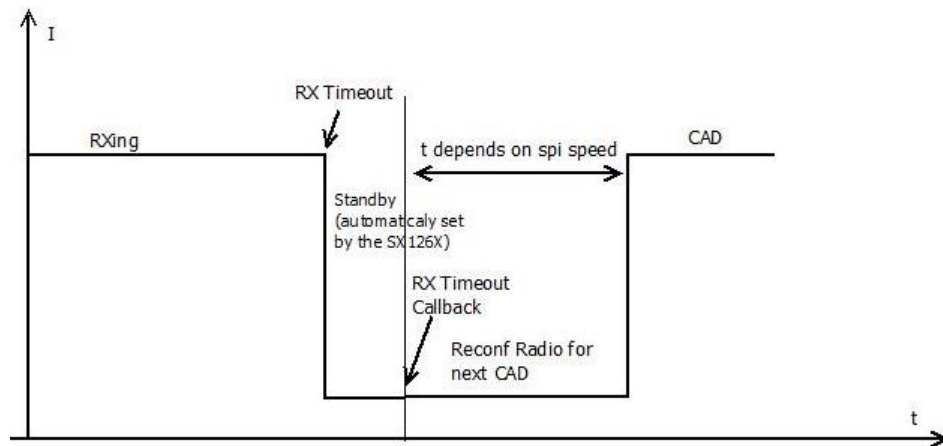


Figure 7 nominal case when RX timeout occurs

New case when a RX Timeout occurs:

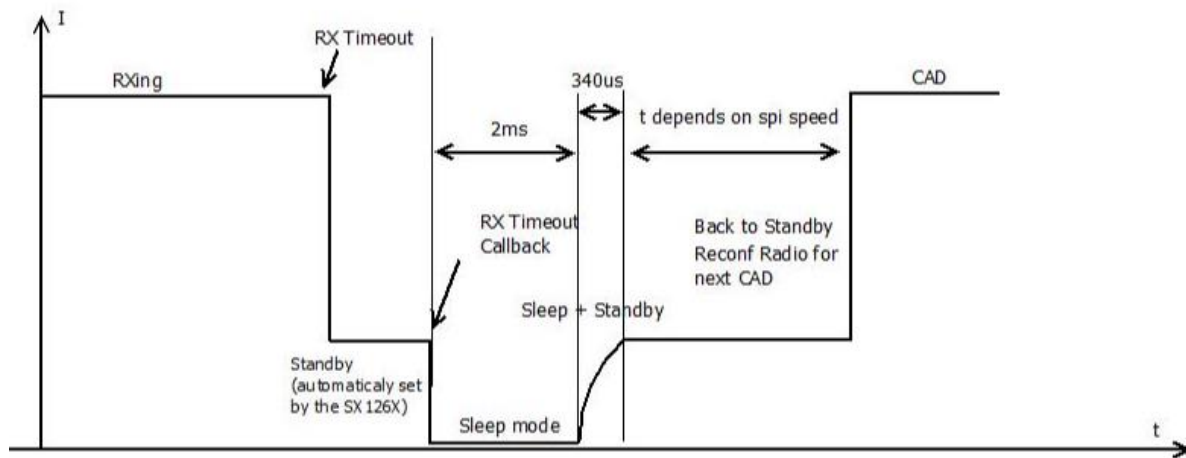


Figure 8 new case when RX timeout occurs

Between these two cases, the application lost 1.34ms, here it is the energy impact

Real measure only on VDD radio

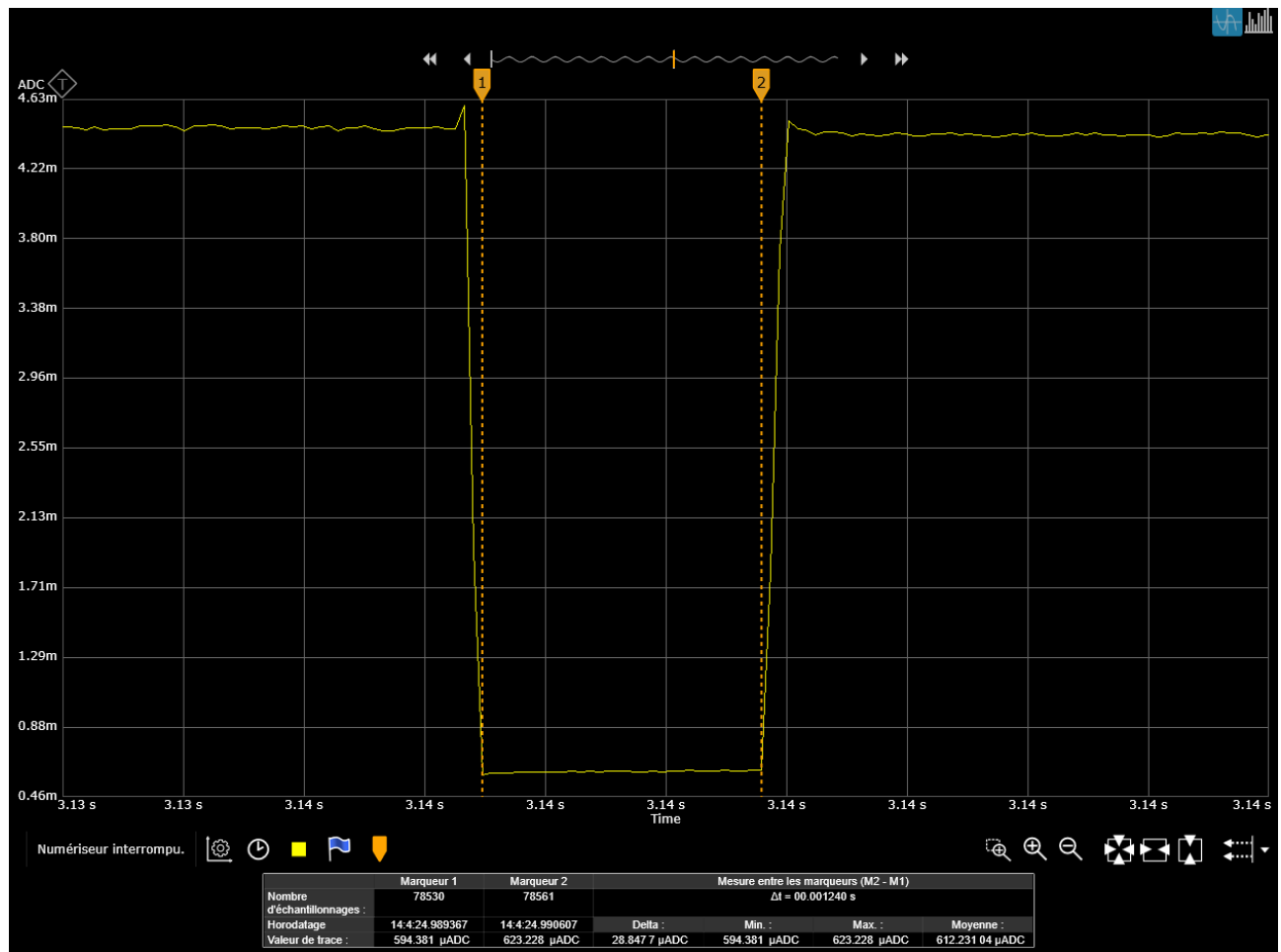


Figure 9 nominal case when RX timeout occurs in real

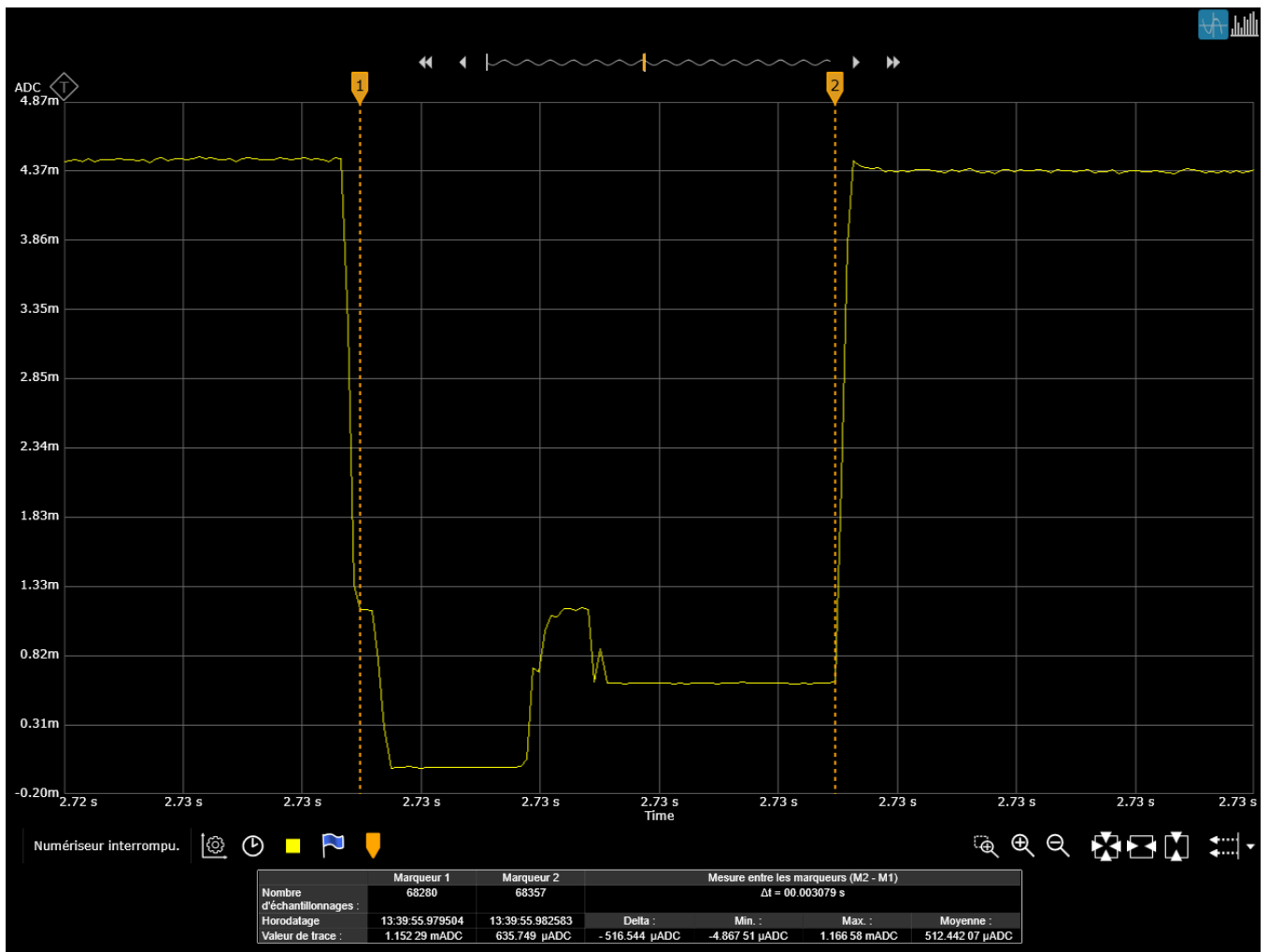


Figure 10 new case when RX timeout occurs in real

On the nominal case the consumption between an RX timeout and the next CAD is:

laverage :612uA on 1.24ms :

$$conso = \frac{0.000612 * 0.00124}{3600} = 0.21nAh$$

On the new case the consumption between an RX timeout and the next CAD is:

laverage :512uA on 3.07ms :

$$conso = \frac{0.000512 * 0.00307}{3600} = 0.436nAh$$

In conclusion, this workaround add 0.226nAh each time that RX timeout occurs.

4. Results

4.1 CAD & PER

4.1.1 Bandwidth 125KHz

4.1.1.1 Best Settings

Hereafter is presented a summary of the best settings to detect a LoRa activity and limit the false detection, using the number of symbols as a parameter, too:

Note: A detection is considered to be false if a CAD is detected and no packet is received.

Spreading Factor	Best CAD settings			CAD consumption (nAh)
	<i>cadDetMin</i>	<i>cadDetPeak</i>	<i>cadSymbolNum</i>	
SF7	10	22	2 Symbols	2.84
SF8	10	22	2 Symbols	5.75
SF9	10	23	4 Symbols	20.44
SF10	10	24	4 Symbols	41.36
SF11	10	25	4 Symbols	134.55
SF12	10	28	4 Symbols	169.54

Table 1: CAD/PER Best Settings

4.1.1.1.1 SF7

Here are the details for SF7, 2 symbols are enough to have a good detection without false detections, LoRa Settings: SF7 | BW = 125 KHz | CR=4/5 | *cadDetMin* = 10.

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-120	100	100	100	100	100
-122	100	100	100	100	100
-123	96	97	97	97	95
-125	94	79	74	58	48
-130	17	8	1	0	0
-140	2	2	1	0	0
OFF	4	0	0	0	0

Table 2: SF7 CAD Rx(%) = f(CAD_SYMBOL_o2 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-120	0	0	0	0	0
-122	0	0	0	0	0
-123	6	6	5	3	5
-125	9	29	29	45	54
-130	100	100	100	100	100
-140	100	100	100	100	100
OFF	100	100	100	100	100

Table 3: SF7 PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF7, 4/5, 125 KHz 2 Symbols, cadDetPeak =22, cadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-120	100	0
-122	100	0
-123	97	5
-125	74	29
-130	1	100
-140	1	100
OFF	0	100

Table 4: SF7 Best setting 2 Symbols

In order to validate these best settings for sensitivity, here is a 10% PER test, performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_02_SYMBOL cadDetPeak = 22 cadDetMin = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-123	10000	9861	9844	1.6	0.17

Table 5: SF7 Best Settings for PER 10%

In order to validate the false detection rate, a slightly different test is then performed: an antenna is connected to the board, but no more packets are transmitted by the signal generator. One thousand CAD attempts are done in order to validate the false detection rate below 1%

CAD SYMBOL = LORA_CAD_02_SYMBOL cadDetPeak = 22 cadDetMin = 10 Antenna					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
OFF	1000	0	0	100	0

Table 6: SF7 False Detection Rate 1% Test

These tests indicate that the above setting fulfills all requirement of a robust CAD, which is a very low probability of false detection in the absence of incoming packet, and a very high probability of proper detection when a packet is in the air, even at very low signal levels (close to sensitivity).

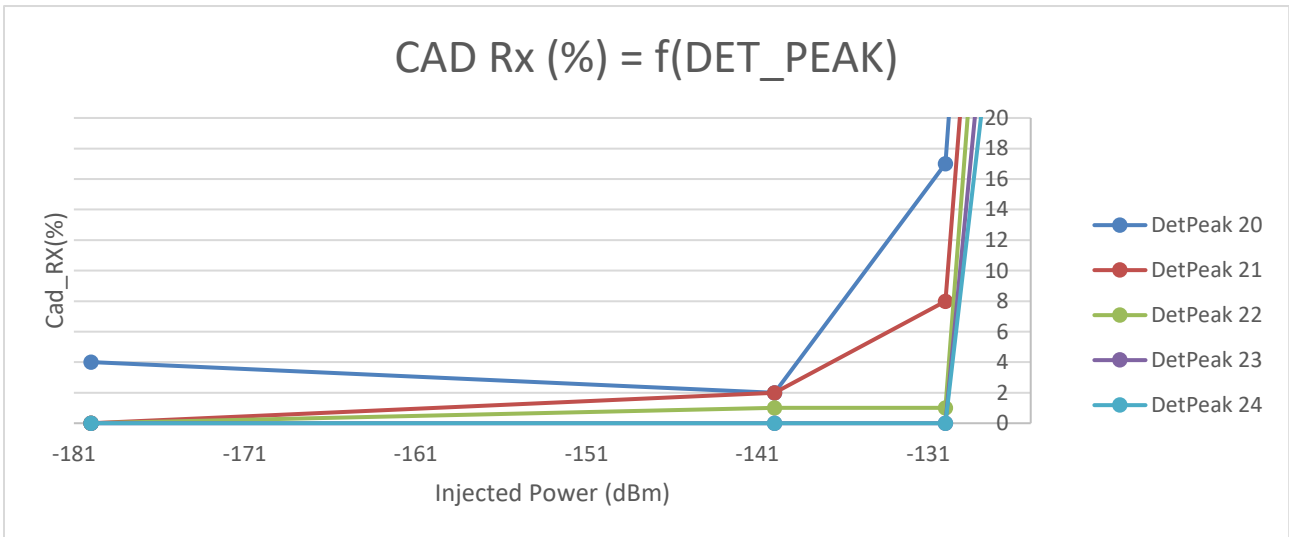
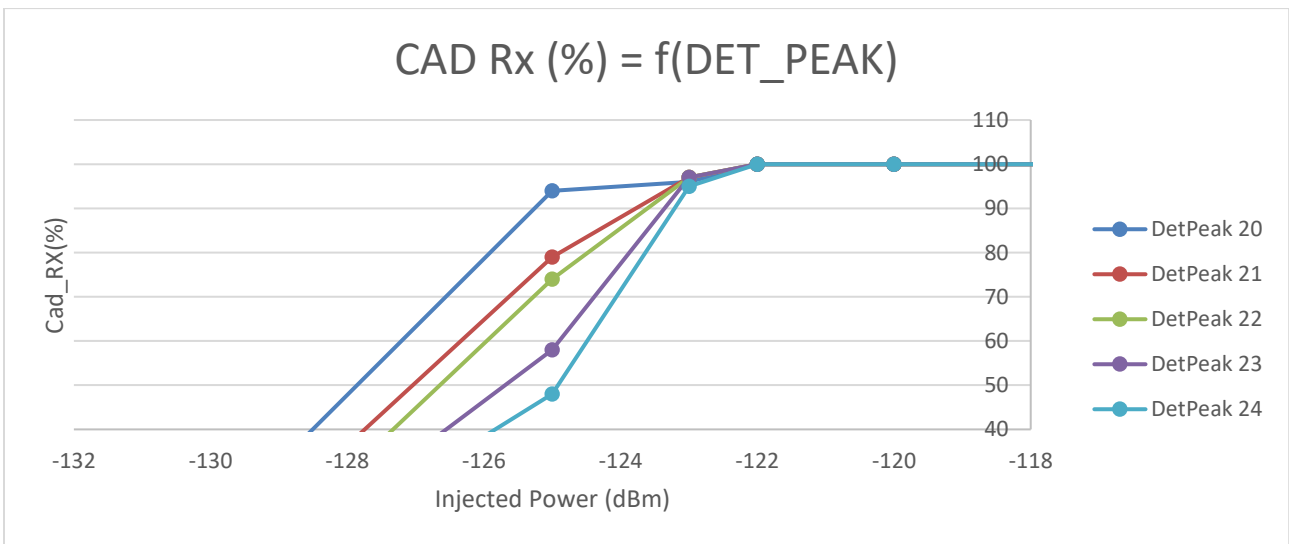
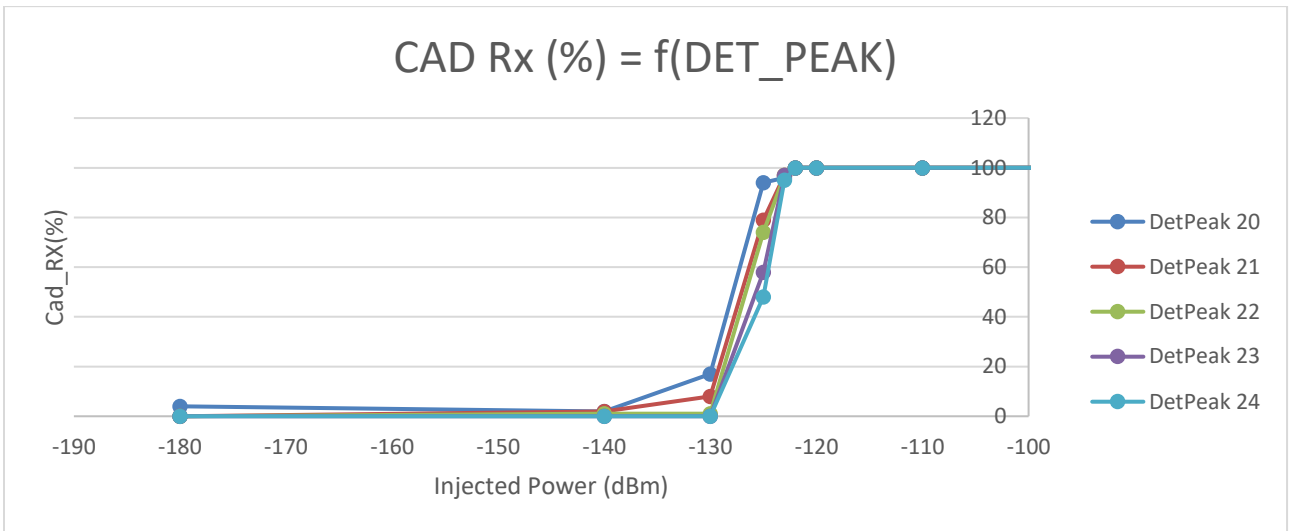


Figure 11: SF7 CAD 2 Symbols vs. *DetPeak*

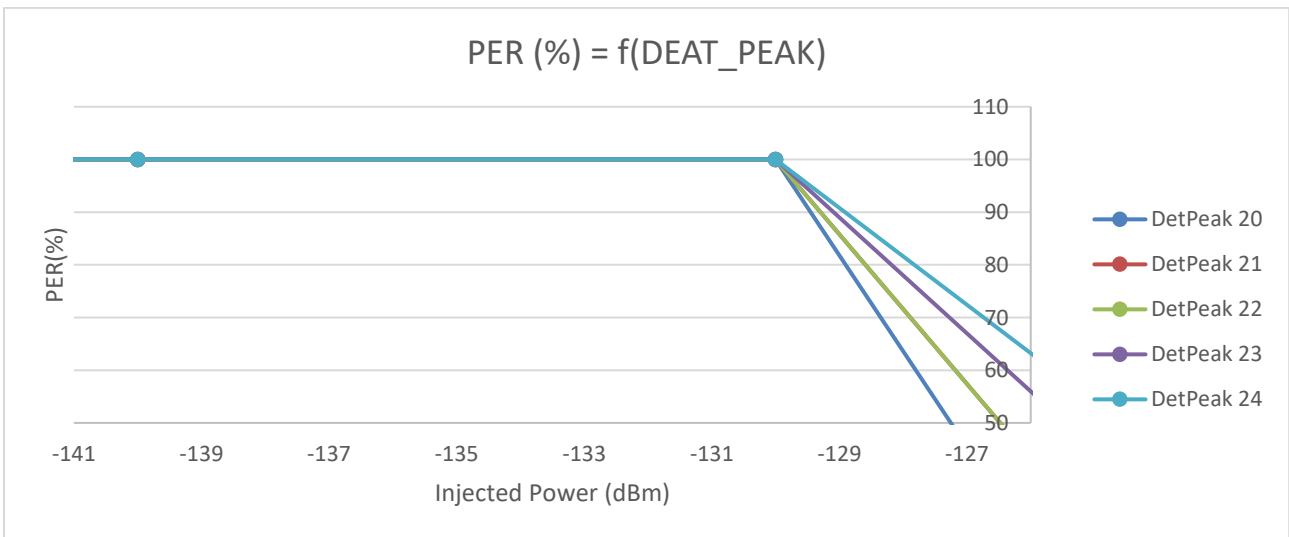
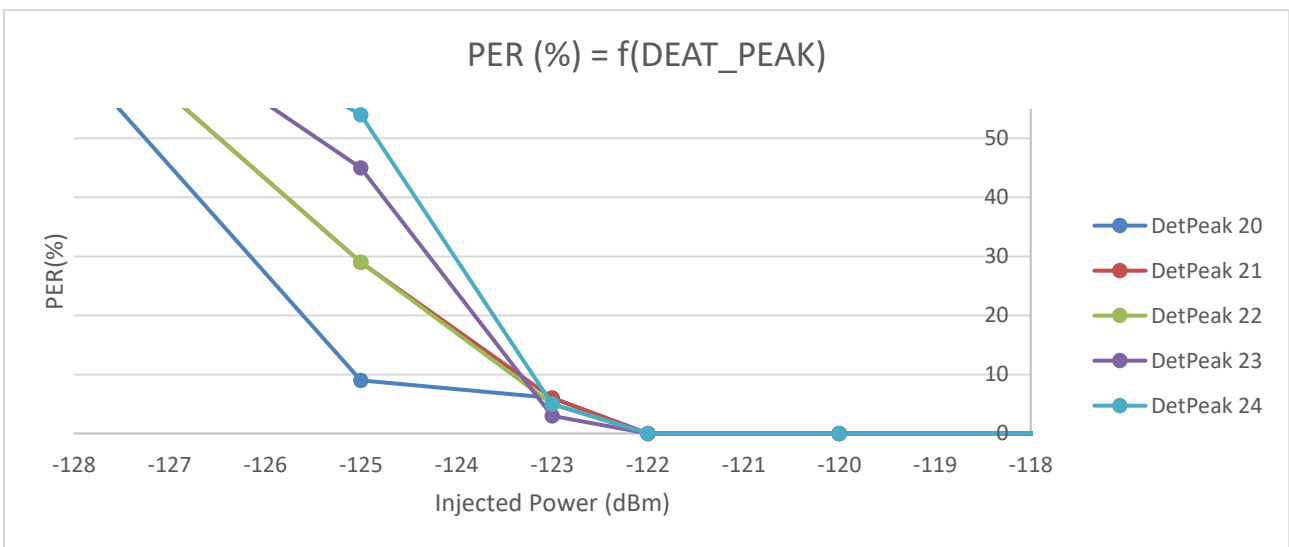
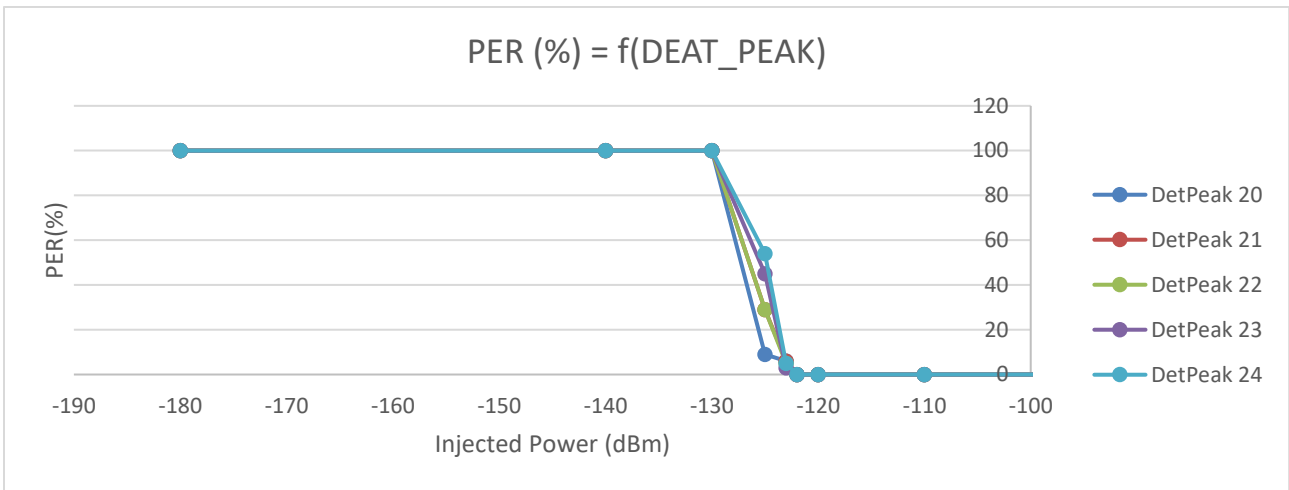


Figure 12: SF7 PER 2 Symbols vs. *DetPeak*

4.1.1.1.2 SF8

Here are the details for SF8, 2 symbols are enough to have a good detection without significant false detection. LoRa Settings: SF8 | BW = 125 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-120	100	100	100	100	100
-123	100	100	100	100	100
-125	100	100	100	97	97
-126	99	99	99	92	86
-130	64	43	23	8	10
-140	16	6	1	0	0
OFF	15	9	0	1	0

Table 7: SF8 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-120	1	1	1	1	1
-123	0	0	1	0	0
-125	1	3	2	4	6
-126	4	7	2	13	17
-130	94	91	96	100	98
-140	100	100	100	100	100
OFF	100	100	100	100	100

Table 8: SF8 PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF8, 4/5, 125 KHz 2 Symbols, CadDetPeak =22, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-120	100	1
-123	100	1
-125	100	2
-126	99	2
-130	23	96
-140	1	100
OFF	0	100

Table 9: SF8 Best Setting 2 Symbols

In order to validate these best settings for sensitivity, here it a PER test performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_02_SYMBOL cadDetPeak = 22 cadDetMin = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-125	10000	9974	9847	1.5	1.27

Table 10: SF8 Best Settings PER 10%

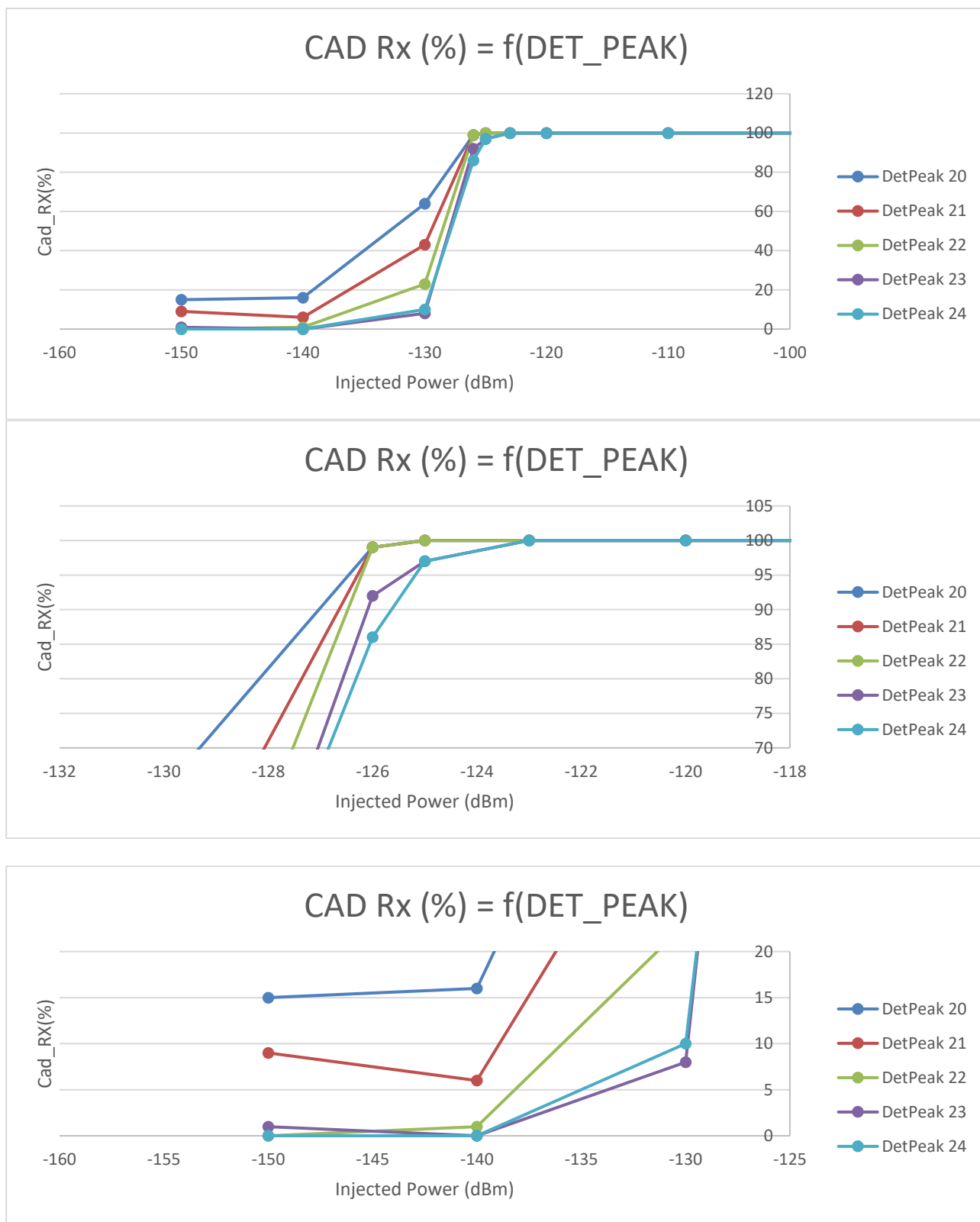


Figure 13: SF8 PER 2 Symbols vs. DetPeak

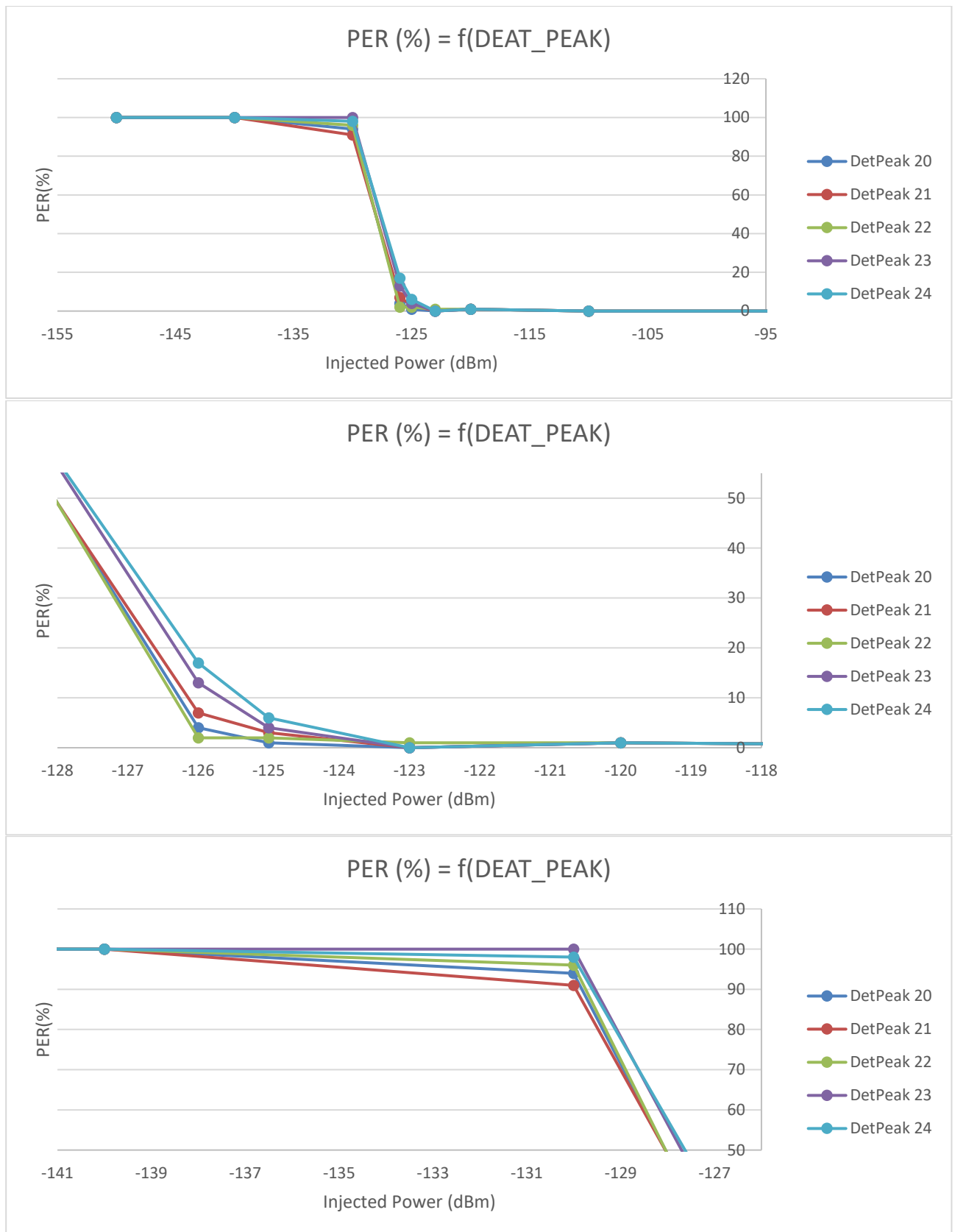


Figure 14: SF8 PER 2 Symbols vs. DetPeak

4.1.1.1.3 SF9

Here are the details for SF9, 4 symbols are necessary to have a good performance without false detection, LoRa Settings: SF9 | BW = 125 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
-120	100	100	100	100	100
-125	100	100	100	100	100
-127	100	100	100	100	100
-128	100	100	100	100	100
-129	100	100	100	100	99
-130	99	99	91	93	74
-132	96	95	81	63	42
-135	79	56	18	4	3
-140	48	29	4	0	0
OFF	57	19	4	0	0

Table 11 SF9 CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
-120	0	0	0	0	0
-125	0	0	0	0	0
-127	1	0	0	0	0
-128	1	1	0	0	2
-129	1	1	2	0	3
-130	7	7	11	11	33
-132	58	75	70	76	88
-135	100	100	100	100	100
-140	100	100	100	100	100
OFF	100	100	100	100	100

Table 12: SF9 PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

SF9, 4/5, 125 KHz 4 Symbols, CadDetPeak =23, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-120	100	0
-125	100	0
-127	100	0
-128	100	0
-129	100	0
-130	93	11
-132	63	76
-135	4	100
-140	0	100
OFF	0	100

Table 13: SF9 Best Setting 4 Symbols

In order to validate these best settings for sensitivity, here is a 10% PER test, performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_04_SYMBOL cadDetPeak = 23 cadDetMin = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-129	10000	9751	9566	4.3	1.90

Table 14: SF9 Best Settings PER 10%

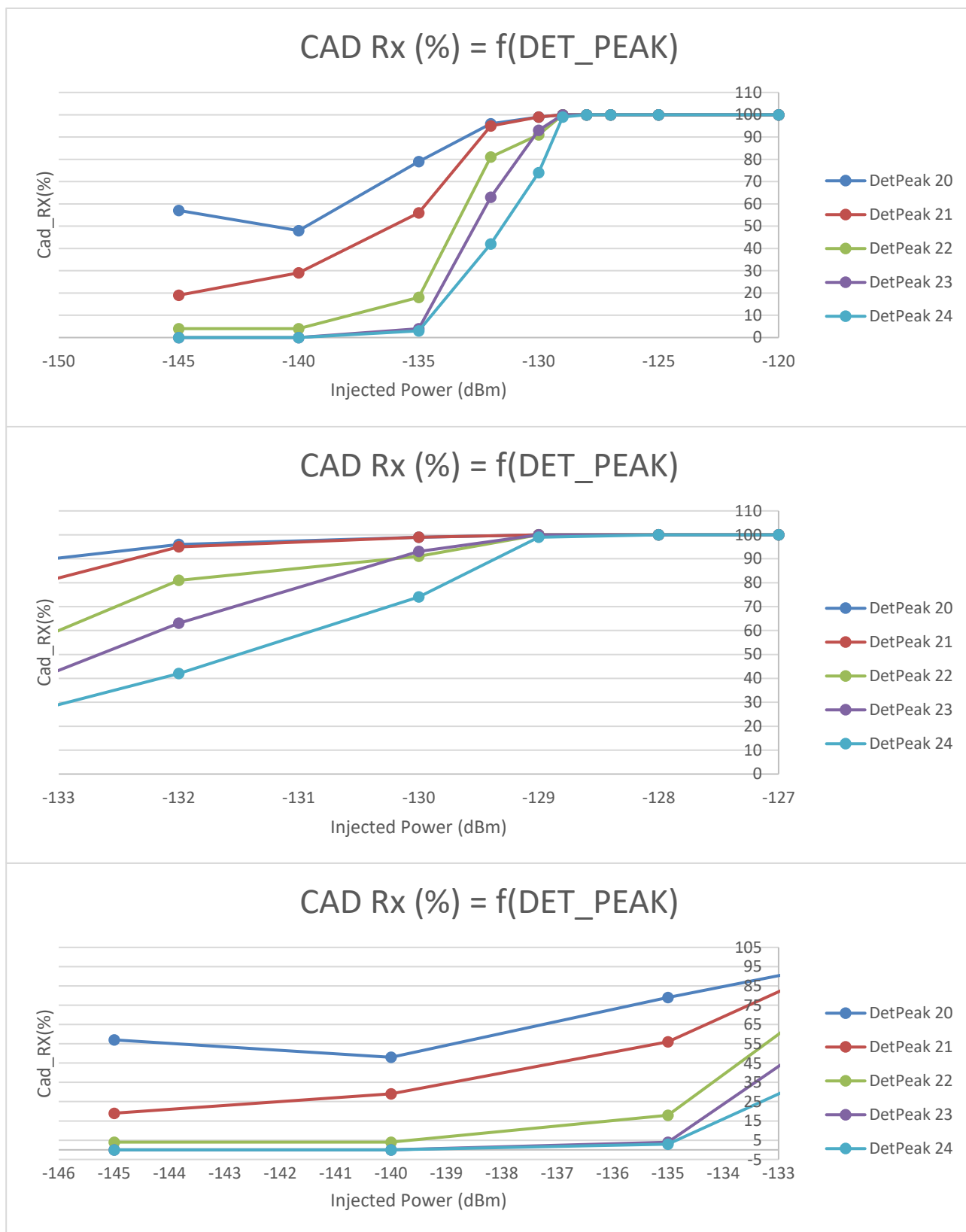


Figure 15: SF9 CAD 4 Symbols vs. DetPeak

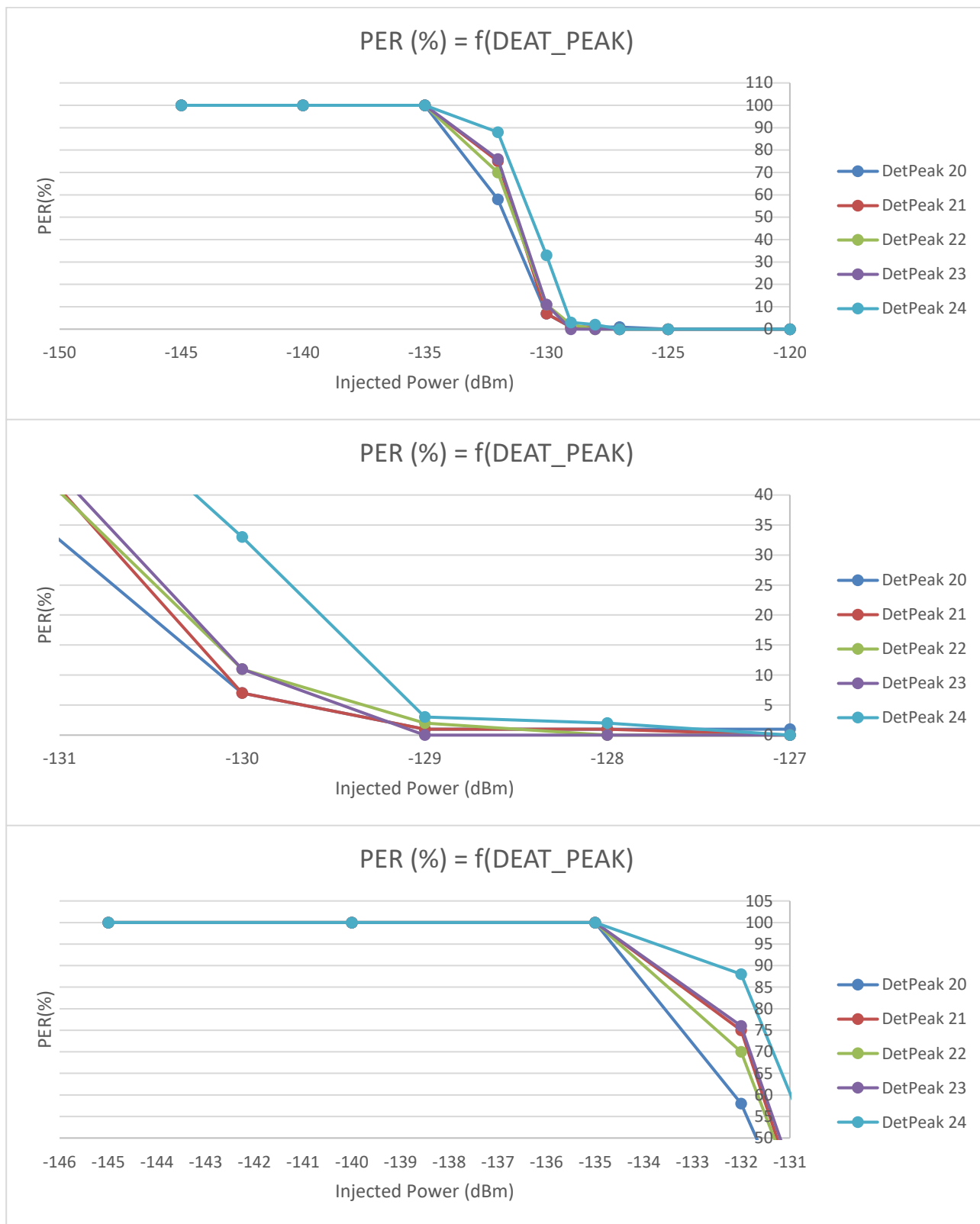


Figure 16: SF9 PER 4 Symbols vs. DetPeak

4.1.1.1.4 SF10

Here are the details for SF10, 4 symbols are necessary to have a good detection without false detection, LoRa Settings: SF10 | BW = 125 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)				
Power (dBm)	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25
-120	100	97	100	100
-125	100	100	100	100
-127	100	100	97	100
-128	100	100	100	100
-129	100	100	100	100
-130	100	100	99	99
-132	100	99	86	78
-135	87	67	5	2
-140	30	10	0	0
OFF	9	3	0	0

Table 15 SF10 CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)				
Power (dBm)	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25
-120	0	7	0	0
-125	0	0	0	0
-127	0	0	3	0
-128	3	0	0	0
-129	1	1	0	0
-130	1	2	1	1
-132	6	7	14	22
-135	89	94	95	95
-140	100	100	100	100
OFF	100	100	100	100

Table 16: SF10 PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

SF10, 4/5, 125 KHz 4 Symbols, CadDetPeak =24, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-120	100	0
-125	100	0
-127	97	3
-128	100	0
-129	100	0
-130	99	1
-132	86	14
-135	5	95
-140	0	100
OFF	0	100

Table 17: SF10 Best Setting 4 Symbols

In order to validate these best settings for sensitivity, here is a 10% PER test, performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_04_SYMBOL cadDetPeak = 24 cadDetMin = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-130	10000	9977	9877	1.2	1.00

Table 18: SF10 Best Settings PER 10%

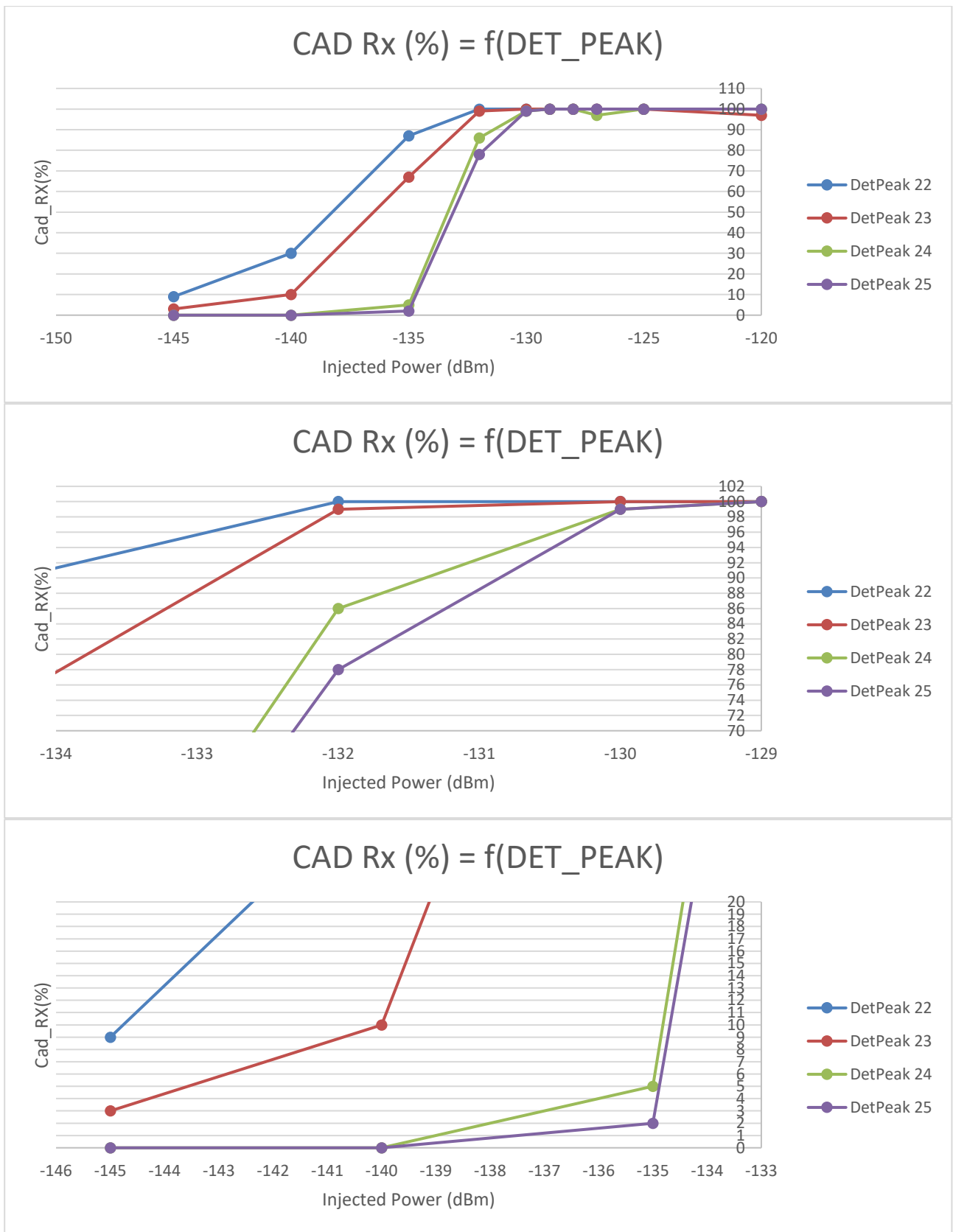


Figure 17: SF10 CAD 4 Symbols vs. DetPeak

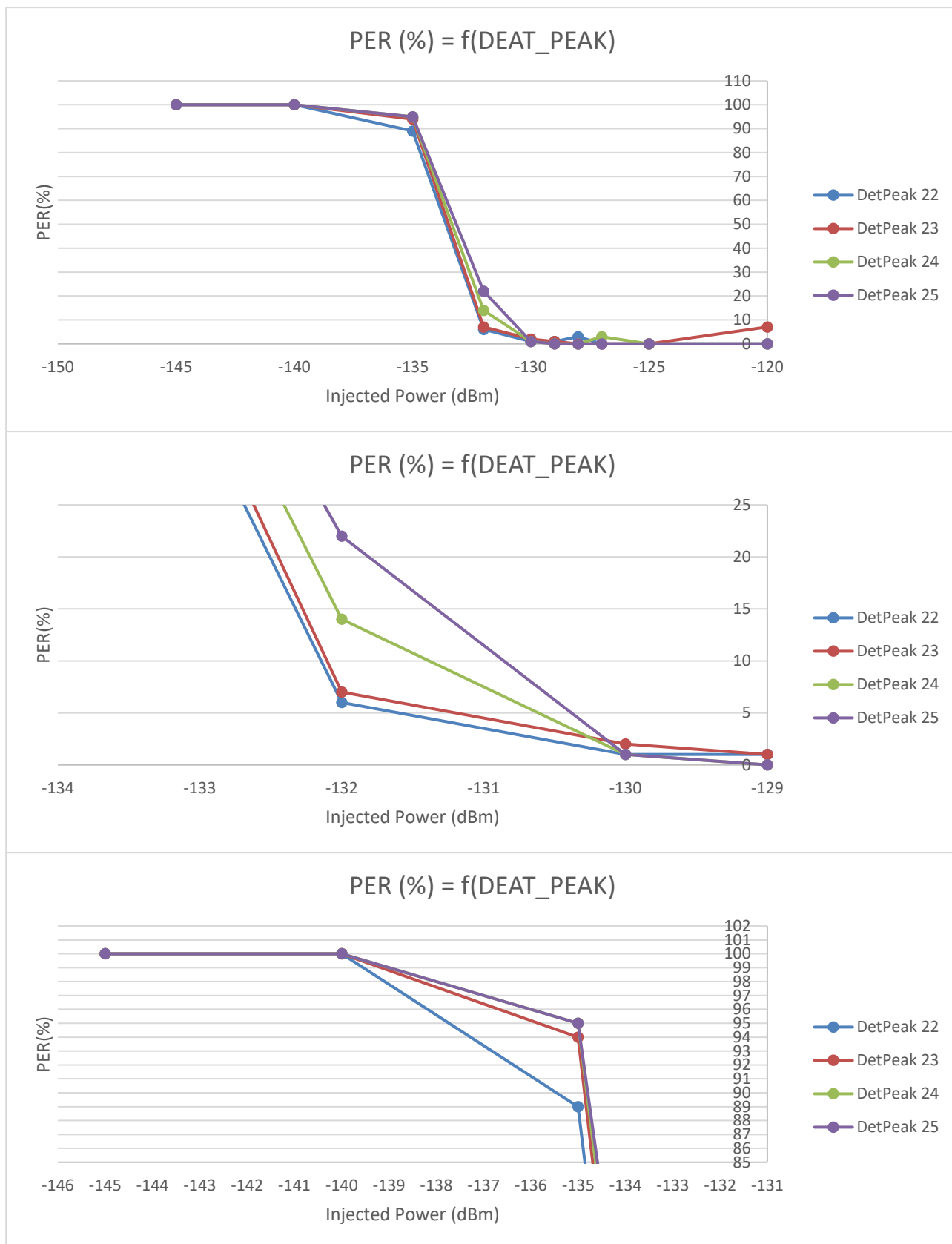


Figure 18: SF10 PER 4 Symbols vs. DetPeak

4.1.1.1.5 SF11

Here are the details for SF11, 4 symbols are necessary to have a good performance without false detection, LoRa Settings: SF11 | BW = 125 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)									
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28
-125	100	100	100	100	100	100	100	100	100
-130	100	100	100	100	100	100	100	100	100
-132	100	100	100	100	100	100	100	100	100
-133	100	100	100	100	100	100	100	99	100
-134	100	100	100	98	100	98	95	93	94
-136	100	100	99	96	83	84	67	41	15
-140	98	90	66	25	3	2	0	0	0
OFF	95	73	28	5	1	1	0	0	0

Table 19: SF11 CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)									
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28
-125	0	0	1	0	0	0	0	0	0
-130	0	1	0	1	0	0	0	0	0
-132	3	1	0	0	0	0	0	0	0
-133	0	0	0	0	0	0	0	1	0
-134	16	3	8	11	0	2	5	7	6
-136	8	13	7	8	22	20	33	59	85
-140	100	100	100	100	100	100	100	100	100
OFF	100	100	100	100	100	100	100	100	100

Table 20: SF11 PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

SF11, 4/5, 125 KHz 4 Symbols, CadDetPeak =25, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-125	100	0
-130	100	0
-132	100	0
-133	100	0
-134	98	2
-136	84	20
-140	2	100
OFF	1	100

Table 21: SF11 Best Setting 4 Symbols

In order to validate these best settings for sensitivity, here is a 10% PER test, performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_04_SYMBOL Det_Peak = 25 Det_Min = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-134	10000	9944	9935	0.7	0.09

Table 22: SF11 Best Settings PER 10%

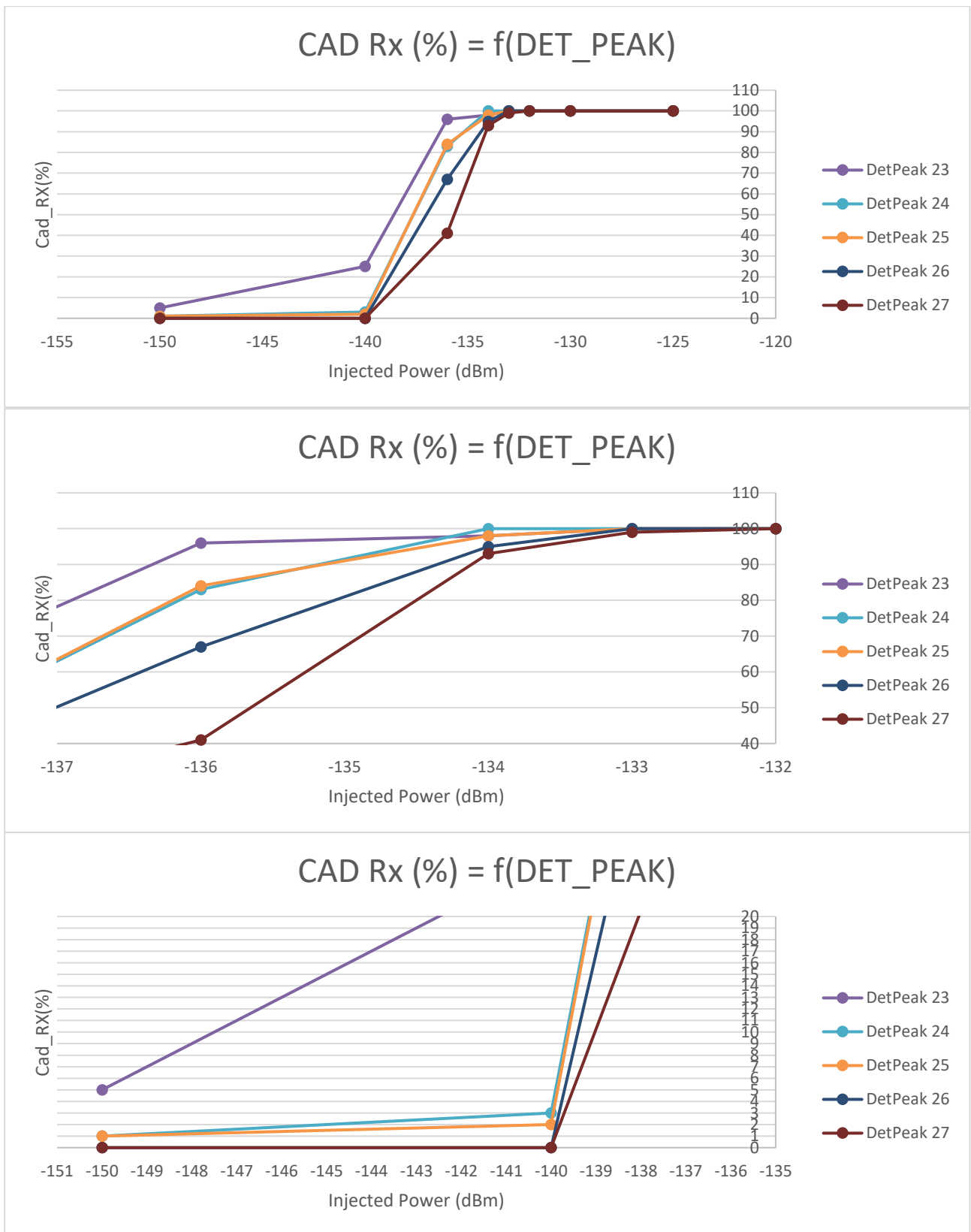


Figure 19: SF11 CAD 4 Symbols vs. DetPeak

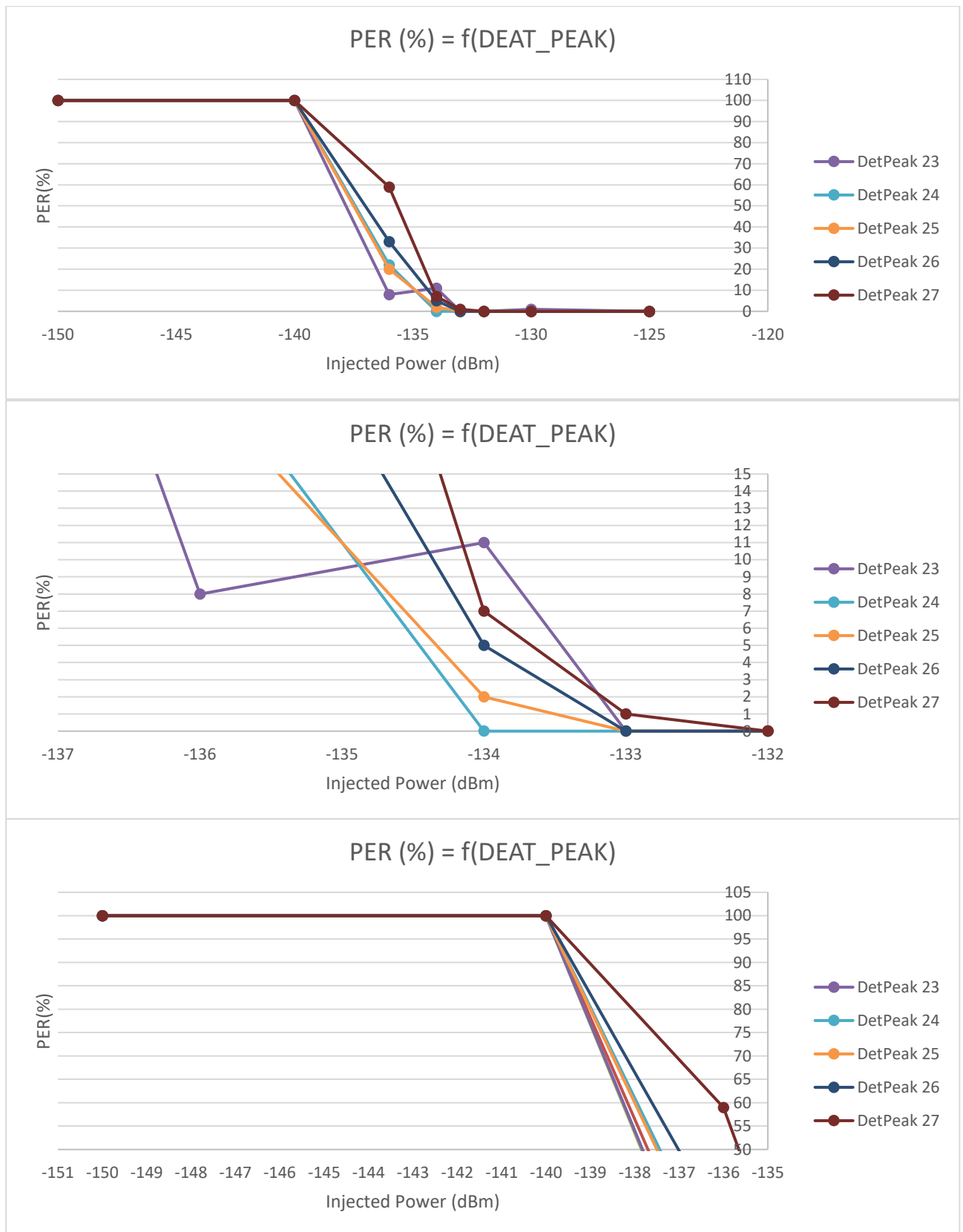


Figure 20: SF11 CAD 4 Symbols vs. DetPeak

4.1.1.1.6 SF12

Here are the details for SF12, 4 symbols are necessary to have a good performance without false detection, LoRa Settings: SF12 | BW = 125 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 DetPeak_n)											
Power (dBm)	DetPe ak 25	DetPe ak 26	DetPe ak 27	DetPe ak 28	DetPe ak 29	DetPe ak 30	DetPe ak 31	DetPe ak 32	DetPe ak 33	DetPe ak 34	DetPe ak 35
-50	100	100	100	100	100	100	100	100	100	100	100
-125	100	100	100	100	100	100	100	100	100	100	100
-130	100	100	100	100	100	100	100	100	100	100	100
-132	100	100	100	100	100	100	100	100	100	100	100
-134	100	100	100	100	100	100	100	100	100	100	100
-135	100	100	100	100	100	100	100	100	100	100	100
-136	100	100	100	100	100	100	100	98	95	94	100
-137	100	100	100	100	96	95	79	47	46	32	79
-138	94	96	92	85	41	33	26	16	13	1	26
-140	58	41	11	3	3	0	1	0	0	0	1
-145	6	2	0	0	0	0	0	0	0	0	0

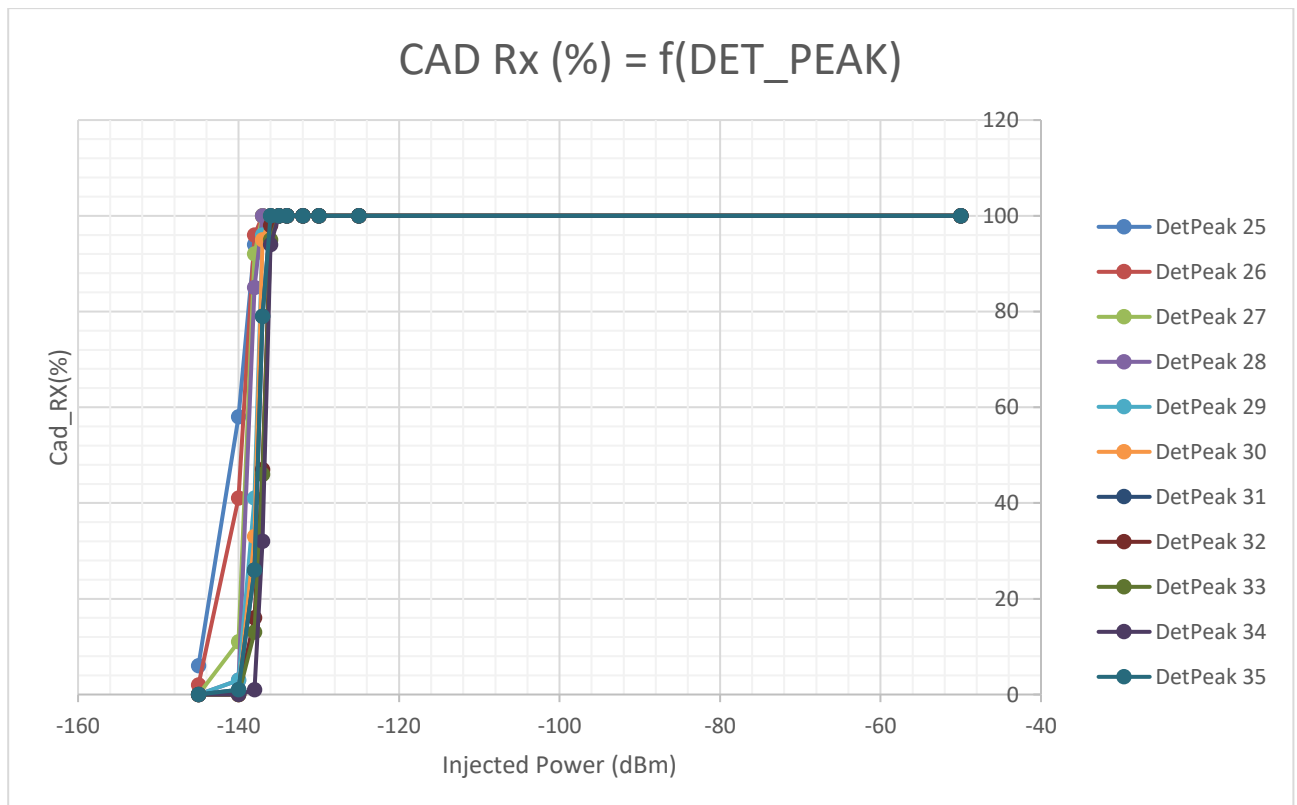
Table 23: SF12 CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 DetPeak_n)											
Power (dBm)	DetPe ak 25	DetPe ak 26	DetPe ak 27	DetPe ak 28	DetPe ak 29	DetPe ak 30	DetPe ak 31	DetPe ak 32	DetPe ak 33	DetPe ak 34	DetPe ak 35
-50	0	0	0	0	0	0	0	0	0	0	0
-125	0	0	0	0	0	0	0	0	0	0	0
-130	0	0	0	0	0	0	0	0	0	0	0
-132	0	0	0	0	0	0	0	0	0	0	0
-134	0	0	0	0	0	0	0	0	0	0	1
-135	0	0	0	0	0	0	0	0	0	0	1
-136	0	0	0	0	0	0	1	2	5	6	19
-137	0	1	1	0	5	5	21	54	54	68	81
-138	20	16	16	27	63	71	76	87	87	99	98
-140	94	91	96	100	99	100	99	100	100	100	100
-145	100	100	100	100	100	100	100	100	100	100	100

Table 24: SF12 PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

SF12, 865MHz, 4/5, 125KHz 4 Symbols, CadDetPeak =28, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-50	100	0
-125	100	0
-130	100	0
-132	100	0
-134	100	0
-135	100	0
-136	100	0
-137	100	0
-138	85	27
-140	3	100
-145	0	100

Table 25: SF12 Best Setting 4 Symbols



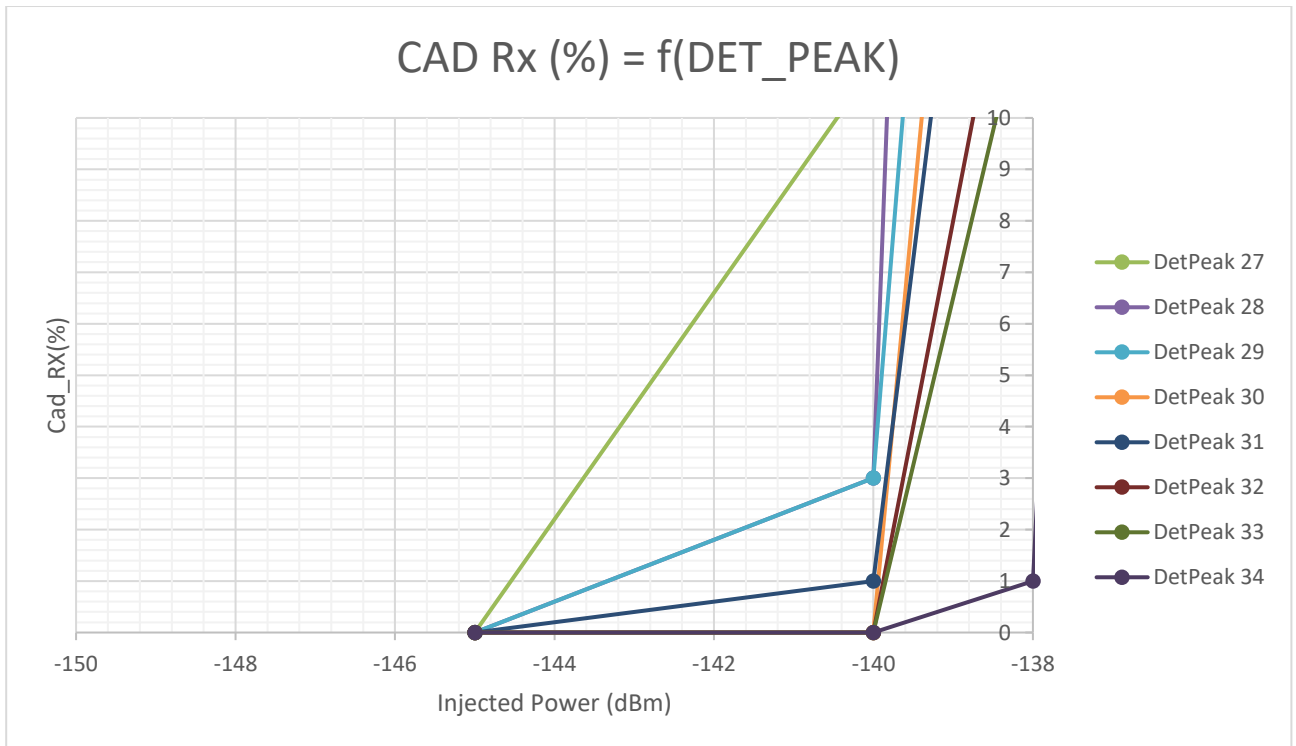
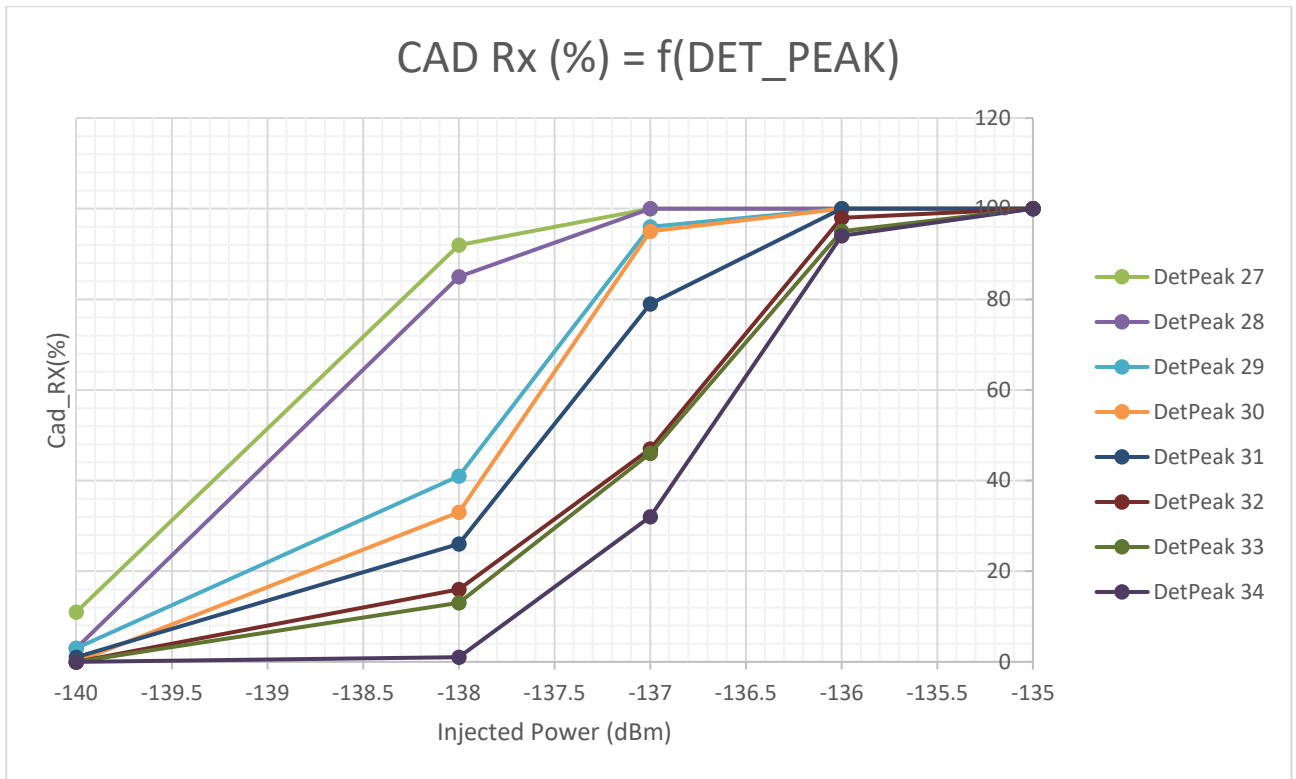
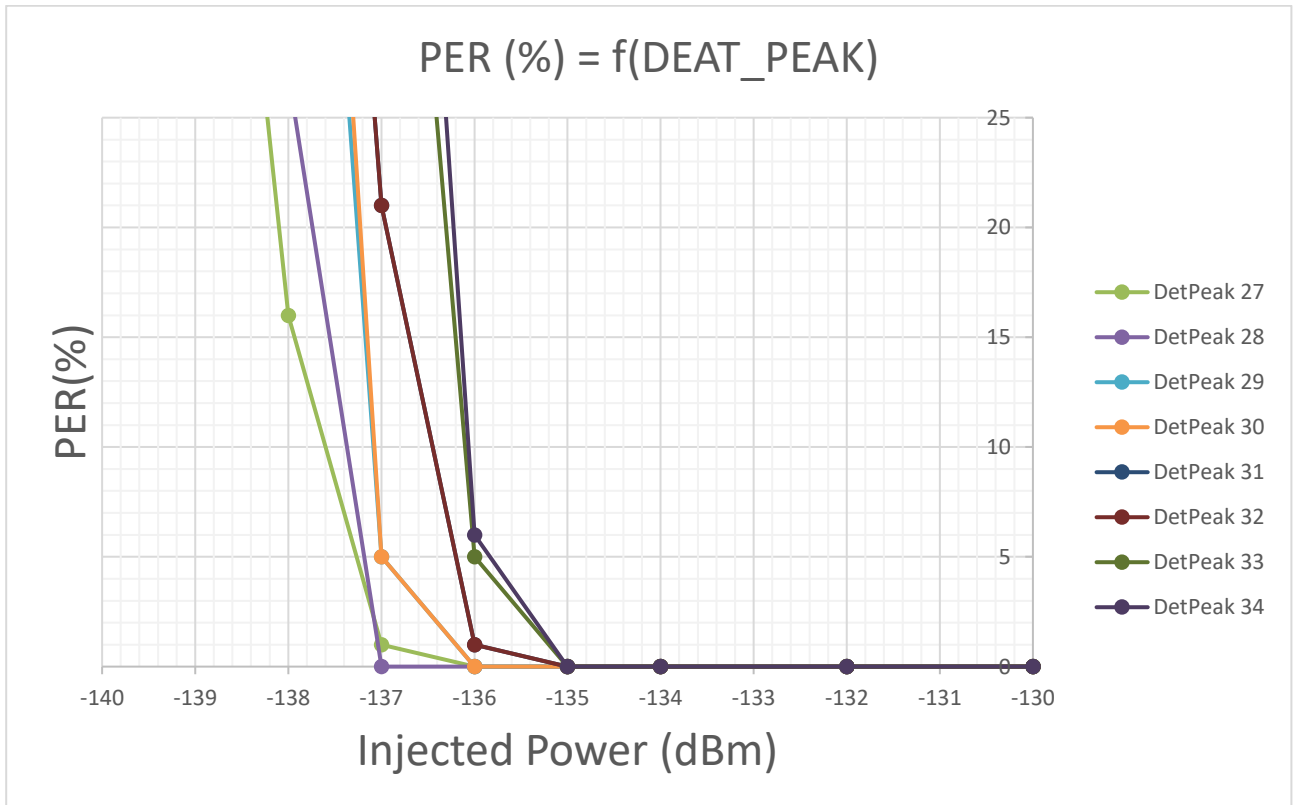
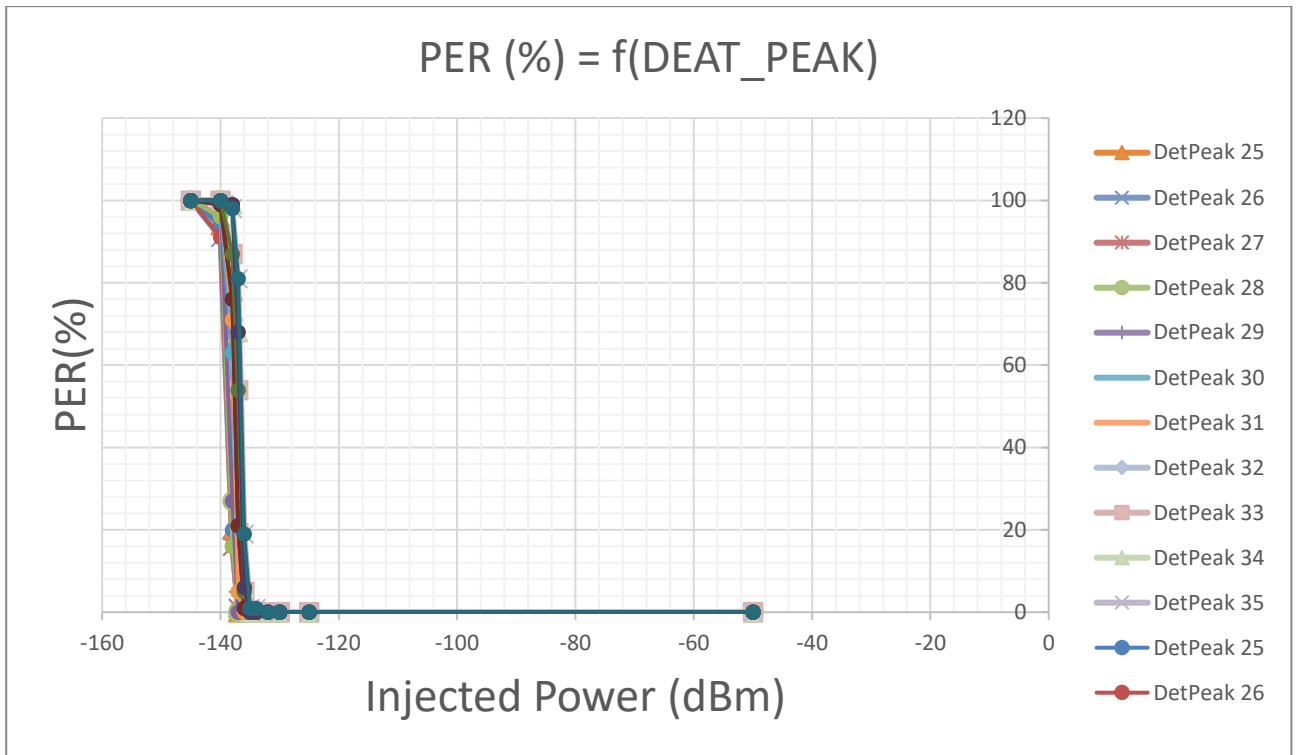


Figure 21 SF12 CAD 4 Symbols vs. DetPeak



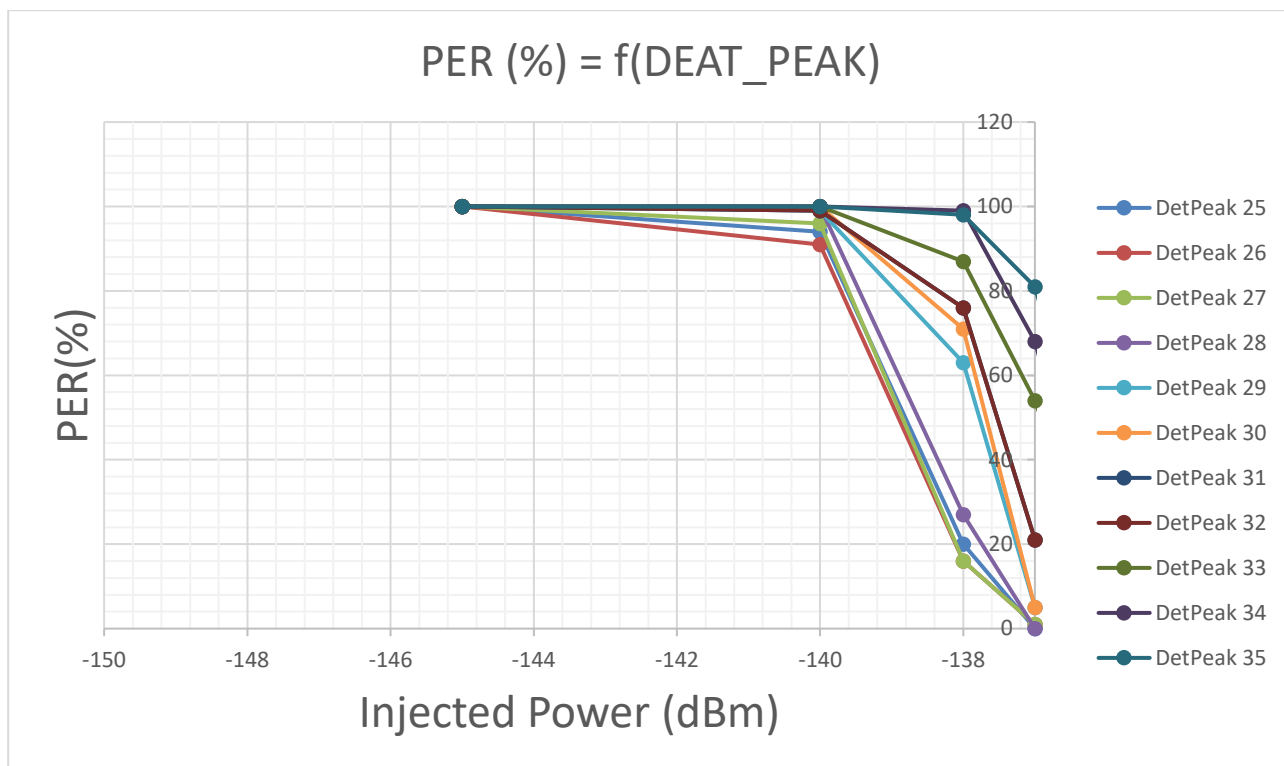


Figure 22 PER 4 Symbols vs. DetPeak

4.1.1.2 Best Settings Using 2 Symbols

The consumption is a really important criterion, so here it is the best settings using only 2 Symbols.

Spreading Factor	Best CAD settings			CAD consumption (nAh)
	<i>cadDetMin</i>	<i>cadDetPeak</i>	<i>cadSymbolNum</i>	
SF7	10	22	2 Symbols	2.84
SF8	10	22	2 Symbols	5.75
SF9	10	24	2 Symbols	11.7
SF10	10	25	2 Symbols	23.86
SF11	10	26	2 Symbols	48.79
SF12	10	30	2 Symbols	64.59

Table 26: CAD/PER Best Settings

4.1.1.2.1 SF7

Please refer to [SF7](#)

4.1.1.2.2 SF8

Please refer to [SF8](#)

4.1.1.2.3 SF9

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
-120	100	100	100	100	100
-125	100	100	100	100	100
-127	100	100	100	100	100
-128	100	100	100	99	100
-129	100	100	99	100	96
-130	99	95	91	84	65
-132	88	75	61	51	37
-135	63	49	30	10	0
-140	34	21	13	2	2
OFF	45	32	17	4	0

Table 27: SF9 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
-120	0	0	0	0	0
-125	0	0	0	0	0
-127	0	1	0	0	0
-128	1	1	2	1	1
-129	1	0	1	2	4
-130	5	9	17	25	37
-132	68	65	76	79	87
-135	100	100	100	100	100
-140	100	100	100	100	100
OFF	100	100	100	100	100

Table 28: SF9 PER (%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF9, 860MHz, 4/5, 125 KHz 2 Symbols, CadDetPeak =24, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-120	100	0
-125	100	0
-127	100	0
-128	100	1
-129	96	4
-130	65	37
-132	37	87
-135	0	100
-140	2	100
OFF	0	100

Table 29: SF9 Best Setting 2 Symbols

Compared to the “perfect” settings (4 symbols used) the performance is slightly degraded but is still acceptable. The PER is still under 10% and the false detection rate is between 0 and 2 % with a low power signal.

	2 Symbols, CadDetPeak =24, CadDetMin=10		4 Symbols, CadDetPeak =23, CadDetMin=10	
Power (dBm)	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
-120	100	0	100	0
-125	100	0	100	0
-127	100	0	100	0
-128	100	1	100	0
-129	96	4	100	0
-130	65	37	93	11
-132	37	87	63	76
-135	0	100	4	100
-140	2	100	0	100
OFF	0	100	0	100

Table 30: SF9 2 Symbols vs. Best settings

4.1.1.2.4 SF10

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)				
Power (dBm)	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25
-120	100	100	100	100
-125	100	100	100	100
-127	100	100	100	100
-128	100	100	99	99
-129	100	100	100	99
-130	100	100	98	96
-132	98	97	89	84
-135	71	55	8	5
-140	19	13	0	0
OFF	23	13	0	0

Table 31: SF10 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)				
Power (dBm)	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25
-120	0	0	0	0
-125	1	0	0	0
-127	0	1	0	0
-128	3	0	1	1
-129	4	0	0	1
-130	1	0	2	4
-132	7	7	11	16
-135	90	90	92	95
-140	100	100	100	100
OFF	100	100	100	100

Table 32: SF10 PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF10, 4/5, 125 KHz 2 Symbols, CadDetPeak =25, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-120	100	0
-125	100	0
-127	100	0
-128	99	1
-129	99	1
-130	96	4
-132	84	16
-135	5	95
-140	0	100
OFF	0	100

Table 33: SF10 Best Settings 2 Symbols

Compared to the “perfect” settings (4 symbols used), the performance is slightly degraded but is still acceptable. The PER is still under 10% and the false detection rate is still 0% with a low power signal.

	2 Symbols, CadDetPeak =25, CadDetMin=10		4 Symbols, CadDetPeak =23, CadDetMin=10	
Power (dBm)	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
-120	100	0	100	0
-125	100	0	100	0
-127	100	0	97	3
-128	99	1	100	0
-129	99	1	100	0
-130	96	4	99	1
-132	84	16	86	14
-135	5	95	5	95
-140	0	100	0	100
OFF	0	100	0	100

Table 34: SF10 2 Symbols vs. Best settings

4.1.1.2.5 SF11

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)									
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28
-125	100	100	100	100	100	100	100	100	100
-130	100	100	100	100	100	100	100	100	100
-132	100	100	99	100	100	99	100	100	99
-133	100	100	100	100	100	100	99	98	88
-134	100	100	100	100	98	97	86	81	67
-136	100	98	96	94	87	76	59	57	37
-140	97	84	42	26	5	6	0	0	0
OFF	89	60	33	9	3	1	0	0	0

Table 35: SF11 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)									
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28
-125	0	0	0	0	0	0	0	0	0
-130	0	0	0	2	0	0	0	0	0
-132	0	0	3	0	2	1	0	0	1
-133	0	0	0	0	0	0	1	2	12
-134	2	0	10	11	13	3	14	19	33
-136	13	12	13	13	18	30	41	43	63
-140	100	100	100	100	100	100	100	100	100
OFF	100	100	100	100	100	100	100	100	100

Table 36: SF11 PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF11, 4/5, 125 KHz 2 Symbols, CadDetPeak =26, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-125	100	0
-130	100	0
-132	100	0
-133	99	1
-134	86	14
-136	59	41
-140	0	100
OFF	0	100

Table 37: SF11 Best Setting 2 Symbols

Compare to the “perfect” setting the performance is slightly degraded, PER < 10% is now achieved at -133dBm instead of -134dBm but the false detection rate is still quite good.

Power (dBm)	2 Symbols, CadDetPeak =26, CadDetMin=10		4 Symbols, CadDetPeak =25, CadDetMin=10	
	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
-125	100	0	100	0
-130	100	0	100	0
-132	100	0	100	0
-133	99	1	100	0
-134	86	14	98	2
-136	59	41	84	20
-140	0	100	2	100
OFF	0	100	1	100

Table 38: SF11 2 Symbols vs. Best Settings

4.1.1.2.6 SF12

CAD Rx(%) = f(CAD_SYMBOL_02 DetPeak_n)											
Power (dBm)	DetPe ak 25	DetPe ak 26	DetPe ak 27	DetPe ak 28	DetPe ak 29	DetPe ak 30	DetPe ak 31	DetPe ak 32	DetPe ak 33	DetPe ak 34	DetPe ak 35
-50	100	100	100	100	100	100	100	100	100	100	100
-125	100	100	100	100	100	100	100	100	100	100	100
-130	100	100	100	100	100	100	100	100	100	100	100
-132	100	100	100	100	100	100	100	100	100	100	100
-134	100	100	100	100	100	100	100	100	97	98	100
-135	100	100	100	99	97	99	97	93	99	98	97
-136	99	99	98	93	93	96	94	84	96	63	94
-137	100	97	97	98	90	74	72	55	41	21	72
-138	99	90	90	63	52	38	23	16	14	10	23
-140	45	34	17	11	5	2	3	1	0	0	3
-145	15	3	0	0	0	0	0	0	0	0	0

Table 39: SF12 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 DetPeak_n)											
Power (dBm)	DetPe ak 25	DetPe ak 26	DetPe ak 27	DetPe ak 28	DetPe ak 29	DetPe ak 30	DetPe ak 31	DetPe ak 32	DetPe ak 33	DetPe ak 34	DetPe ak 35
-50	0	0	0	0	0	0	0	0	0	0	0
-125	0	0	0	0	0	0	0	0	0	0	0
-130	0	0	0	0	0	0	0	0	0	0	0
-132	0	0	0	0	0	0	0	0	0	0	0
-134	0	0	0	0	0	0	0	0	3	2	4
-135	0	0	0	1	3	1	3	7	1	2	13
-136	1	2	2	7	7	4	6	16	4	37	56
-137	0	4	6	4	11	28	30	45	61	79	85
-138	14	20	18	45	53	68	83	85	84	93	97
-140	95	95	98	99	99	100	99	100	100	100	100
-145	100	100	100	100	100	100	100	100	100	100	100

Table 40: SF11 PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF12, 860MHz, 4/5, 125KHz 2 Symbols, CadDetPeak =30, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-50	100	0
-125	100	0
-130	100	0
-132	100	0
-134	100	0
-135	99	1
-136	96	4
-137	74	28
-138	38	68
-140	2	100
-145	0	100

Table 41: SF12 Best Setting 2 Symbols

Compare to the “perfect” setting the performance is slightly degraded, PER < 10% is now achieved at -133dBm instead of -134dBm but the false detection rate is still quite good.

Power (dBm)	2 Symbols, CadDetPeak =30, CadDetMin=10		4 Symbols, CadDetPeak =28, CadDetMin=10	
	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
-50	100	0	100	0
-125	100	0	100	0
-130	100	0	100	0
-132	100	0	100	0
-134	100	0	100	0
-135	99	1	100	0
-136	96	4	100	0
-137	74	28	100	0
-138	38	68	85	27
-140	2	100	3	100
-145	0	100	0	100

Table 42: SF11 2 Symbols vs. Best Settings

4.1.2 Bandwidth 500KHz

4.1.2.1 Best Settings

Hereafter is presented a summary of the best settings to detect a LoRa activity and limit the false detection, using the number of symbols as a parameter, too:

Note: A detection is considered to be false if a CAD is detected and no packet is received.

Spreading Factor	Best CAD settings			CAD consumption (nAh)
	<i>cadDetMin</i>	<i>cadDetPeak</i>	<i>cadSymbolNum</i>	
SF7	10	21	4 Symbols	1.43
SF8	10	22	4 Symbols	2.87
SF9	10	22	4 Symbols	5.69
SF10	10	23	4 Symbols	11.43
SF11	10	25	4 Symbols	22.86
SF12	10	29	8 Symbols	91.44

Table 43 : CAD/PER Best Settings

4.1.2.1.1 SF7

Here are the details for SF7, 4 symbols are enough to have a good detection without false detections, LoRa Settings: SF7 | BW = 500 KHz | CR=4/5 | *cadDetMin* = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-113	100	100	100	97	93
-114	100	100	100	93	90
-115	97	97	95	91	82
-116	95	90	79	75	59
-117	80	80	70	64	45
-118	84	65	51	32	17
-120	28	17	12	3	0
-130	2	0	0	0	0
-140	0	0	0	0	0
-180	0	0	0	0	0

Table 44: SF7 CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-113	0	0	0	3	7
-114	0	0	0	7	10
-115	3	3	5	9	18
-116	5	10	21	25	41
-117	22	26	33	40	56
-118	31	46	74	86	93
-120	96	96	99	100	100
-130	100	100	100	100	100
-140	100	100	100	100	100
OFF	100	100	100	100	100

Table 45: SF7 PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

SF7, 4/5, 500 KHz		
4 Symbols, cadDetPeak =21, cadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-113	100	0
-114	100	0
-115	97	3
-116	90	10
-117	80	26
-120	65	46
-130	17	96
-140	0	100
OFF	0	100

Table 46: SF7 Best setting 4 Symbols

In order to validate these best settings for sensitivity, here is a 10% PER test, performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_04_SYMBOL cadDetPeak = 21 cadDetMin = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-115	10000	9815	9799	2	0.16

Table 47: SF7 Best Settings for PER 10%

In order to validate the false detection rate, a slightly different test is then performed: an antenna is connected to the board, but no more packets are transmitted by the signal generator. One thousand CAD attempts are done in order to validate the false detection rate below 1%

CAD SYMBOL = LORA_CAD_04_SYMBOL cadDetPeak = 21 cadDetMin = 10 Antenna					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
OFF	1000	0	0	100	0

Table 48: SF7 False Detection Rate 1% Test

These tests indicate that the above setting fulfills all requirement of a robust CAD, which is a very low probability of false detection in the absence of incoming packet, and a very high probability of proper detection when a packet is in the air, even at very low signal levels (close to sensitivity).

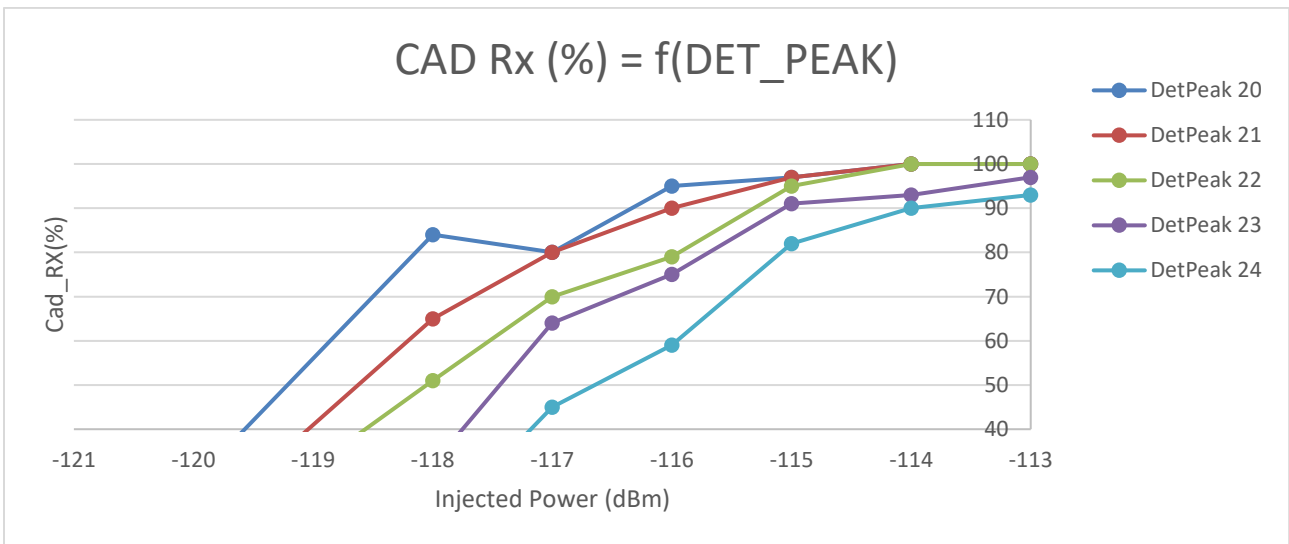
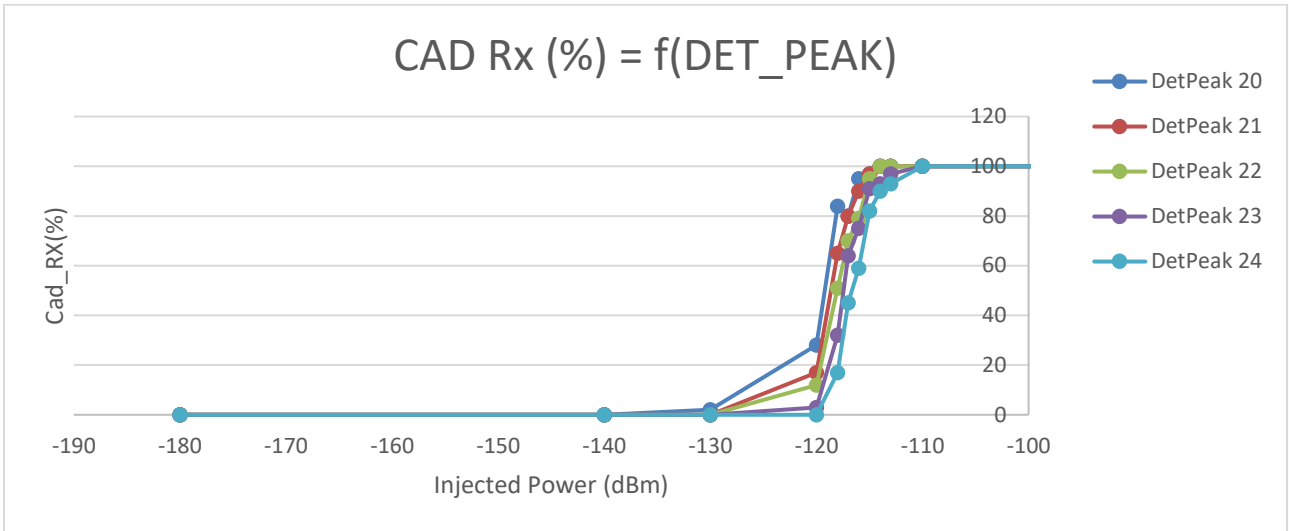


Figure 23: SF7 CAD 4 Symbols vs. *DetPeak*

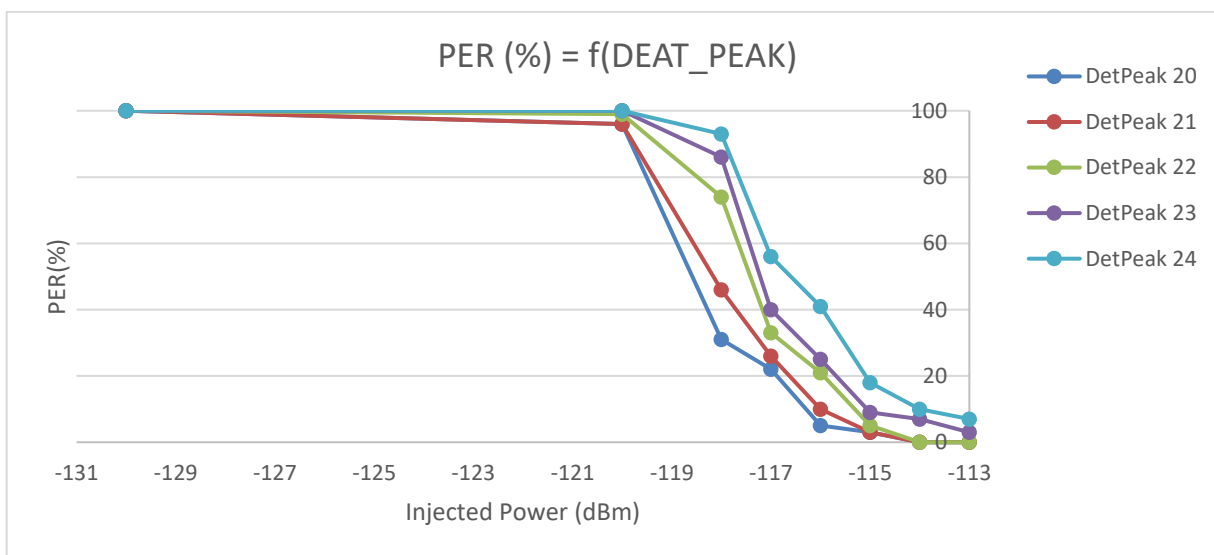
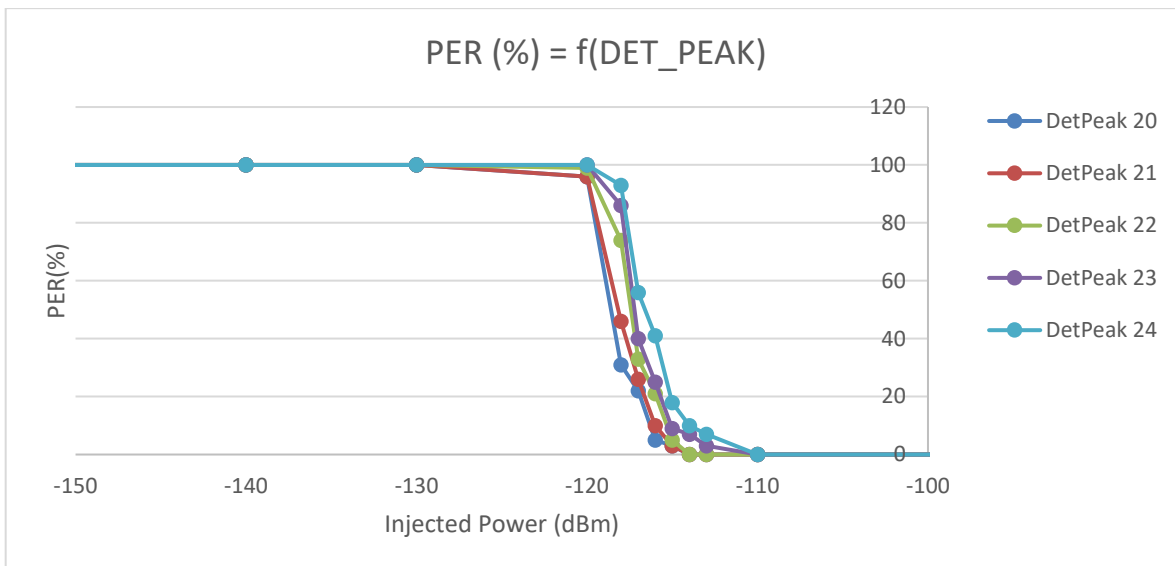


Figure 24: SF7 PER 4 Symbols vs. *DetPeak*

4.1.2.1.2 SF8

Here are the details for SF8, 4 symbols are enough to have a good detection without significant false detection. LoRa Settings: SF8 | BW = 500 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-116	100	100	100	100	100
-117	100	100	100	97	93
-118	100	99	99	93	91
-119	97	98	89	88	80
-120	96	95	82	69	54
-121	90	83	64	57	32
-123	76	42	26	17	8
-125	42	17	8	0	0
-130	19	6	5	1	0
-140	19	8	2	0	0
-180	0	0	0	0	0

Table 49: SF8 CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-116	0	0	0	0	0
-117	0	0	0	3	7
-118	0	1	1	7	9
-119	5	2	12	14	20
-120	7	12	21	36	48
-121	29	40	51	55	74
-123	86	98	98	97	100
-125	100	100	100	100	100
-130	100	100	100	100	100
-140	100	100	100	100	100
-180	100	100	100	100	100

Table 50: SF8 PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

SF8, 4/5, 500 KHz 4 Symbols, CadDetPeak =22, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-116	100	0
-117	100	0
-118	99	1
-119	89	12
-120	82	21
-121	64	51
-123	26	98
-125	8	100
-130	5	100
-140	2	100
-180	0	100

Table 51: SF8 Best Setting 4 symbols

In order to validate these best settings for sensitivity, here it a PER test performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_04_SYMBOL cadDetPeak = 22 cadDetMin = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-118	10000	9762	9746	2.5	0.16

Table 52: SF8 Best Settings PER 10%

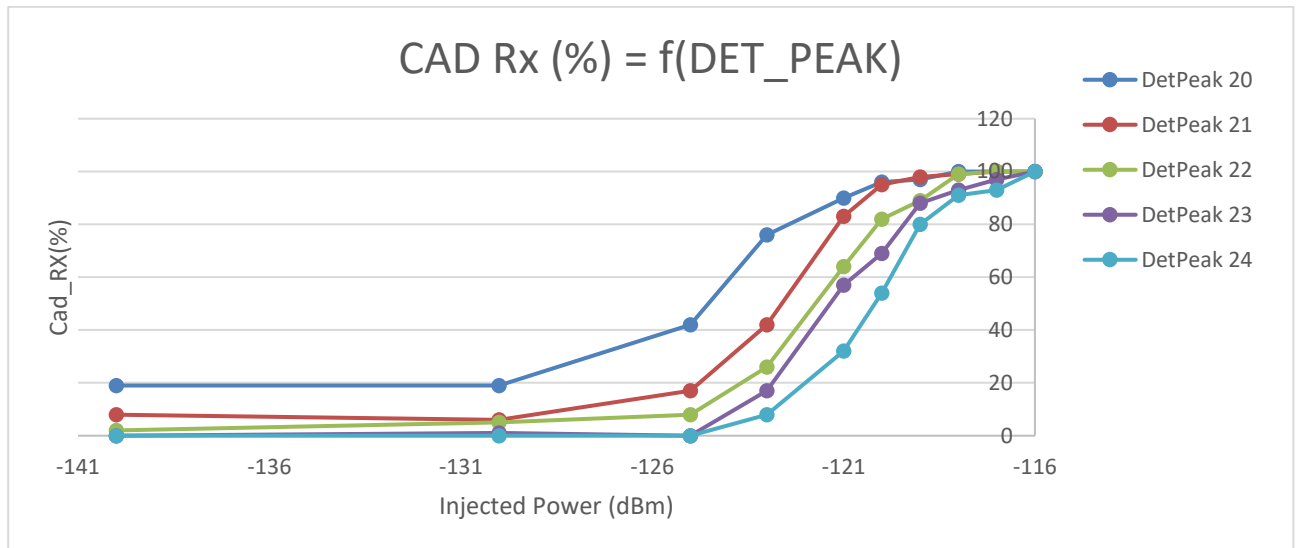
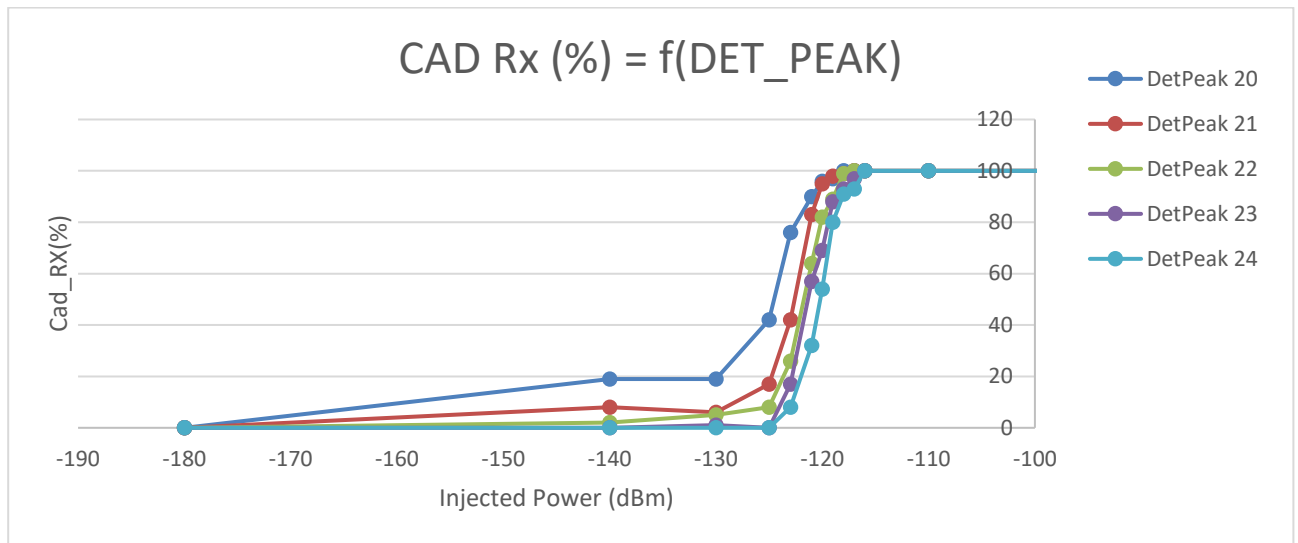


Figure 25: SF8 PER 4 Symbols vs. DetPeak

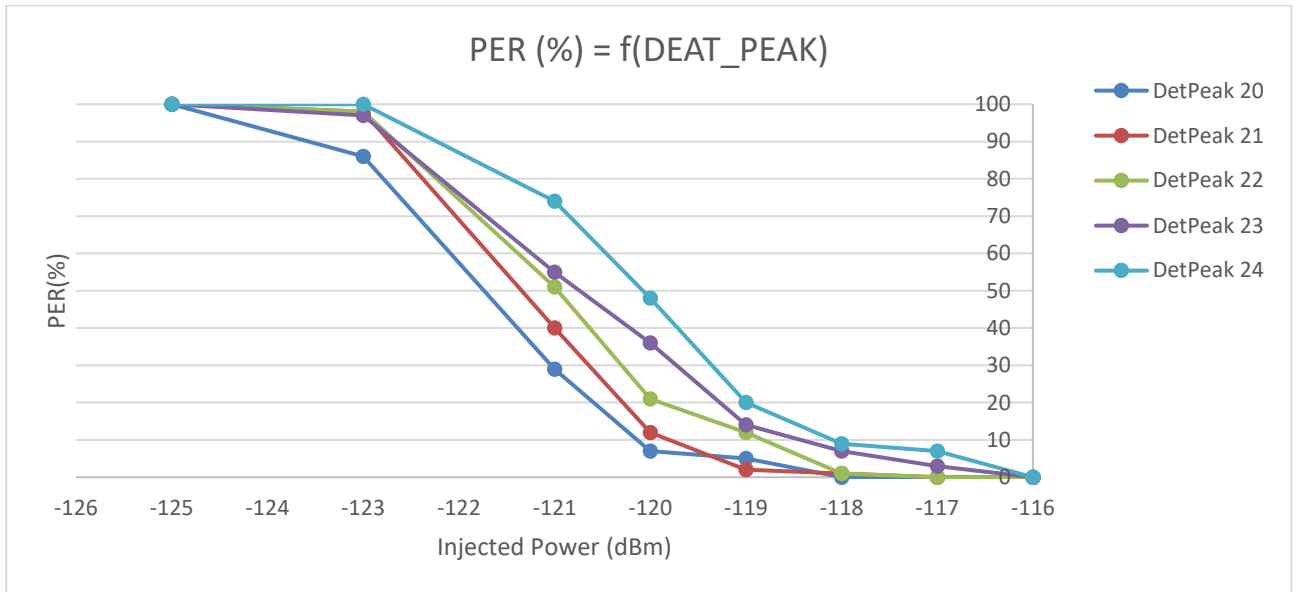
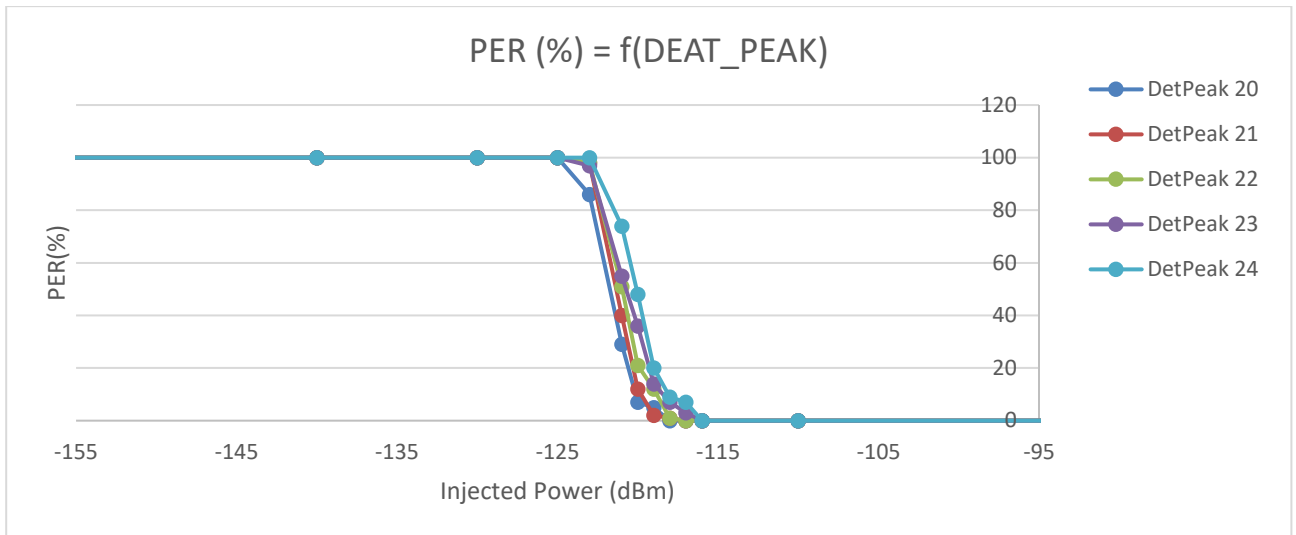


Figure 26: SF8 PER 4 Symbols vs. DetPeak

4.1.2.1.3 SF9

Here are the details for SF9, 4 symbols are necessary to have a good performance without false detection, LoRa Settings: SF9 | BW = 500 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-120	99	100	100	100	98
-121	99	99	99	96	88
-122	99	99	95	90	78
-123	97	98	91	73	54
-125	94	82	64	33	20
-130	79	47	25	8	2
-140	64	54	20	4	0
-180	0	0	0	0	0

Table 53 SF9 CAD Rx(%) = f(CAD_SYMBOL_o4 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-120	1	0	0	0	2
-121	1	1	1	4	13
-122	3	1	6	13	23
-123	10	11	15	36	51
-125	78	87	84	92	93
-130	100	100	100	100	100
-140	100	100	100	100	100
-180	100	100	100	100	100

Table 54: SF9 PER(%) = f(CAD_SYMBOL_o4 cadDetPeak_n)

SF9, 4/5, 500 KHz 4 Symbols, CadDetPeak =22, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-120	100	0
-121	99	1
-122	95	6
-123	91	15
-125	64	84
-130	25	100
-140	20	100
-180	0	0

Table 55: SF9 Best Setting 4 Symbols

In order to validate these best settings for sensitivity, here is a 10% PER test, performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_04_SYMBOL cadDetPeak = 22 cadDetMin = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-122	10000	9826	9655	3.4	1.7

Table 56: SF9 Best Settings PER 10%

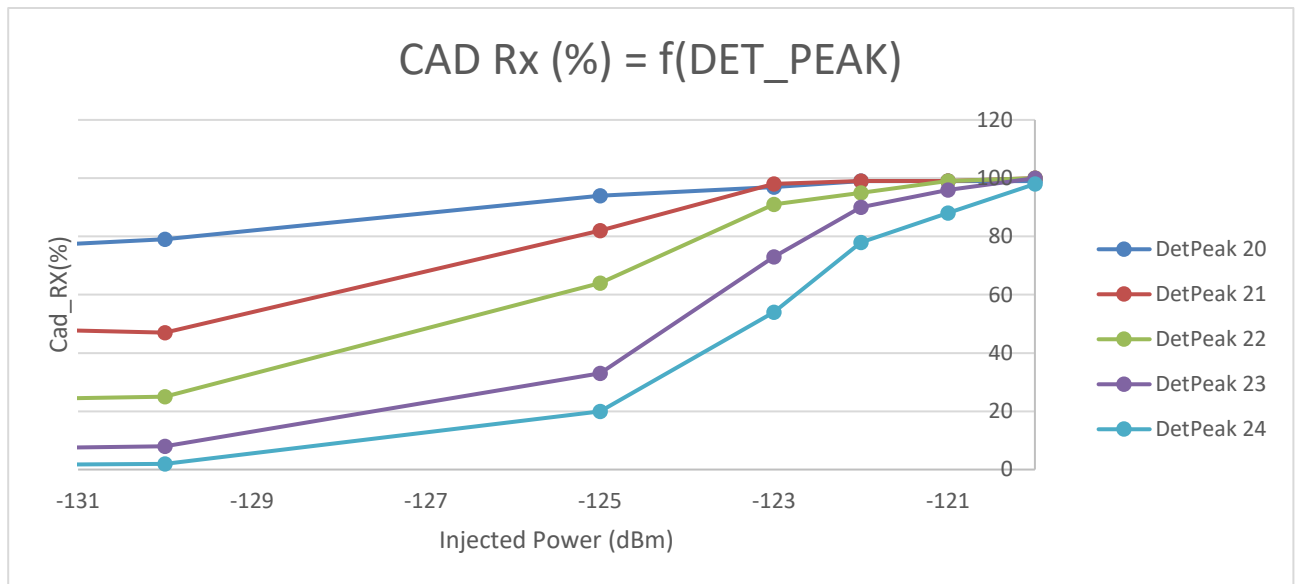
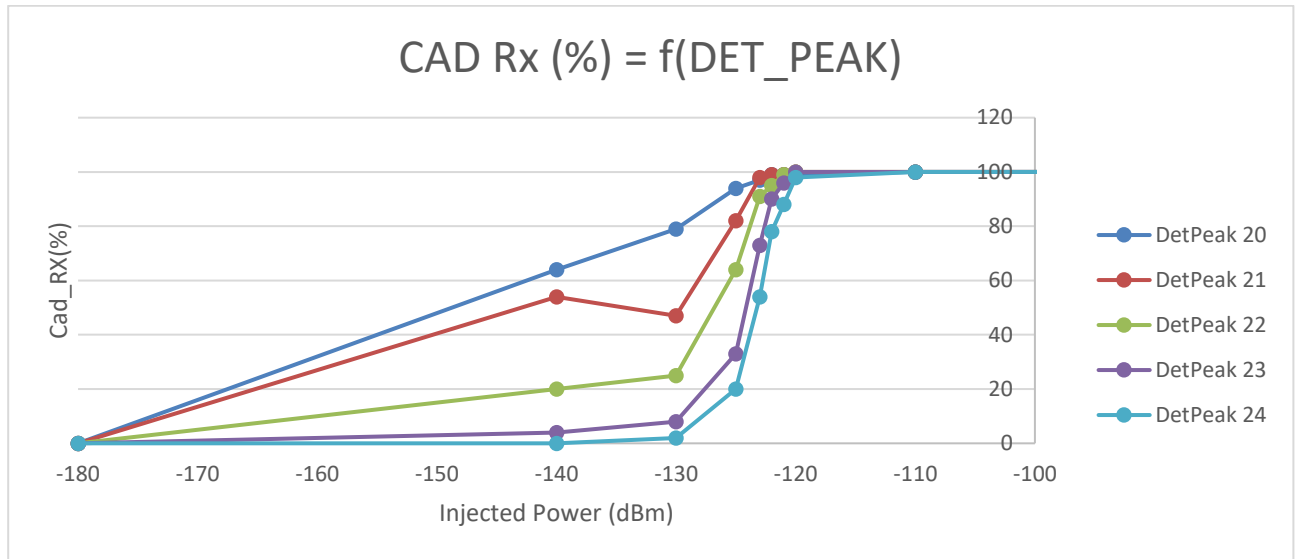


Figure 27: SF9 CAD 4 Symbols vs. DetPeak

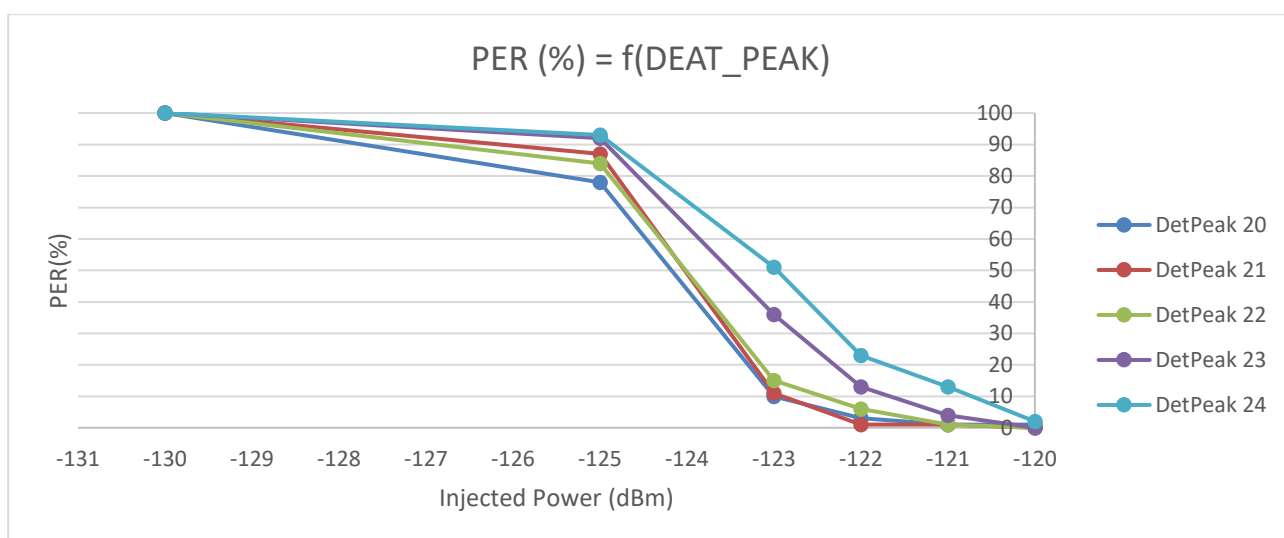
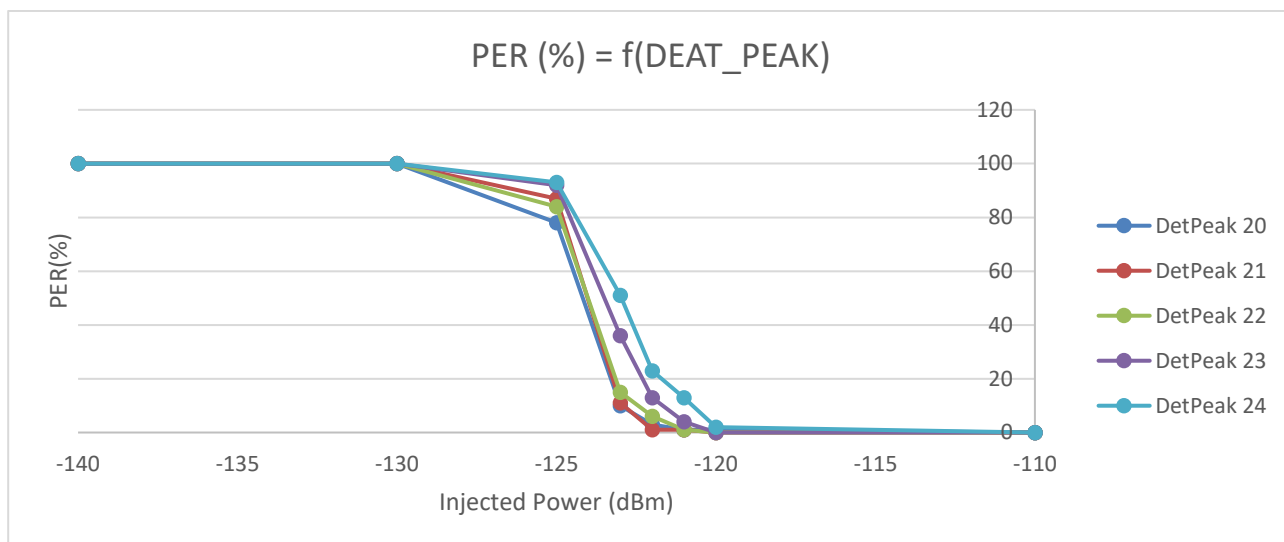


Figure 28: SF9 PER 4 Symbols vs. DetPeak

4.1.2.1.4 SF10

Here are the details for SF10, 4 symbols are necessary to have a good detection without false detection, LoRa Settings: SF10 | BW = 500 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-120	100	100	100	100	100
-123	100	100	100	100	98
-124	99	100	99	97	99
-125	100	100	100	96	90
-126	100	99	99	88	77
-130	96	93	78	52	20
-140	94	91	63	33	14
-180	0	0	0	0	0

Table 57 SF10 CAD Rx(%) = f(CAD_SYMBOL_o4 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-120	0	0	0	0	0
-123	0	0	0	0	0
-124	4	1	1	4	3
-125	8	5	4	11	12
-126	14	15	18	25	34
-130	100	100	100	100	100
-140	100	100	100	100	100
-180	100	100	100	100	100

Table 58: SF10 PER(%) = f(CAD_SYMBOL_o4 cadDetPeak_n)

SF10, 4/5, 500 KHz 4 Symbols, CadDetPeak =23, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-120	100	0
-123	100	0
-124	99	1
-125	100	4
-126	99	18
-130	78	100
-140	63	100
-180	0	100

Table 59: SF10 Best Setting 4 Symbols

In order to validate these best settings for sensitivity, here is a 10% PER test, performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_04_SYMBOL cadDetPeak = 23 cadDetMin = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-125	10000	9931	9851	1.5	0.79

Table 60: SF10 Best Settings PER 10%

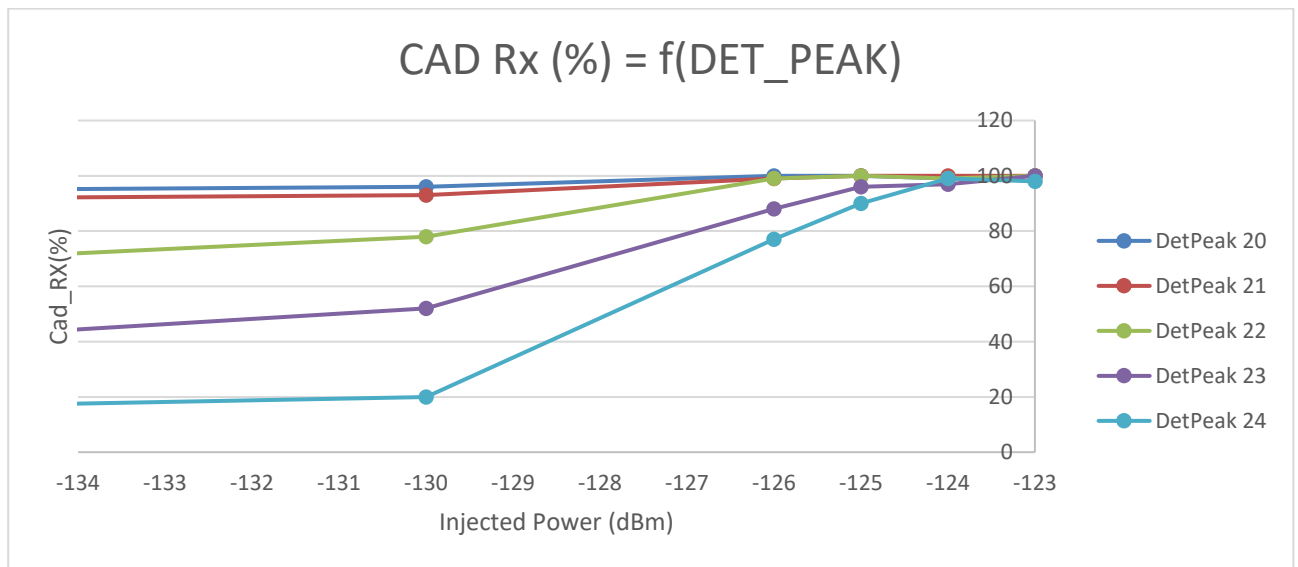
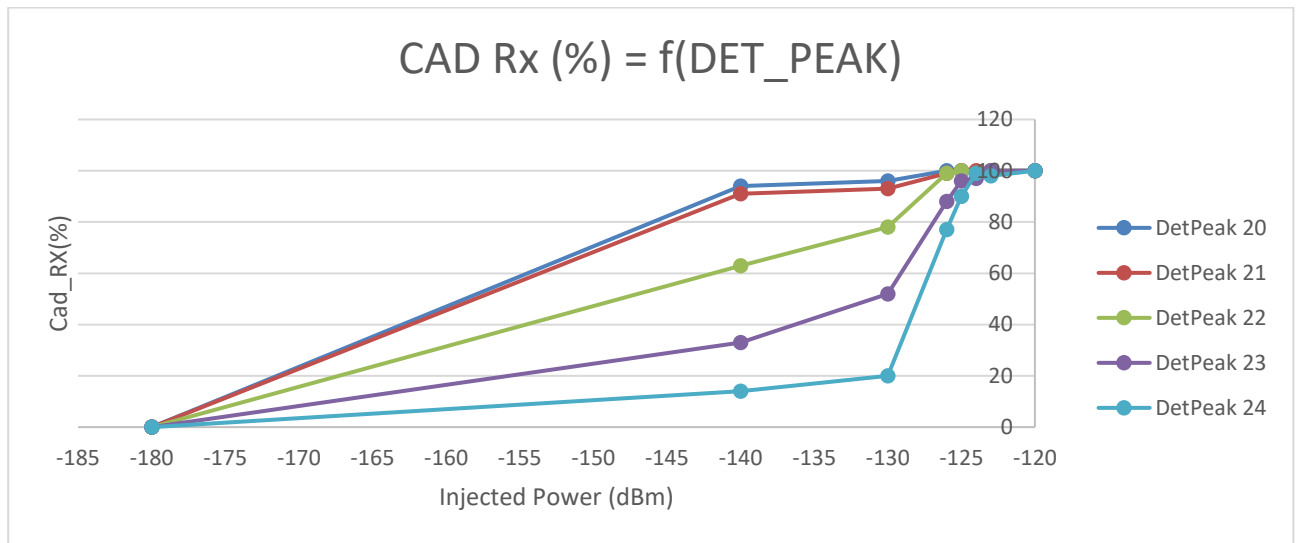


Figure 29: SF10 CAD 4 Symbols vs. DetPeak

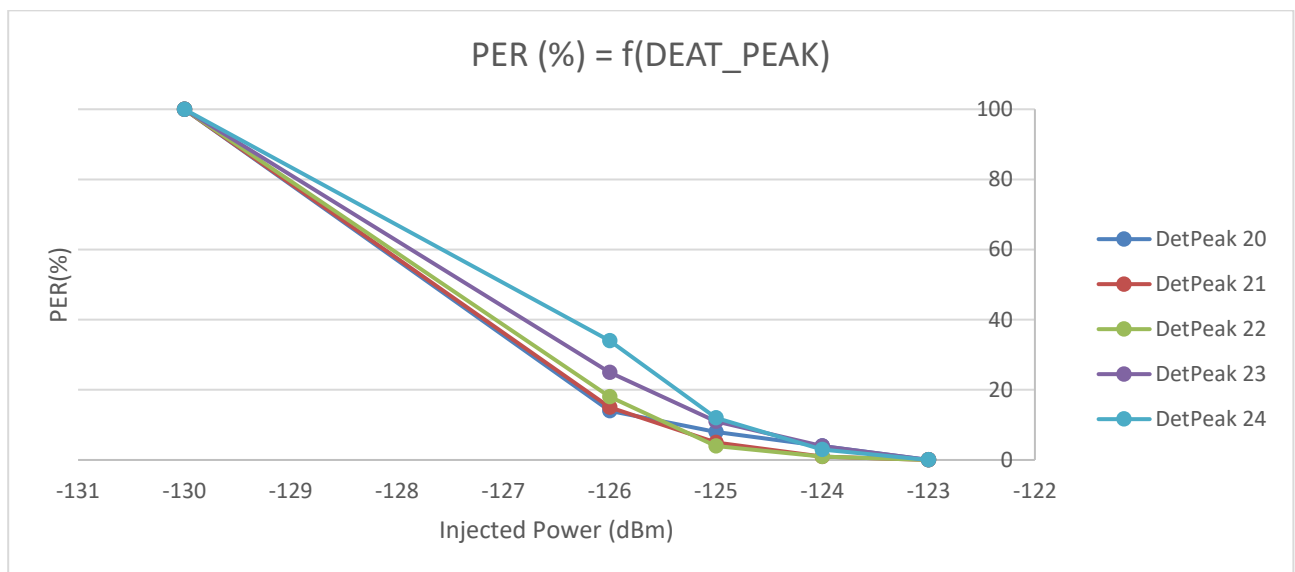
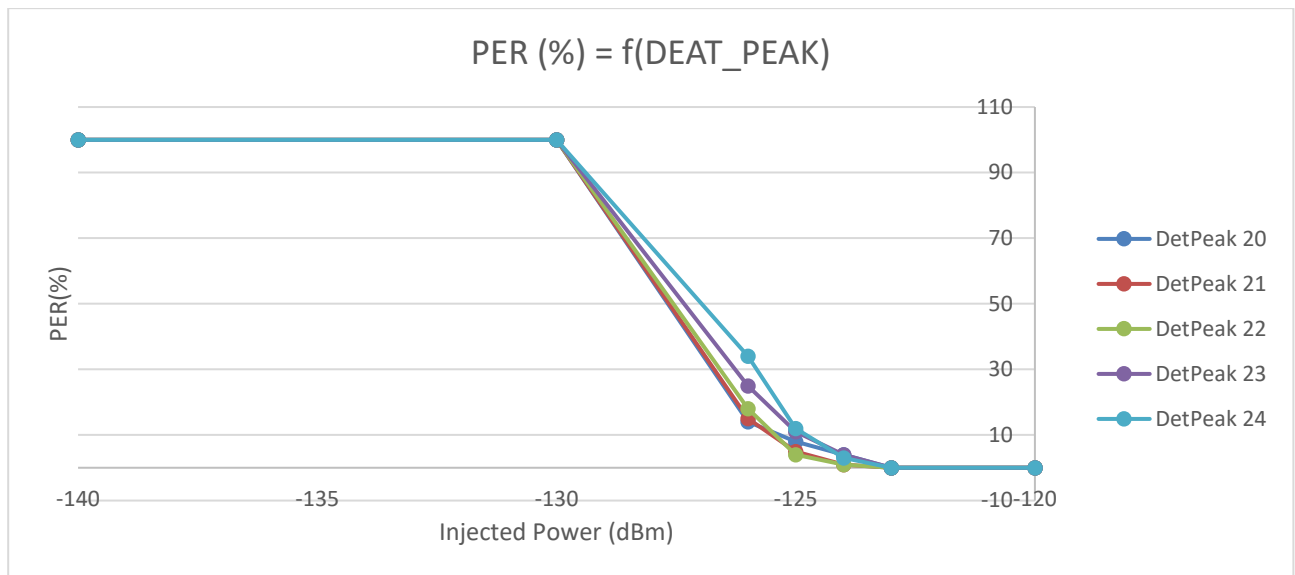


Figure 30: SF10 PER 4 Symbols vs. DetPeak

4.1.2.1.5 SF11

Here are the details for SF11, 4 symbols are necessary to have a good performance without false detection, LoRa Settings: SF10 | BW = 500 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)									
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28
0	100	100	100	100	100	100	100	100	100
-40	100	100	100	100	100	100	100	100	100
-110	100	100	100	100	100	100	100	100	100
-120	100	100	100	100	100	100	100	100	100
-125	100	99	100	99	100	100	98	99	96
-126	100	100	100	98	98	96	95	89	88
-127	99	100	99	99	99	93	85	66	69
-128	99	100	99	96	87	85	65	47	36
-130	99	100	94	80	65	50	28	9	8
-180	0	0	0	0	0	0	0	0	0

Table 61: SF11 CAD Rx(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)									
Power (dBm)	DetPeak k 20	DetPeak k 21	DetPeak k 22	DetPeak k 23	DetPeak k 24	DetPeak 25	DetPeak k 26	DetPeak k 27	DetPeak k 28
0	0	0	0	0	0	0	0	0	0
-40	0	0	0	0	0	0	0	0	0
-110	0	0	0	0	0	0	0	0	0
-120	0	0	0	0	0	0	0	0	0
-125	0	1	0	1	0	0	2	1	4
-126	3	1	0	2	4	4	5	11	13
-127	6	1	2	3	5	8	17	37	32
-128	16	9	16	11	21	24	37	59	68
-130	63	57	69	71	72	79	86	99	97
-180	100	100	100	100	100	100	100	100	100

Table 62: SF11 PER(%) = f(CAD_SYMBOL_04 cadDetPeak_n)

SF11, 4/5, 500 KHz 4 Symbols, CadDetPeak =25, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-120	100	0
-125	100	0
-126	96	4
-127	93	8
-128	85	24
-130	50	79
-180	0	100

Table 63: SF11 Best Setting 4 Symbols

In order to validate these best settings for sensitivity, here is a 10% PER test, performing the same sequence than previously but 10000 time instead of 100:

CAD SYMBOL = LORA_CAD_04_SYMBOL Det_Peak = 25 Det_Min = 10					
RX input level [dBm]	Nb Try	CAD [%]	RX OK [%]	PER (%)	False detect (%)
-126	10000	9819	9788	2.1	0.16

Table 64: SF11 Best Settings PER 10%

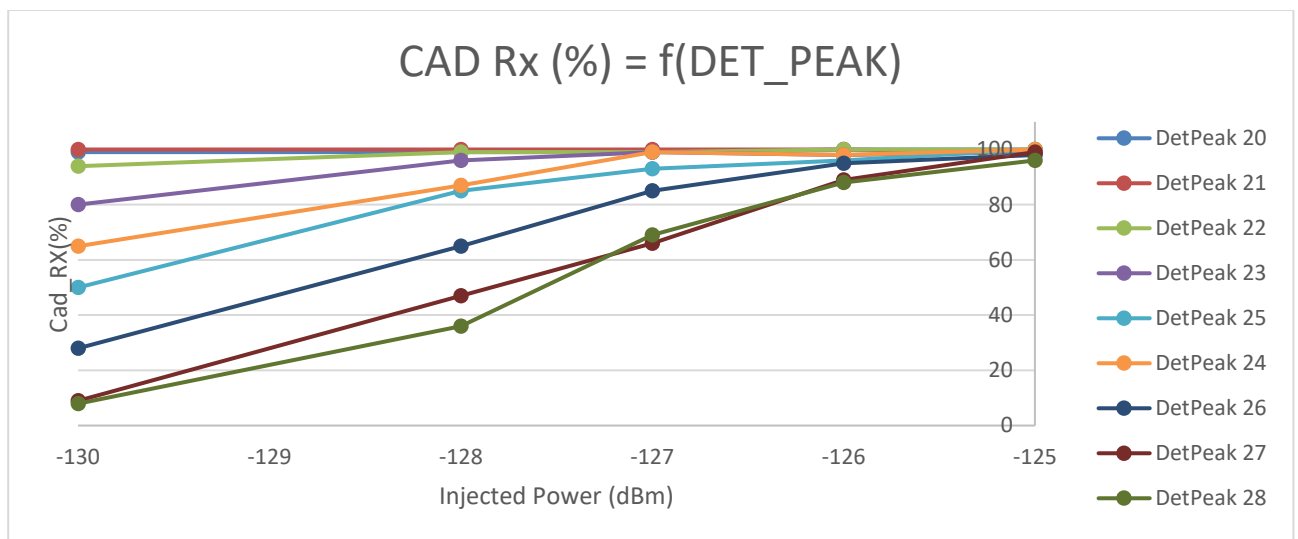
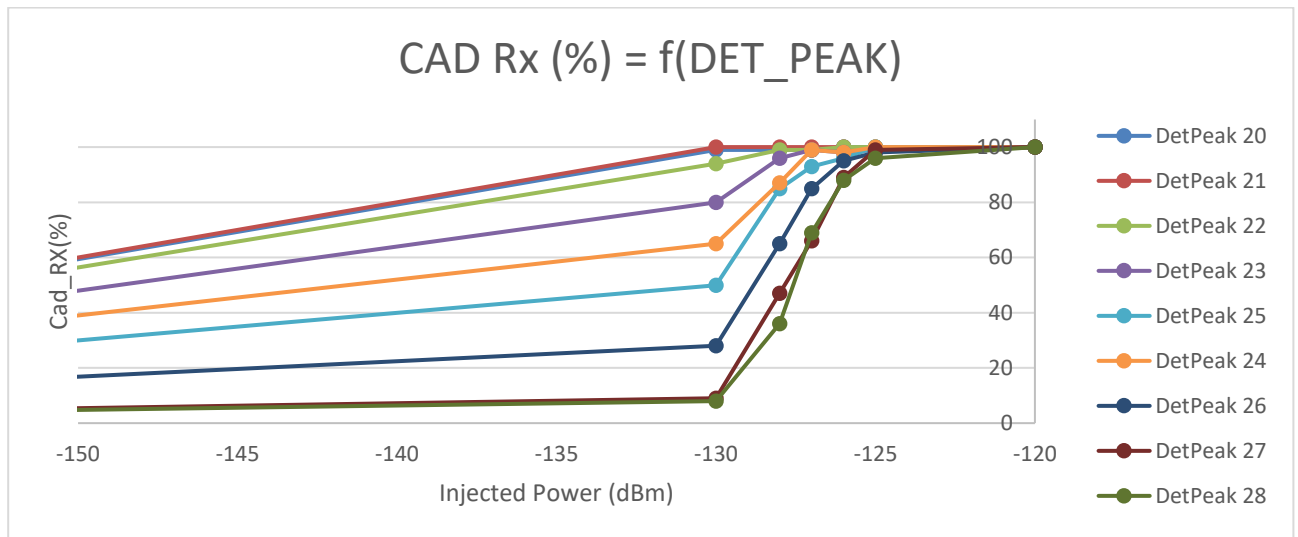


Figure 31: SF11 CAD 4 Symbols vs. DetPeak

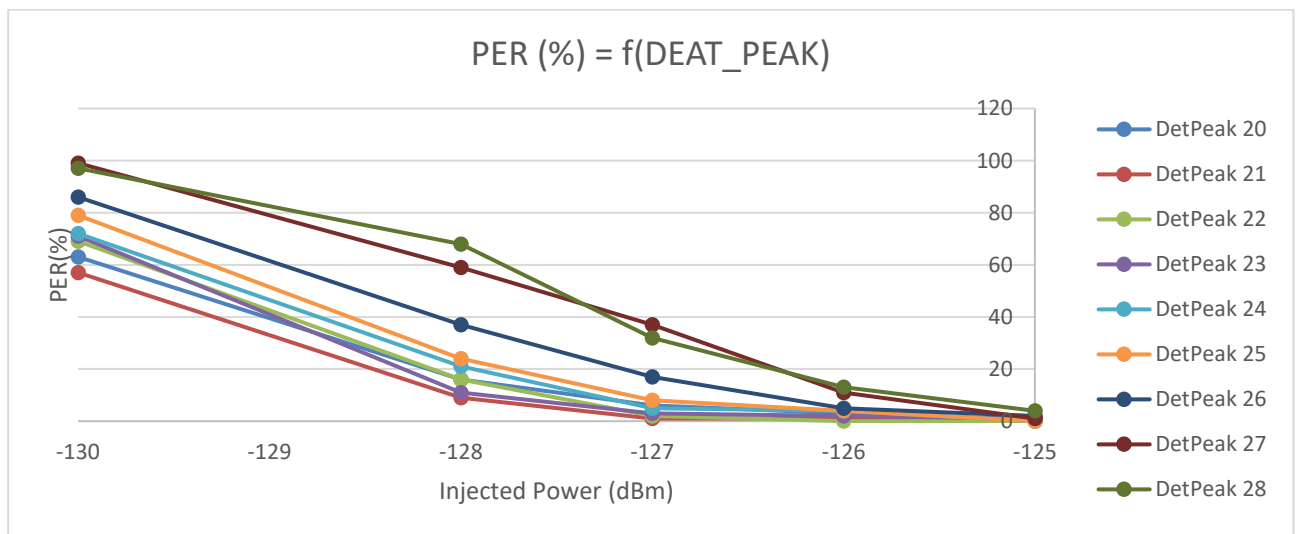
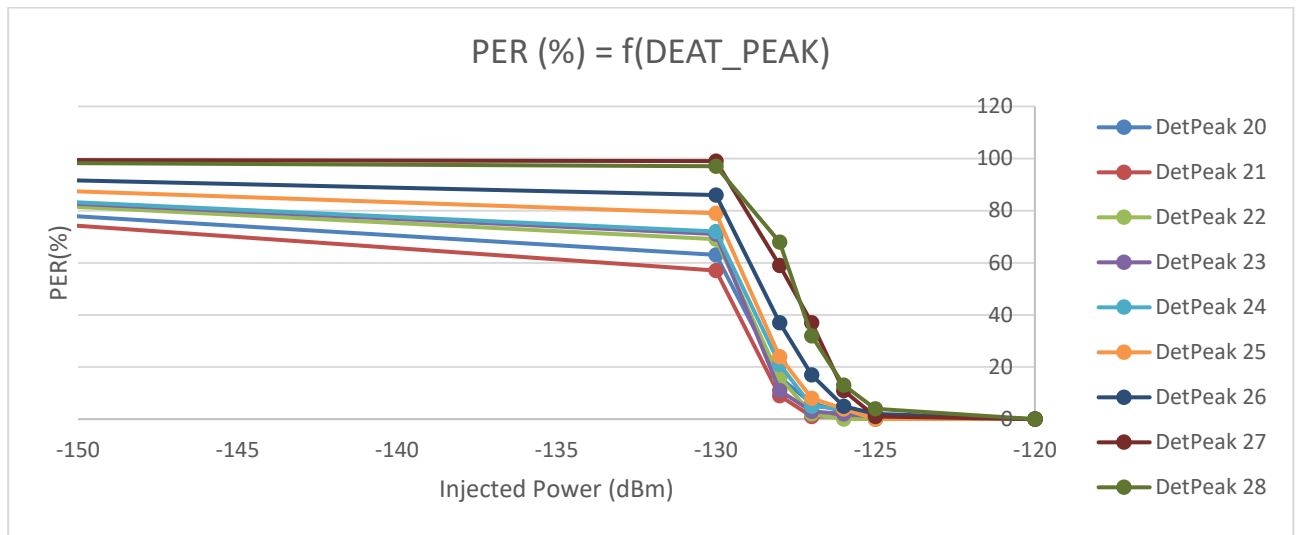


Figure 32: SF11 CAD 4 Symbols vs. DetPeak

4.1.2.1.6 SF12

Here are the details for SF12, 8 symbols are necessary to have a good performance without false detection, LoRa Settings: SF12 | BW = 500 KHz | CR=4/5 | cadDetMin = 10.

CAD Rx(%) = f(CAD_SYMBOL_08 DetPeak_n)							
Power (dBm)	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28	DetPeak 29	DetPeak 30	DetPeak 31
-50	100	100	100	100	100	100	100
-110	100	100	100	100	100	100	100
-125	100	100	100	100	100	100	100
-127	100	100	100	100	100	100	100
-128	100	100	100	100	100	99	99
-129	99	100	100	99	97	92	96
-130	98	100	99	96	87	74	62
-131	92	98	93	71	46	33	14
-132	66	92	68	44	32	22	2
-134	3	53	15	0	2	0	0
-140	0	0	0	0	0	0	0

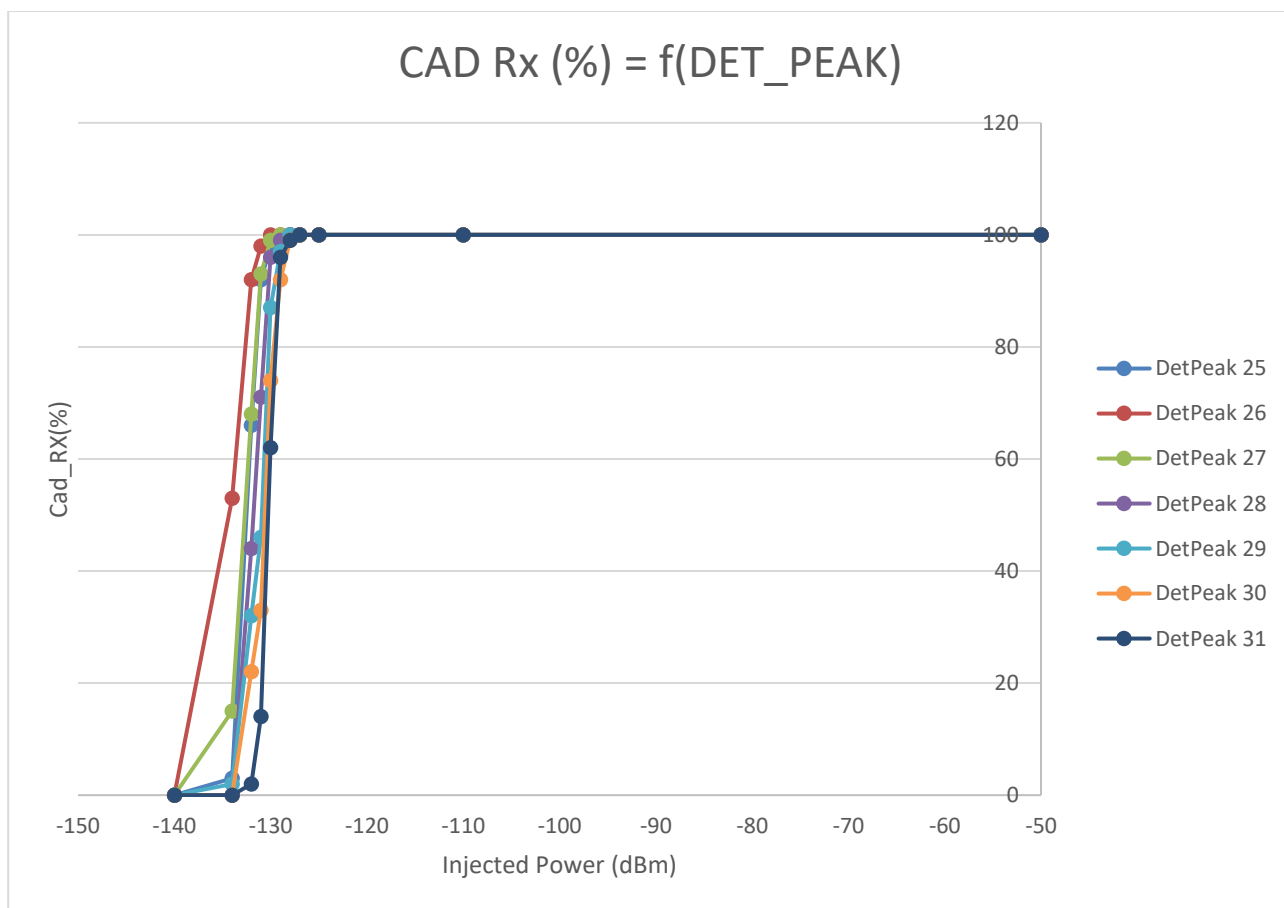
Table 65: SF12 CAD Rx(%) = f(CAD_SYMBOL_o8 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_08 DetPeak_n)							
Power (dBm)	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28	DetPeak 29	DetPeak 30	DetPeak 31
-50	0	0	0	0	0	0	0
-110	0	0	0	0	0	0	0
-125	0	0	0	0	0	0	0
-127	0	0	0	0	0	0	0
-128	0	0	0	0	0	1	1
-129	1	0	0	1	3	8	5
-130	2	1	3	5	14	27	40
-131	8	8	10	33	55	70	87
-132	34	34	61	75	80	85	98
-134	97	99	100	100	100	100	100
-140	100	100	100	100	100	100	100

Table 66: SF12 PER(%) = f(CAD_SYMBOL_o8 cadDetPeak_n)

SF12, 865MHz, 4/5, 500KHz 8 Symbols, CadDetPeak =28, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-50	100	0
-110	100	0
-125	100	0
-127	100	0
-128	100	0
-129	99	1
-130	96	5
-131	71	33
-132	44	75
-134	0	100
-140	0	100

Table 67: SF12 Best Setting 8 Symbols



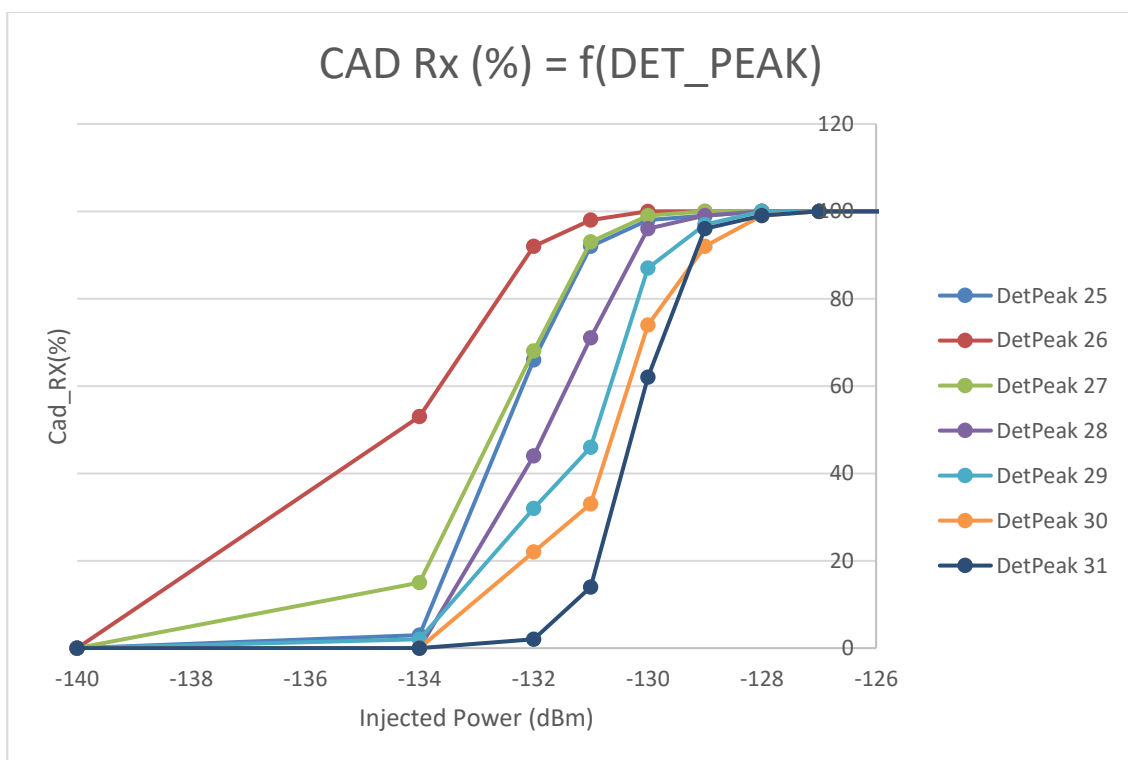
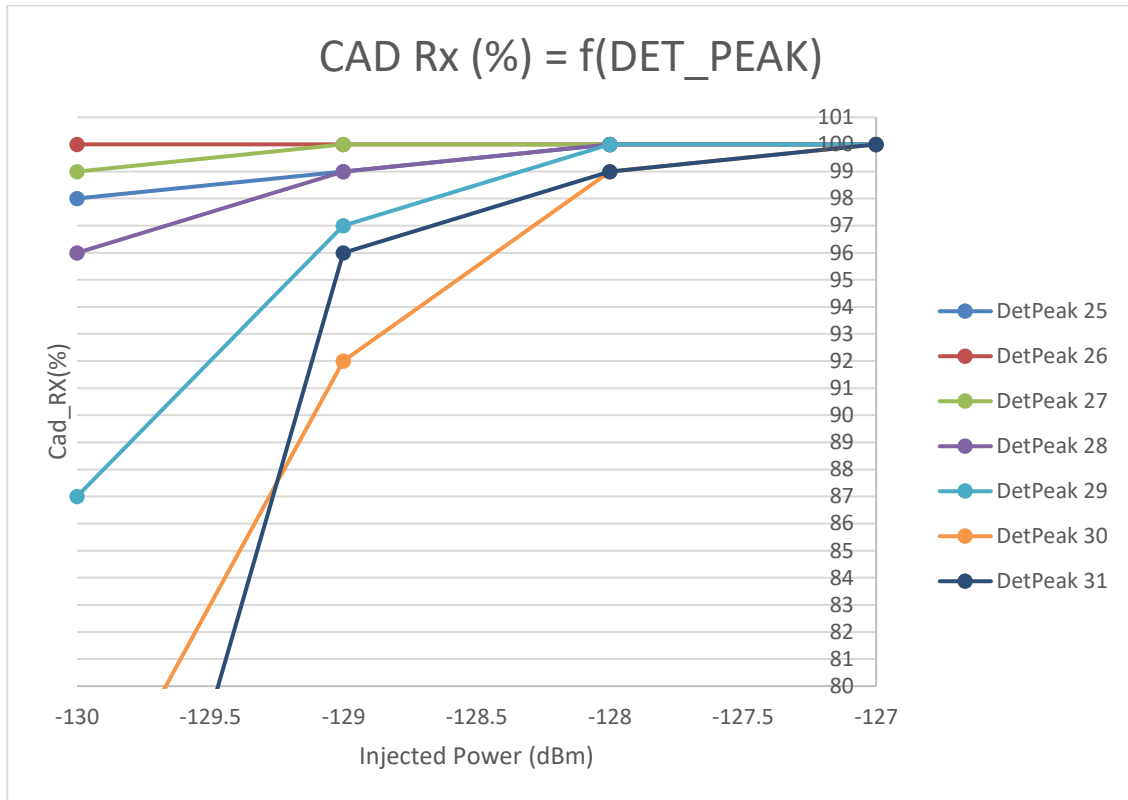
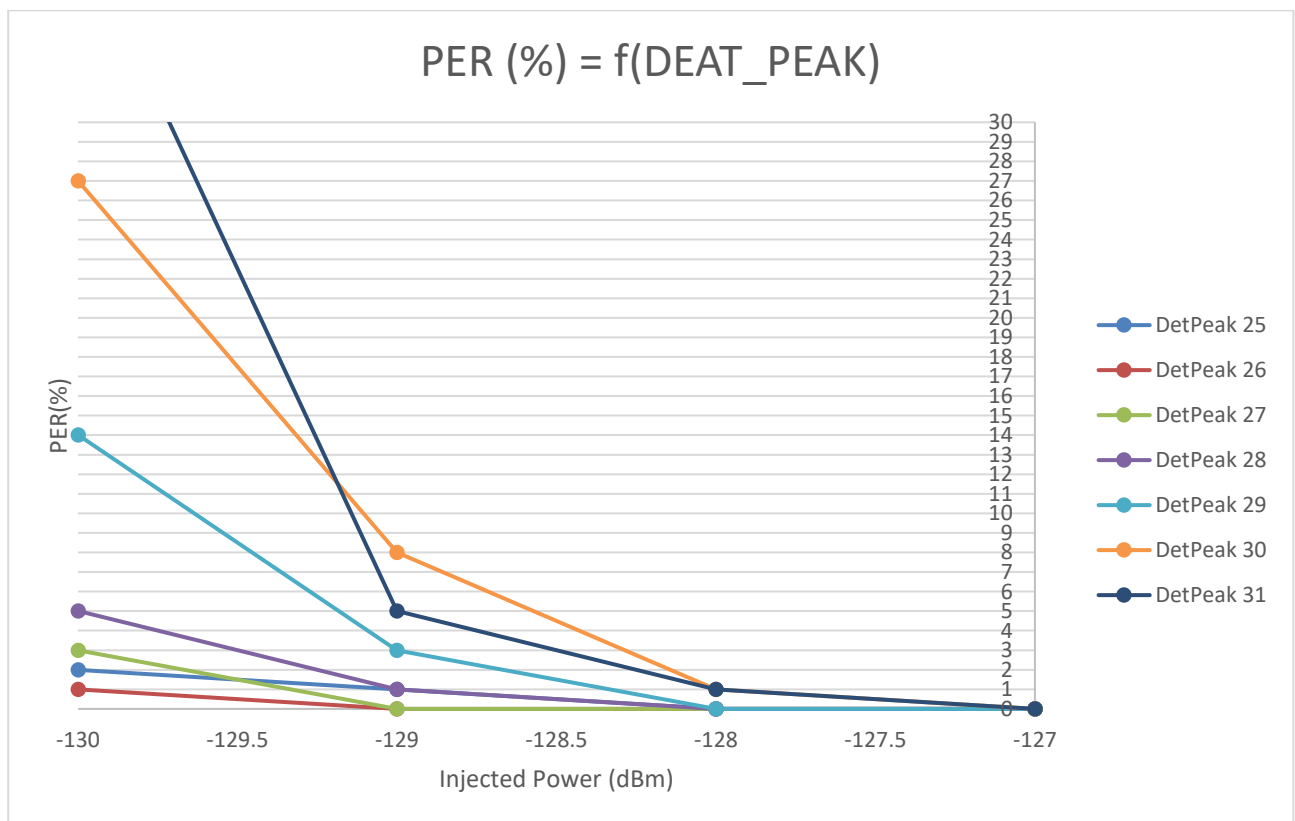
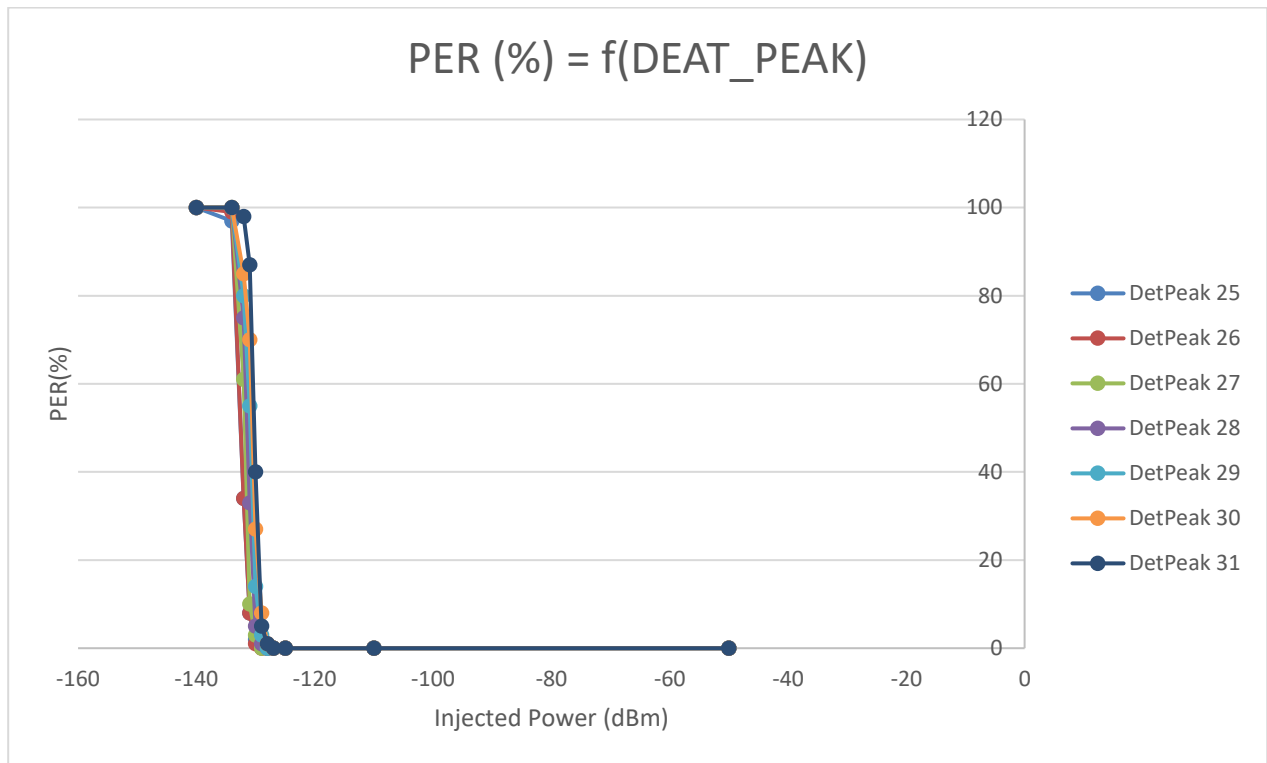


Figure 33 SF12 CAD 8 Symbols vs. DetPeak



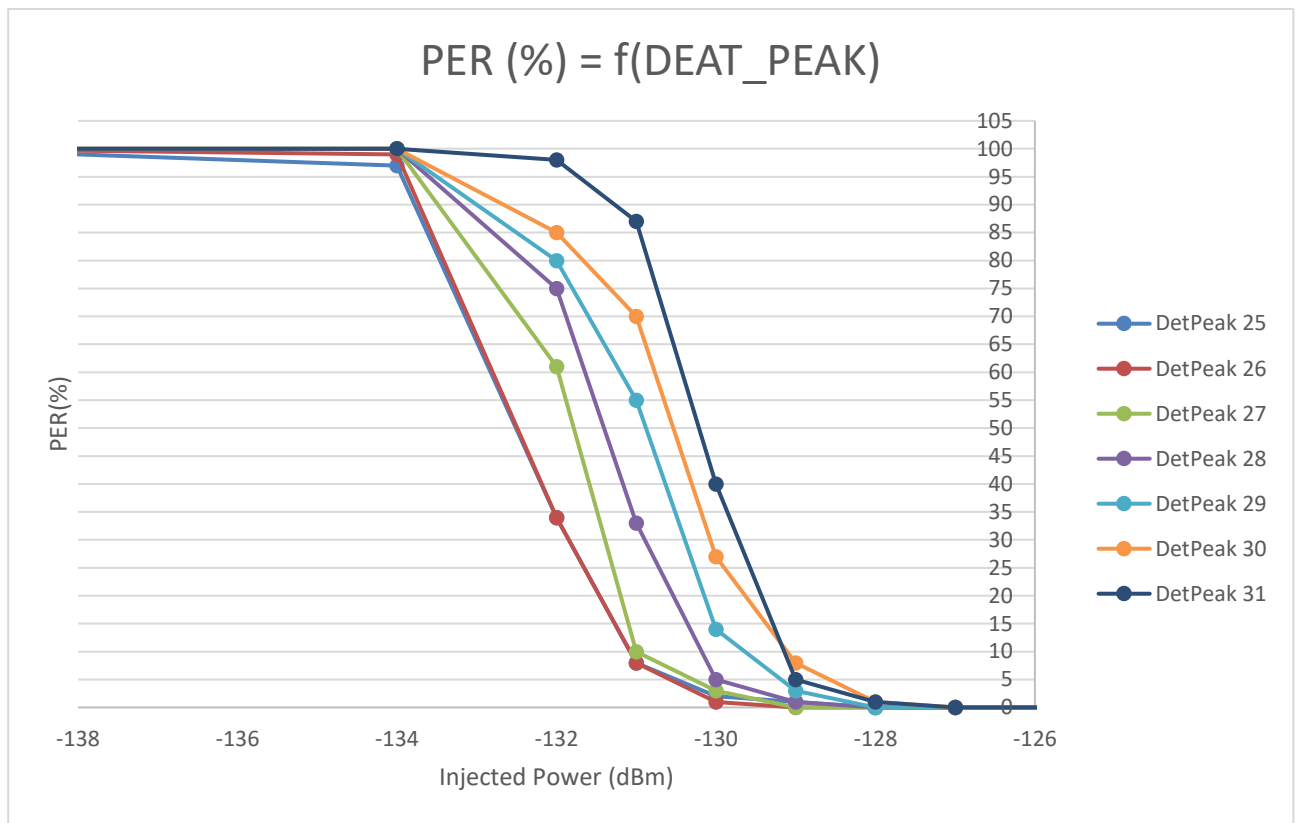


Figure 34 PER 8 Symbols vs. DetPeak

4.1.2.2 Best Settings Using 2 Symbols

The consumption is a really important criterion, so here it is the best settings using only 2 Symbols.

Spreading Factor	Best CAD settings			CAD consumption (nAh)
	<i>cadDetMin</i>	<i>cadDetPeak</i>	<i>cadSymbolNum</i>	
SF7	10	22	2 Symbols	2.84
SF8	10	22	2 Symbols	5.75
SF9	10	24	2 Symbols	11.7
SF10	10	25	2 Symbols	23.86
SF11	10	26	2 Symbols	48.79

Table 68: CAD/PER Best Settings

4.1.2.2.1 SF7

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-113	95	97	97	86	86
-114	91	95	90	82	72
-115	84	80	78	75	61
-116	72	67	64	48	46
-117	68	59	48	37	36
-118	51	49	39	20	21
-120	28	19	15	7	2
-130	4	0	0	0	0
-140	0	0	0	0	0
OFF	0	0	0	0	0

Table 6g: SF7 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-113	5	3	3	14	14
-114	9	5	10	18	28
-115	17	20	22	26	39
-116	29	33	36	52	54
-117	33	42	54	64	64
-118	56	57	67	83	83
-120	91	98	97	100	100
-130	100	100	100	100	100
-140	100	100	100	100	100
OFF	100	100	100	100	100

Table 70: SF7 PER (%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF9, 860MHz, 4/5, 125 KHz 2 Symbols, CadDetPeak =2, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-113	100	1
-114	96	4
-115	65	37
-116	37	87
-117	0	100
-118	2	100
-120	0	100
-130	0	100
-140	0	100
OFF	0	100

Table 71: SF7 Best Setting 2 Symbols

Compare to the "perfect" setting the performance is slightly degraded, PER < 10% is now achieved at -113dBm instead of -115dBm but the false detection rate is still quite good.

	2 Symbols, CadDetPeak =22, CadDetMin=10		4 Symbols, CadDetPeak =21, CadDetMin=10	
Power (dBm)	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
0	100	0	100	0
-40	100	0	100	0
-110	100	0	100	0
-113	97	3	100	0
-114	90	10	100	0
-115	78	22	97	3
-116	64	36	90	10
-117	48	54	80	26
-118	39	67	65	46
-120	15	97	17	96
-130	0	100	0	100
-140	0	100	0	100
OFF	0	100	0	100

Table 72: SF7 2 Symbols vs. Best settings

4.1.2.2.2 SF8

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-116	96	96	93	91	88
-117	96	92	91	83	84
-118	89	89	83	75	69
-119	77	81	72	65	63
-120	78	73	52	49	33
-121	70	52	58	31	24
-123	54	37	19	8	10
-125	41	14	9	4	2
-130	23	7	7	0	1
-140	20	12	2	0	0
-180	0	0	0	0	0

Table 73: SF8 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-116	4	4	7	9	12
-117	4	8	9	17	16
-118	12	11	17	25	31
-119	24	20	31	36	37
-120	28	32	50	52	70
-121	48	59	70	80	81
-123	96	95	98	99	100
-125	100	100	100	100	100
-130	100	100	100	100	100
-140	100	100	100	100	100
OFF	100	100	100	100	100

Table 74: SF8 PER (%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF8, 4/5, 500 KHz 2 Symbols, CadDetPeak =21, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-116	96	4
-117	92	8
-118	89	11
-119	81	20
-120	73	32
-121	52	59
-123	37	95
-125	14	100
-130	7	100
-140	12	100
OFF	0	100

Table 75: SF8 Best Setting 2 Symbols

Compare to the “perfect” setting the performance is slightly degraded, PER < 10% is now achieved at -116dBm instead of -118dBm but the false detection rate is still quite good.

Power (dBm)	2 Symbols, CadDetPeak =21, CadDetMin=10		4 Symbols, CadDetPeak =22, CadDetMin=10	
	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
0	100	0	100	0
-40	100	0	100	0
-110	100	0	100	0
-116	96	4	100	0
-117	92	8	100	0
-118	89	11	99	1
-119	81	20	89	12
-120	73	32	82	21
-121	52	59	64	51
-123	37	95	26	98
-125	14	100	8	100
-130	7	100	5	100
-140	12	100	2	100
OFF	0	100	0	100

Table 76: SF8 2 Symbols vs. Best settings

4.1.2.2.3 SF9

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-120	100	96	93	96	86
-121	96	95	90	85	82
-122	92	84	75	79	58
-123	88	70	70	62	39
-125	73	67	45	22	25
-130	57	34	27	11	2
-140	49	28	16	6	2
-180	0	0	0	0	0

Table 77: SF9 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	1	0	0	0	0
-120	1	4	7	4	14
-121	4	5	10	16	18
-122	9	16	27	22	43
-123	18	35	35	45	63
-125	81	76	85	94	94
-130	100	100	100	100	100
-140	100	100	100	100	100
-180	0	0	0	0	0

Table 78: SF9 PER (%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF9, 4/5, 500 KHz 2 Symbols, CadDetPeak =21, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-120	96	4
-121	95	8
-122	84	11
-123	70	20
-125	67	32
-130	34	59
-140	28	95
-180	0	100

Table 79: SF9 Best Setting 2 Symbols

Compare to the “perfect” setting the performance is slightly degraded, PER < 10% is now achieved at -120dBm instead of -122dBm but the false detection rate is still quite good.

Power (dBm)	2 Symbols, CadDetPeak =21, CadDetMin=10		4 Symbols, CadDetPeak =22, CadDetMin=10	
	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
0	100	0	100	0
-40	100	0	100	0
-110	100	0	100	0
-120	96	4	100	0
-121	95	8	99	1
-122	84	11	95	6
-123	70	20	91	15
-125	67	32	64	84
-130	34	59	25	100
-140	28	95	20	100
OFF	0	100	0	100

Table 80: SF9 2 Symbols vs. Best settings

4.1.2.2.4 SF10

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	100	100	100	100	100
-40	100	100	100	100	100
-110	100	100	100	100	100
-120	100	100	100	100	100
-123	99	98	96	98	93
-124	99	98	98	94	85
-125	98	98	90	75	74
-126	96	96	84	76	55
-130	85	79	54	28	22
-140	74	59	44	24	18
-180	0	0	0	0	0

Table 81: SF10 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)					
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24
0	0	0	0	0	0
-40	0	0	0	0	0
-110	0	0	0	0	0
-120	0	0	0	0	0
-123	2	3	4	2	7
-124	1	2	5	6	15
-125	9	9	13	25	30
-126	18	14	28	33	56
-130	98	100	100	100	100
-140	100	100	100	100	100
-180	100	100	100	100	100

Table 82: SF10 PER (%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF10, 4/5, 500 KHz 2 Symbols, CadDetPeak =23, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-120	100	0
-123	98	2
-124	94	6
-125	75	25
-126	76	33
-130	28	100
-140	24	100
-180	0	100

Table 83: SF10 Best Setting 2 Symbols

Compare to the “perfect” setting the performance is slightly degraded, PER < 10% is now achieved at -124dBm instead of -125dBm but the false detection rate is still quite good.

Power (dBm)	2 Symbols, CadDetPeak =23, CadDetMin=10		4 Symbols, CadDetPeak =22, CadDetMin=10	
	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
0	100	0	100	0
-40	100	0	100	0
-110	100	0	100	0
-120	100	0	100	0
-123	98	2	100	0
-124	94	6	99	1
-125	75	25	100	4
-126	76	33	99	18
-130	28	100	78	100
-140	24	100	63	100
-180	0	100	0	100

Table 84: SF10 2 Symbols vs. Best settings

4.1.2.2.5 SF11

CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)									
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28
0	100	100	100	100	100	100	100	100	100
-40	100	100	100	100	100	100	100	100	100
-110	100	100	100	100	100	100	100	100	100
-120	100	100	100	100	100	100	100	100	100
-125	99	99	96	95	97	90	91	75	69
-126	99	95	94	88	87	83	82	72	58
-127	96	92	91	86	77	72	63	59	50
-128	95	86	85	78	68	63	42	35	30
-130	93	87	71	59	50	27	32	21	7
-180	0	0	0	0	0	0	0	0	0

Table 85: SF11 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 cadDetPeak_n)									
Power (dBm)	DetPeak 20	DetPeak 21	DetPeak 22	DetPeak 23	DetPeak 24	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28
0	0	0	0	0	0	0	0	0	0
-40	0	0	0	0	0	0	0	0	0
-110	0	0	0	0	0	0	0	0	0
-120	0	0	0	0	0	0	0	0	0
-125	1	1	4	5	3	10	9	25	31
-126	3	6	7	12	14	18	18	28	42
-127	6	12	12	15	24	30	38	44	53
-128	8	21	25	31	39	41	64	69	75
-130	56	62	72	74	75	90	86	95	96
-180	100	100	100	100	100	100	100	100	100

Table 86: SF11 PER (%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF11, 4/5, 500 KHz 2 Symbols, CadDetPeak =24, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
0	100	0
-40	100	0
-110	100	0
-120	100	0
-125	97	3
-126	87	14
-127	77	24
-128	68	39
-130	50	75
-180	0	100

Table 87: SF11 Best Setting 2 Symbols

Compare to the “perfect” setting the performance is slightly degraded, PER < 10% is now achieved at -125dBm instead of -126dBm but the false detection rate is still quite good.

Power (dBm)	2 Symbols, CadDetPeak =24, CadDetMin=10		4 Symbols, CadDetPeak =25, CadDetMin=10	
	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
0	100	0	100	0
-40	100	0	100	0
-110	100	0	100	0
-120	100	0	100	0
-125	97	3	100	0
-126	87	14	96	4
-127	77	24	93	8
-128	68	39	85	24
-130	50	75	50	79
-180	0	100	0	100

Table 88: SF11 2 Symbols vs. Best settings

4.1.2.2.6 SF12

CAD Rx(%) = f(CAD_SYMBOL_02 DetPeak_n)							
Power (dBm)	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28	DetPeak 29	DetPeak 30	DetPeak 31
-50	100	100	100	100	100	100	100
-110	100	100	100	100	100	100	100
-125	100	100	100	100	100	100	100
-127	99	100	95	99	98	89	93
-128	97	97	91	94	87	88	82
-129	91	87	85	85	80	70	63
-130	85	76	77	66	55	47	50
-131	72	64	60	40	30	26	16
-132	70	57	45	47	31	25	15
-134	89	84	79	63	29	26	20
-140	0	0	0	0	0	0	0

Table 8g: SF12 CAD Rx(%) = f(CAD_SYMBOL_02 cadDetPeak_n)

PER(%) = f(CAD_SYMBOL_02 DetPeak_n)							
Power (dBm)	DetPeak 25	DetPeak 26	DetPeak 27	DetPeak 28	DetPeak 29	DetPeak 30	DetPeak 31
-50	0	0	0	0	0	0	0
-110	0	0	0	0	0	0	0
-125	0	0	0	0	0	0	0
-127	1	0	5	1	2	11	3
-128	3	3	9	6	13	12	9
-129	9	13	15	15	20	30	17
-130	15	29	23	37	47	53	56
-131	35	41	48	63	72	75	85
-132	58	65	68	75	78	83	93
-134	99	98	99	99	100	100	100
-140	100	100	100	100	100	100	100

Table 90: SF12 PER (%) = f(CAD_SYMBOL_02 cadDetPeak_n)

SF11, 4/5, 500 KHz 2 Symbols, CadDetPeak =24, CadDetMin=10		
Power (dBm)	Cad Detected (%)	PER (%)
-50	100	0
-110	100	0
-125	100	0
-127	93	3
-128	82	9
-129	63	17
-130	50	56
-131	16	85
-132	15	93
-134	20	100
-140	0	100

Table g1: SF12 Best Setting 2 Symbols

Compare to the "perfect" setting the performance is slightly degraded, PER < 10% is now achieved at -125dBm instead of -126dBm but the false detection rate is still quite good.

Power (dBm)	2 Symbols, CadDetPeak =31, CadDetMin=10		8 Symbols, CadDetPeak =29, CadDetMin=10	
	Cad Detected (%)	PER (%)	Cad Detected (%)	PER (%)
-50	100	0	100	0
-110	100	0	100	0
-125	100	0	100	0
-127	93	3	100	0
-128	82	9	100	0
-129	63	17	99	1
-130	50	56	96	5
-131	16	85	71	33
-132	15	93	44	75
-134	20	100	0	100
-140	0	100	0	100

Table g2: SF9 2 Symbols vs. Best settings

4.1.3 CAD & PER Conclusion

Looking at the different test results, we can see that an increase of the *cadDetPeak* value will reduce the number of false detections, as well as the CAD sensitivity. It means *cadDetPeak* should be changed with caution to avoid deteriorating the receiver performance. It is advised to change *cadDetPeak* by steps of 1.

For each spreading factor, a combination of *cadDetPeak/cadDetMin* and *cadSymbolNum* is defined with good PER and low false detection.

Notes:

1. On the SX126X family, the CAD detects reliably not only on preambles but also modulated data (header and payload). Therefore, in the tests presented in the document, a small fraction of the PER is certainly due to a late preamble detection, or detection over modulated data, which therefore represents a worse case PER scenario.
2. The CAD over 1 symbol is very prone to false detection, leading to bad PER. It is therefore not recommended to use this setting
3. For 500 KHz bandwidth, the CAD over 2 symbol affects sensitivity leading to bad PER but on the other hand it has less energy consumption for higher spreading factors, system current consumption should be carefully looked into to save energy. Hence it is always a tradeoff between sensitivity and current consumption while selecting CAD over 2 symbol or 4 or 8 symbols.

4.2 Consumption

A really important facet of CAD is its energy consumption, as it is typically used in very low-power applications. The current is measured using a shunt as following:

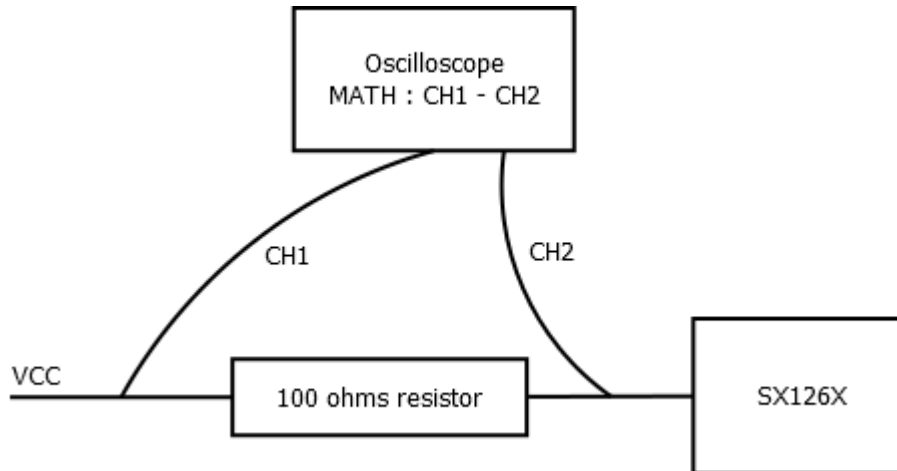


Figure 35: Current Measurement

4.2.1 Bandwidth 125KHz

Below is tabulated the energy consumption data for each spreading factor, depending on *cadSymbolNum* for Bandwidth 125KHz:

SF7 BW125 KHz							
NbSymbol	Cad Time measured (ms)	Cad Time measured (Symbols)	Cad Time Theoretical (ms)	Thoery/ Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	1.6439	1.61	1.024	0.62	378.13	3.78	1.73
2	2.6641	2.60	2.048	0.77	384.38	3.84	2.84
4	4.7155	4.60	4.096	0.87	384.38	3.84	5.03
8	8.8088	8.60	8.192	0.93	384.38	3.84	9.41
16	17.01	16.61	16.384	0.96	384.38	3.84	18.16

Table 93: SF7 BW125 KHz Energy Consumption Data

Here it the consumption profile of a 2-symbol CAD, SF7 BW125 KHz KHz:

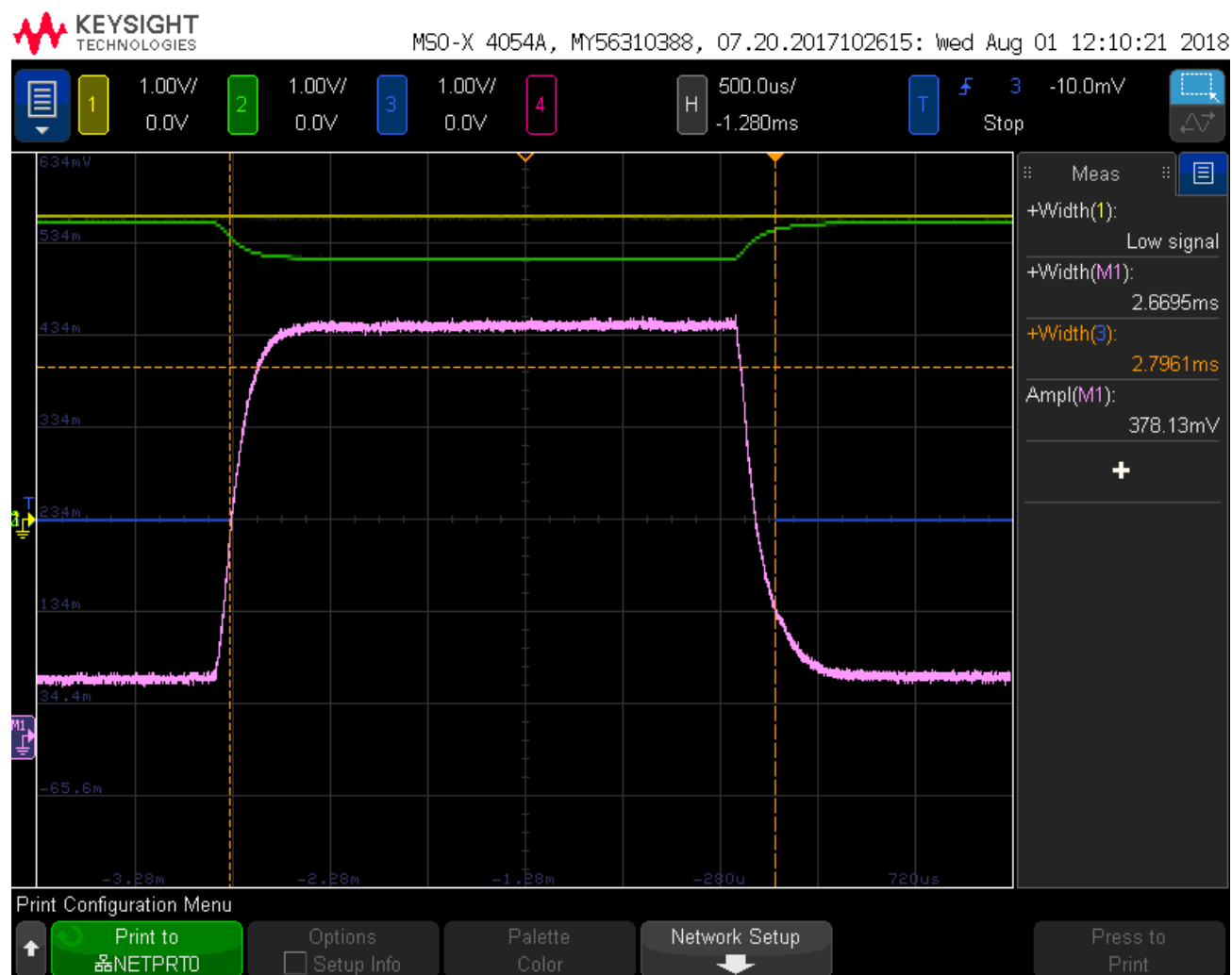


Table 94: CAD 2 Symbols SF7 BW125 KHz KHz consumption prof

SF8 BW125 KHz							
NbSymbol	Measured Consumption (ms)	Cad Time measured (Symbols)	Cad Time Theoretical (Symbols)	Thoery/Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	3.3384	1.63	2.048	0.61	384.38	3.84	3.56
2	5.3872	2.63	4.096	0.76	384.38	3.84	5.75
4	9.4806	4.63	8.192	0.86	384.38	3.84	10.12
8	17.676	8.63	16.384	0.93	384.38	3.84	18.87
16	34.057	16.63	32.768	0.96	384.38	3.84	36.36

Table 95: SF8 BW125 KHz Energy Consumption Data

	SF9 BW125 KHz						
NbSymbol	Measured Consumption (ms)	Cad Time measured (Symbols)	Theoretical (ms)	Thoery/Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	6.8625	1.68	4.096	0.60	384.38	3.84	7.33
2	10.955	2.67	8.192	0.75	384.38	3.84	11.70
4	19.145	4.67	16.384	0.86	384.38	3.84	20.44
8	35.531	8.67	32.768	0.92	384.38	3.84	37.94
16	68.29	16.67	65.536	0.96	384.38	3.84	72.91

Table 96: SF9 BW125 KHz Energy Consumption Data

	SF10 BW125 KHz						
NbSymbol	Measured Consumption (ms)	Cad Time measured (Symbols)	Theoretical (ms)	Thoery/Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	14.156	1.73	8.192	0.58	384.38	3.84	15.11
2	22.345	2.73	16.384	0.73	384.38	3.84	23.86
4	38.732	4.73	32.768	0.85	384.38	3.84	41.36
8	71.496	8.73	65.536	0.92	384.38	3.84	76.34
16	137.03	16.73	131.072	0.96	384.38	3.84	146.31

Table 97: SF10 BW125 KHz Energy Consumption Data

	SF11 BW125 KHz						
NbSymbol	Measured Consumption (ms)	Cad Time measured (Symbols)	Theoretical (ms)	Thoery/Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	29.26	1.79	16.384	0.56	384.38	3.84	31.24
2	45.64	2.79	32.768	0.72	384.38	3.84	48.73
4	78.409	4.79	65.536	0.84	384.38	3.84	83.72
8	143.95	8.79	131.072	0.91	384.38	3.84	153.70
16	275.02	16.79	262.144	0.95	384.38	3.84	293.64

Table 98: SF11 BW125 KHz Energy Consumption Data

SF12 BW125 KHz							
NbSymbol	Measured Consumption (ms)	Cad Time measured (Symbols)	Theorical (ms)		Ampl (mV)	I (mA)	Consumption (nAh)
1	60.493	1.85	32.768	0.54	384.38	3.84	64.59
2	93.256	2.85	65.536	0.70	384.38	3.84	99.57
4	158.79	4.85	131.072	0.83	384.38	3.84	169.54
8	289.87	8.85	262.144	0.90	384.38	3.84	309.50
16	552.01	16.85	524.288	0.95	384.38	3.84	589.39

Table 99 SF12 BW125 KHz Energy Consumption Data

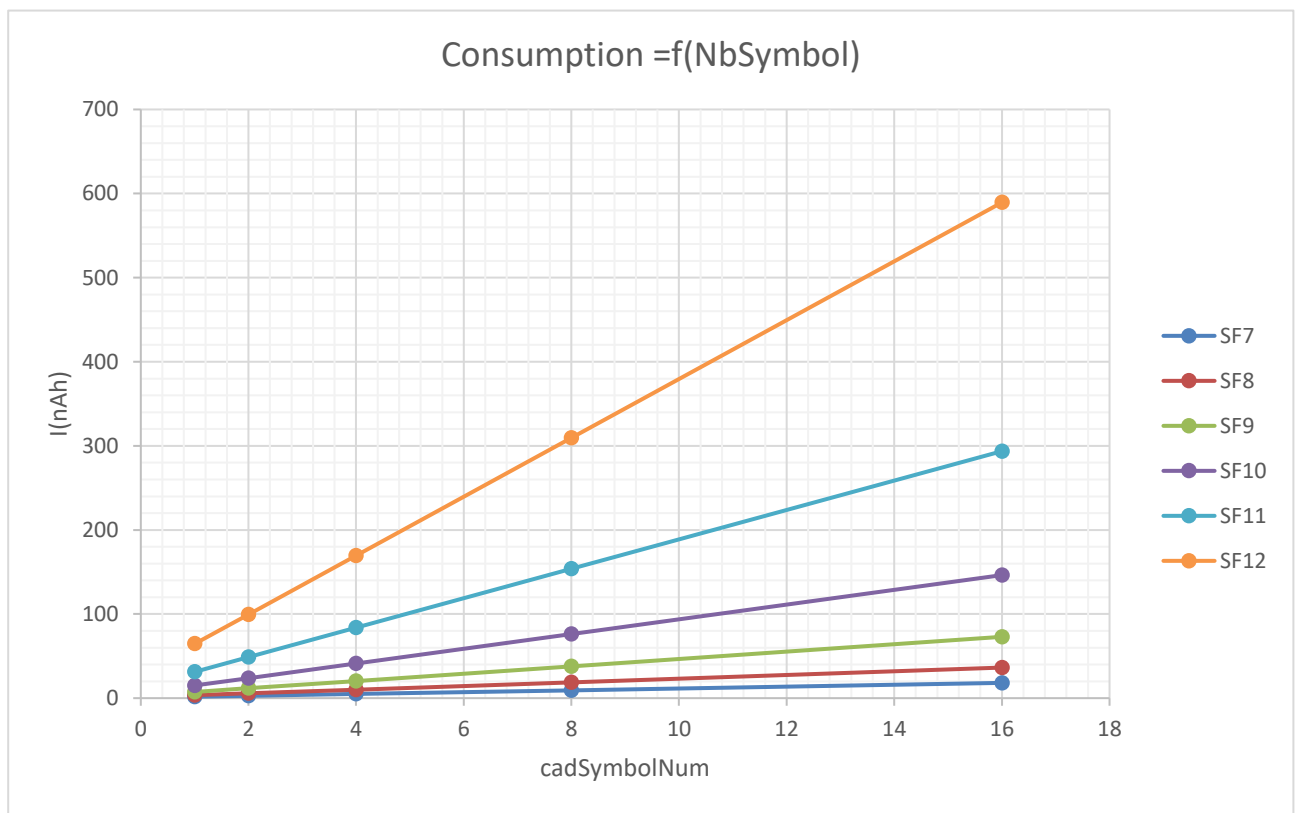


Figure 36: Consumption for Bandwidth 125 KHz = f(cadSymbolNum)

4.2.2 Bandwidth 500KHz

SF7 BW500 KHz							
NbSymbol	Cad Time measured (ms)	Cad Time measured (Symbols)	Cad Time Theoretical (ms)	Thoery/ Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	0.447	1.746	0.256	0.572	419.8	4.19	0.502
2	0.696	2.71	0.512	0.735	419.8	4.19	0.81
4	1.258	4.8	1.024	0.829	419.8	4.19	1.43
8	2.254	8.804	2.048	0.9086	419.8	4.19	2.62
16	4.274	16.69	4.096	0.958	419.8	4.19	4.97

Table 100: SF7 BW500 KHz Energy Consumption Data

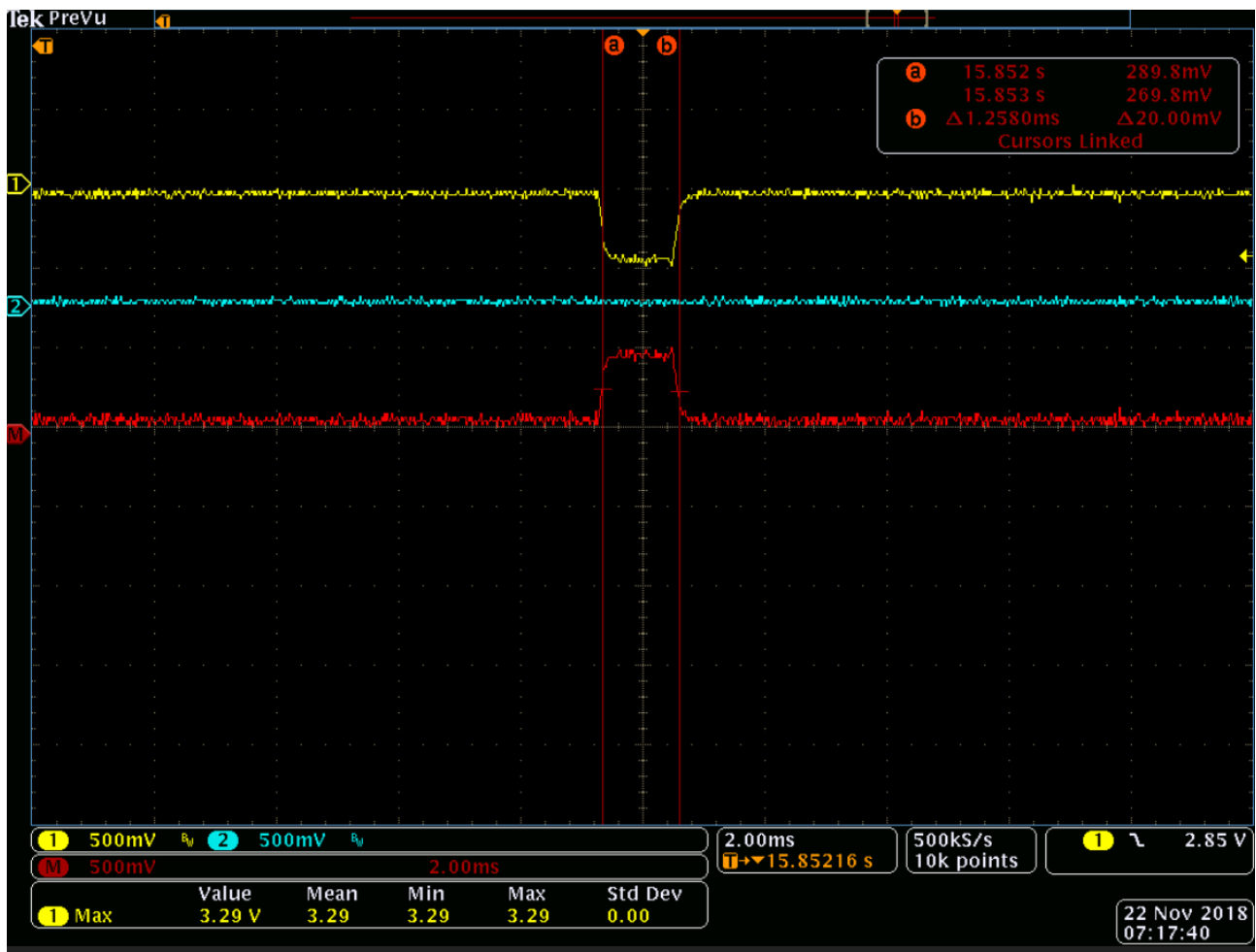


Table 101: CAD 4 Symbols SF7 BW500 KHz consumption

	SF8 BW500 KHz						
NbSymbol	Cad Time measured (ms)	Cad Time measured (Symbols)	Cad Time Theoretical (ms)	Thoery/ Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	0.874	1.707	0.512	0.5858	419.8	4.19	1.017
2	1.476	2.88	1.024	0.693	419.8	4.19	1.71
4	2.474	4.832	2.048	0.83	419.8	4.19	2.87
8	4.496	8.78	4.096	0.911	419.8	4.19	5.2
16	8.596	16.78	8.192	0.953	419.8	4.19	10

Table 102: SF8 BW500 KHz Energy Consumption Data

	SF9 BW500 KHz						
NbSymbol	Cad Time measured (ms)	Cad Time measured (Symbols)	Cad Time Theoretical (ms)	Thoery/ Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	1.772	1.73	1.024	0.577	419.8	4.19	20.6
2	2.812	2.74	2.048	0.728	419.8	4.19	3.27
4	4.892	4.77	4.096	0.837	419.8	4.19	5.69
8	8.926	8.716	8.192	0.917	419.8	4.19	10.38
16	17.23	16.82	16.384	0.95	419.8	4.19	20.05

Table 103: SF9 BW500 KHz Energy Consumption Data

	SF10 BW500 KHz						
NbSymbol	Cad Time measured (ms)	Cad Time measured (Symbols)	Cad Time Theoretical (ms)	Thoery/ Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	3.58	7.33	2.048	0.572	419.8	4.19	4.16
2	5.62	11.5	4.096	0.728	419.8	4.19	6.5
4	9.76	19.99	8.192	0.83	419.8	4.19	11.3
8	17.92	36.7	16.384	0.914	419.8	4.19	20.85
16	33.92	69.46	32.768	0.96	419.8	4.19	39.47

Table 104: SF10 BW500 KHz Energy Consumption Data

SF11 BW500							
NbSymbol	Measured Consumption (ms)	Cad Time measured (Symbols)	Theoretical (ms)	Thoery/Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	7.315	1.79	4.096	0.56	384.38	3.84	7.81
2	11.41	2.79	8.192	0.72	384.38	3.84	12.18
4	19.60225	4.79	16.384	0.84	384.38	3.84	20.93
8	35.9875	8.79	32.768	0.91	384.38	3.84	38.42
16	68.755	16.79	65.536	0.95	384.38	3.84	73.41

Table 105: SF11 BW500 KHz Energy Consumption Data

SF12 BW500							
NbSymbol	Measured Consumption (ms)	Cad Time measured (Symbols)	Theoretical (ms)	Thoery/Measured	Ampl (mV)	I (mA)	Consumption (nAh)
1	15.12325	1.85	8.192	0.54	384.38	3.84	16.15
2	23.314	2.85	16.384	0.70	384.38	3.84	24.89
4	39.6975	4.85	32.768	0.83	384.38	3.84	42.39
8	72.4675	8.85	65.536	0.90	384.38	3.84	77.38
16	138.0025	16.85	131.072	0.95	384.38	3.84	147.35

Table 106 SF12 BW500 KHz Energy Consumption Data

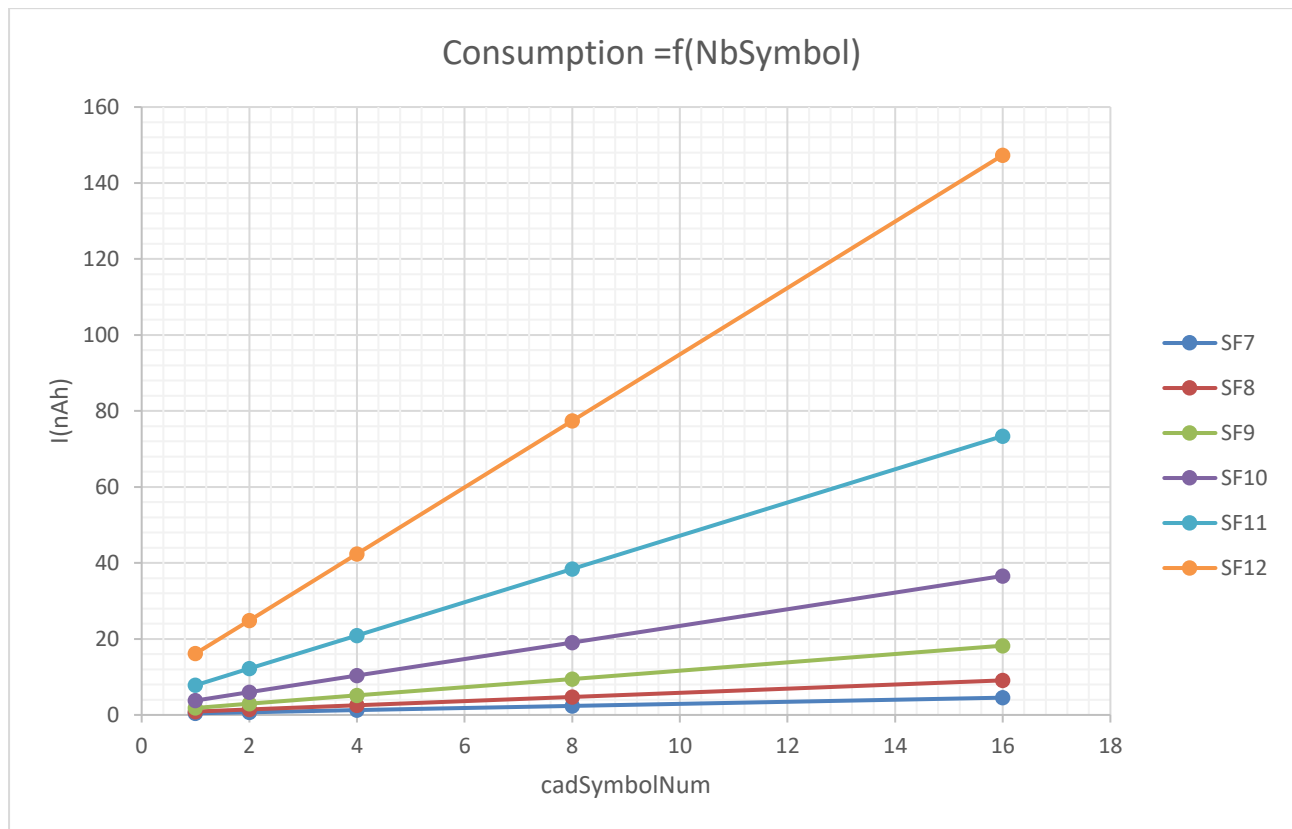


Figure 37: Consumption for Bandwidth 500 KHz = f(cadSymbolNum)

4.2.3 Consumption Conclusion

As anticipated, the more symbols are used, the more the energy consumption will be. Up to 4 symbols, SF7/8/9 remain quite low power, but for higher spreading factors, system current consumption should be carefully looked into to save energy.

5. Revision History

Version	Date	Modifications
2.0	December 2018	First Release
2.1	November 2019	Add SF12 operation and firmware workaround

6. Glossary

BW	BandWidth
CAD	Channel Activity Detection
DUT	Device Under Test
LoRa®	LOng RANGE modulation technique
LoRaWAN™	LoRa® low power Wide Area Network protocol
PSD	Power Spectral Density
RF	Radio-Frequency
BW	BandWidth
TX	Transmitter
RX	Receiver



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