Application Report
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CC13xx Long Range Modes

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ABSTRACT

CC13xx uses a well-known and established method to obtain sensitivity gains by means of coding and spreading the information bits into a series of transmitted symbols.

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1 Introduction

Throughout this document, the term Long Range Mode (LRM) is used to identify the physical layer encoding technique that trades data rate for sensitivity gains. These gains are achieved by digital coding. The term “data rate” refers to the available information rate to the upper protocol layers. The term “symbol rate” refers to the actual over-the-air modulation rate. When referring to “uncoded” formats, those formats in which the “data rate” is equal to the “symbol rate” is implied. When referring to “coded” formats, the “data rate” is lower than the “symbol rate” is implied. It is also assumed throughout this document that the modulation kernel used by LRM is in all cases 2-level (G)FSK. In other words, there are only two available (G)FSK symbols: +1 and-1. Therefore, every (G)FSK symbol can only indicate one bit.

Two different long range modes are discussed in this document:

- Mode 1: Legacy Long Range Mode
- Mode 2: SimpleLink™ Long Range Mode

CC13xx Long Range Modes have a data rate span from 50 kbps to 625 bps.

2 Why Use TI Long Range Mode

In general, when aiming at lower sensitivity values, you have the option of reducing the symbol rates transmitted over the air. Reducing the symbol rate normally implies a lower signal bandwidth. This approach is valid for a reasonable range of rates and signal bandwidths. However, when trying to reach very low rates or signal bandwidth, there are several factors that need to be carefully balanced:

- The ability of a real transmitter to modulate with very low deviation values (modulation accuracy)
- The crystal oscillator trade-offs. More accurate crystals are in general more expensive. Less accurate crystals might produce a frequency offset which is relatively larger the smaller the signal bandwidth is. A receiver that needs to take into account large frequency offsets would perform more poorly than a receiver that precisely knows where the wanted signal is.
- The receiver’s ability to receive and discriminate very narrowband signals

Just looking at the above reasons, one could come to the conclusion that maximizing the signal bandwidth is always beneficial. That argument holds only when noise impairments are considered (the channel is modelled as an AWGN channel). There are, however, other factors to take into consideration. One crucial parameter in the design and deployment of radio networks is the ability to co-exist with other radio communication systems or networks. The wider the receiver’s filter is the more interferers could potentially be seen together with the wanted signal. Even if the receiver would be available to demodulate the wanted signal at very low SNR levels, blockers are significantly more difficult to deal with when they are present in the desired channel. As opposed, when interferers are present in the adjacent or neighboring channels they can simply be filtered out. In general, filtering is more efficient than coding when dealing with interferers.

Figure 1 tries to illustrate this scenario. On the left-hand side, a narrowband system shares the spectrum with three aggressors. Since the narrowband system does not share its channel with any of them, very good selectivity performance can be achieved. On the right-hand side, a very wideband system is illustrated. Although the minimal SNR required to operate in such a system is lower, all three aggressors are located directly in the signal channel. This might mislead the receiver, especially during the long acquisition times that such systems often require. Note that wideband architectures are typically quoted based on pure AWGN simulations, conducted measurements or single-interferer simulations. Multiple-interferer simulations or measurements are rarely performed.

Finally, the middle scenario represents the Long Range Modes described in this application report. Signal BW is expanded and the probability of collision with other aggressors increases. However, this expansion is not as dramatic as the wideband case. Just to put some numbers, imagine a reference narrowband system of bandwidth 1. Using SimpleLink Long Range Mode with its default coding value of 4 would give approximately 6 dB of theoretical sensitivity gain. Co-channel performance is increased accordingly. Now, assume a wideband system claiming 20 dB of coding gain. The spreading factor there would actually be 100, or 12.5 times larger spectrum needed to transmit, receive and increases the probability of multiple collisions and aggressors.

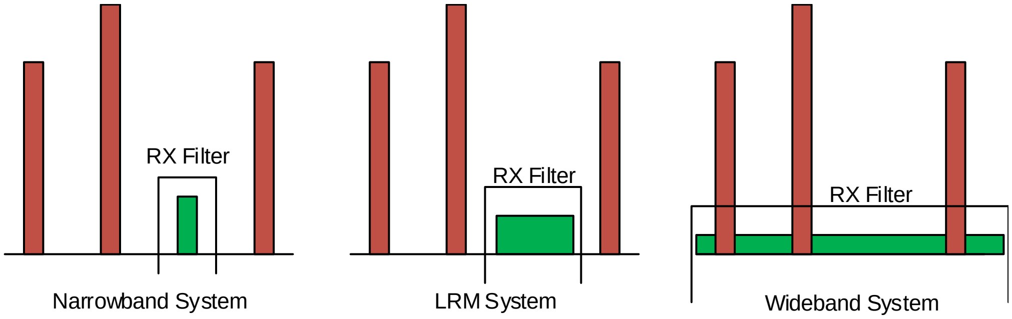

Figure 1. Receiver's BW vs Aggressors

TI Long Range Modes present a balanced and reasonable way to take into account all these factors. It introduces redundancy at the transmitter level in a range of 2 to 16 times the original signal information (default is 8 times in Mode 1 and 4 times in Mode 2). That additional redundant information increases the over-the-air signal bandwidth by the same factor. At the receiver, that redundancy is exploited to reduce the probability of bit errors and thus provide a better sensitivity, or accordingly, a lower minimal signal-to-noise operating point.

The inner modulation kernel of CC13xx Long Range Modes is well-known, well-deployed, industry-standard FSK or GFSK modulations. The coding gains obtained are purely of digital (numerical) nature. In that sense, CC13xx Long Range Modes are coding schemes, not modulation schemes.

3 Encoding Scheme

The scheme is depicted in Figure 2. A convolutional encoder of rate ½ is followed by a direct sequence spreader (DSSS) with variable spreading length. The output of that module is finally fed to the 2-(G)FSK modulator. The modulation kernel (symbol rate, frequency deviation) can be user defined within the limits given in this application report.

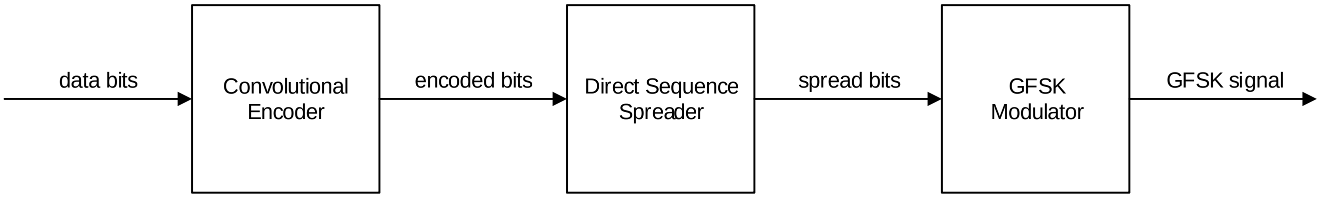

Figure 2. Coding Scheme

3.1 Convolutional Encoder

A convolutional encoder is defined by its rate, its constrain-length and the connections between its internal states.

The rate determines the number of output bits (m) produced by every set of input bits (n) and is normally expressed as n/m. The CC13xx Long Range modes only support ½ rate. For every input bit, the encoder produces two output bits.

The constrain-length (K) represents the number of stages in the encoding shift register. An important characteristic of convolutional codes is that the encoder has memory: the output of the encoder is not only function of the current input, but also function of the previous K-1 inputs. The CC13xx Long Range modes supports a constrain length of 7 (K=7).

The connections between internal states are a fundamental way of defining the code. In general the code can by systematic or non-systematic, or recursive or non-recursive. A systematic code always directly transmits the input bits in the output stream. A recursive code has feedback paths between its internal states (which makes it more like an IIR filter). The CC13xx Long Range Modes, however, is based on non-systematic, non-recursive convolutional code. Figure 3 depicts the code supported by the CC13xx Long Range Modes. The black dots represent logic XOR operations. This encoder is the optimum K=7 non-recursive, non-systematic, as documented in Bernard Sklar, *Digital Communications – Fundamentals and Applications*, 2nd Edition. The output of the encoder is always two bits (a0, a1) that are serialized, in such form that a0 is transmitted first and a1 is transmitted last.

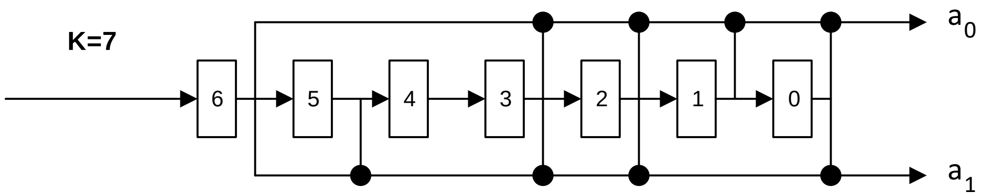

Figure 3. Convolutional Encoder Used in CC13xx Long Range Modes

3.2 Direct Sequence Spreader

The Direct Sequence Spreader (or Direct Sequence Spread-Spectrum, DSSS) assigns a known bit pattern to each of the incoming bits to the module. In the CC13xx Long Range Modes, the spreader length can be configured to be [1, 2, 4, 8]. Table 1 illustrates the mapping for each of the options.

Table 1. LRM DSSS Mapping

DSSS	‘0’	‘1’
1	‘0’	‘1’
2	‘00’	‘11’
4	‘1100’	‘0011’
8	‘11001100’	‘00110011’

Note that sequences are transmitted LSB first (rightmost bit first).

There is no further interleaving applied to the symbols after the direct sequence spreader. The CC13xx Long Range Modes do not use any form of interleaving.

3.3 Information Rate, Symbol Rates, and Sensitivity Gains

The relationship between data rate (the actual amount of information bits available to the higher protocol layers) and the symbol rate (the actual modulation rate used in the radio) can be expressed as shown in Equation 1.

$$\text{Data Rate} = \frac{\text{Symbol Rate}}{(2 \times \text{DSSS})} \tag{1}$$

Table 2 illustrates the overall coding rate and expected coding gain for the CC13xx Long Range Modes. Sensitivity gain is given at BER 10-3 and BER 10-5 points, where “gain” refers to the distance in the BER curve between uncoded GFSK and the coded Long Range modes. The choice of reference point is given by the application and higher level protocols. A protocol that normally uses short packets (20 to 60 bytes) would have an acceptable PER when the BER is 10-3. On the other hand, a protocol that normally uses long packets (200 to 2000 bytes) would need at least a BER of 10-5 to properly operate.

The relationship between PER and BER is properly explained in PER vs BER.

Table 2. LRM Coding Rate and Coding Gain

DSSS	Coding Rate	Sensitivity Gain (K=7) BER = 10-3	Sensitivity Gain (K=7) BER = 10-5
1	1:2	3.5 dB	4.0 dB
2	1:4	5.5 dB	6.0 dB
4	1:8	8.0 dB	9.0 dB
8	1:16	8.5 dB	10.0 dB

There are several takeaways from Table 2. First of all, higher DSSS rates offer higher sensitivity gain. This, of course, comes at the expense of longer packet durations. Secondly, when comparing BER=10-3 and BER=10-5 values, the gain is larger for the BER=10-5 reference points. The reason for this is the fact that when using coded modulations, the BER curves are more abrupt (converge quicker towards zero BER values). This is a well-known effect of convolutional coding or coding in general.

Note that the default operation mode for Mode 1 is DSSS = 4 and K = 7, as it offers the best compromise between sensitivity gain and packet duration. For Mode 2, the default operation mode is DSSS = 2 and K = 7, offering higher data rates.

Example: The reference CC13xx 50 kbps 2-GFSK mode in CC13xx offers a sensitivity level of -109.5 dBm (BER=10-3). Using Mode 1 and K=7 mode with DSSS=4, one could obtain a 6.25 kbps mode with sensitivity of -117.5 dBm (8.0 dB of link budget increase). If sensitivity is measured at the BER=10-5 point, the link budget increase would be 9.0 dB.

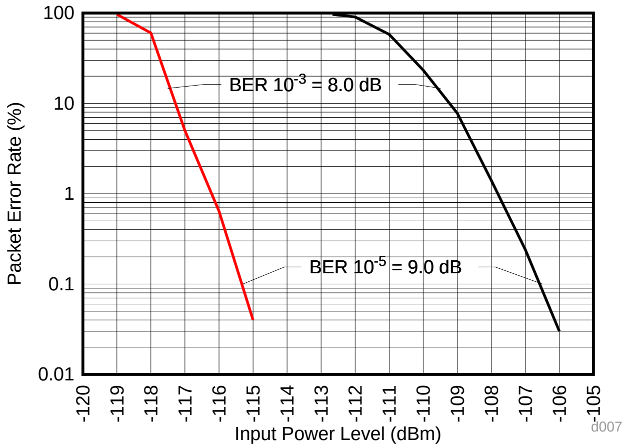

Figure 4. Uncoded vs DSSS=4, K=7 PER (20-bytes) Performance

4 Packet Format

The CC13xx Long Range Modes payload is byte oriented. Definition of packet lengths, headers, CRC, whitening must follow the same rules as in the standard CC13xx Generic FSK modes (using the CMD_PROP_RADIO_DIV_SETUP, CMD_PROP_TX, as defined in *CC13x0, CC26x0 SimpleLink™ Wireless MCU Technical Reference Manual* and *CC13x2, CC26x2 SimpleLink™ Wireless MCU Technical Reference Manual*). The only exception to this rule is that when using the Long Range Modes, the value programmed by *.formatConf.nSwBits* will be ignored, as the Modem will always use a 64-bit synchronization word (sync word) in all cases.

Due to binary coding, the demodulator actually operates in very low SNR conditions (the higher the DSSS value, the lower minimum SNR at the demodulator). Synchronization to the packet must also occur at very low SNR levels. The initial symbol sequence in front of the packet is needed to enable proper synchronization. The CC13xx Long Range Modes offer two different flavors of the synchronization sequence

4.1 Mode 1- Legacy Long Range Packet Format

Mode 1 uses a standard preamble sequence (010101..) followed by a fixed 64-bit sync word. The 64-bit sync word used in Mode 1 is 0xFE6B_2840_0194_D7BF, LSB-first. This sync word is not user-programmable.

The default preamble length in Mode 1 is 5-bytes long, but it can be user selectable in both length and pattern and follows the same standard rules as other (G)FSK modulations. The parameter *.preamConf.nPreamBytes* is used to select the number of bytes.

The entire packet structure is illustrated in Figure 5.

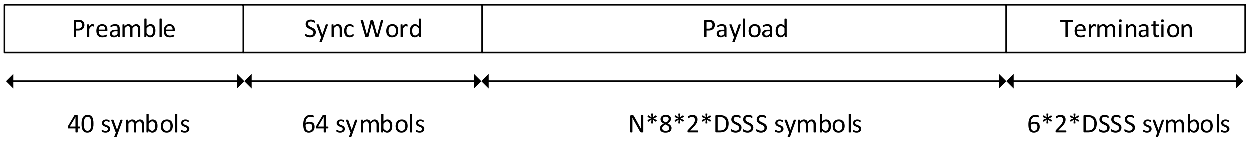

Figure 5. Mode 1 Packet Structure

The payload is encoded first by FEC and then spread through the DSSS element, as described in Section 3. The modem automatically inserts six termination bits at the end of the payload. Each termination bit results in 2*DSSS transmitted over-the-air symbols

The modulation kernel used for Mode 1 is FSK. The default modulation index for Mode 1 is h=1. The total duration of the preamble and sync word in Mode 1 is 104 symbols.

Mode 1 is optimized for achieving the shortest packet length. The drawback of this mode is its low frequency offset tolerance and a TCXO is recommended at both sides of the link. The minimum recommended setting is 10 ksps with a deviation of 5 kHz.

NOTE: Mode 1 is not recommended for future designs.

4.2 Mode 2- SimpleLink Long Range Packet Format

Mode 2 has been developed to address the drawbacks of Mode 1 when it comes to frequency offset performance. The differences between Mode 1 and Mode 2 are the initial synchronization sequence and the selection of the default modulation kernel.

Mode 2 uses GFSK with h=0.5. The minimum recommended setting is 10 ksps with a deviation of 2.5 kHz. The recommended default setting is 20 ksps, 5 kHz of deviation and a DSSS=2 (providing 5 kbps effective data rate).

The packet format of Mode 2 is illustrated in Figure 6.

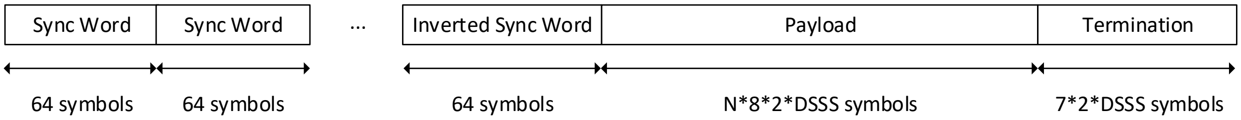

Figure 6. Mode 2 Packet Structure

Mode 2 uses no preamble. Instead, it uses a 64-bit sync word that is repeated M+1 times. The first M times, the inverted sync word is sent. The final repetition is as specified. The sync word in Mode 2 is hardware coded (0xCCC3_C3CC_C33C_3333, LSB first) and cannot be modified by the user. The number of repetitions (M) is configured through the .preamConf.nPreamBytes variable of CMD_PROP_RADIO_DIV_SETUP. The default value is 2. The repetition of multiple sync words prior to the final one allows the demodulator to run a very effective frequency offset tracking algorithm. Mode 2 can operate with normal 10 ppm crystals on both sides of the link.

Figure 7 illustrates the frequency offset performance. The plot shows PER vs frequency offset vs input power level. The black color corresponds to 100% PER and white is 0 PER. The packet used was 20 bytes long (payload).

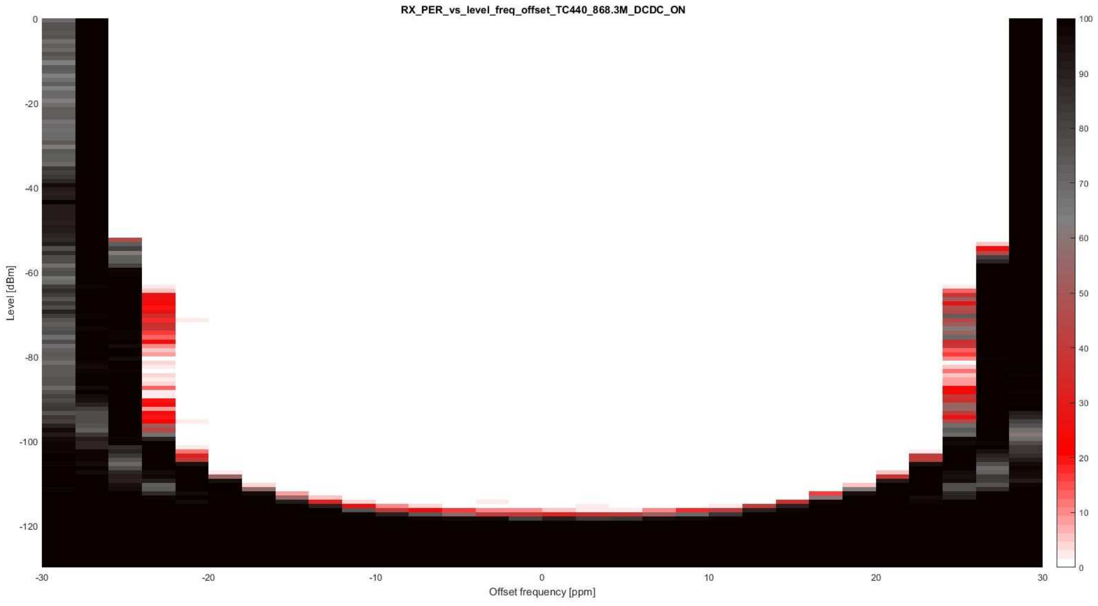

Figure 7. Mode 2 Frequency Offset Performance (868 MHz, 5 kbps)

The payload in Mode 2 is coded in the same fashion as in Mode 1. The same applies to the termination bits.

The number of symbols ($n_{symbols}$) and the total packet duration (t_{pd}, in us) for Mode 2 is given in Equation 2:

$$\eta_{symbols} = (M+1)\times 64 + N\times 8\times 2\times DSSS + 7\times 2\times DSSS \tag{2}$$

where, M is the number of sync word repetitions and N is the number of payload bytes.

$$t_{pd} = 1e6\times\left(\frac{\eta_{symbols}}{f_{symbols}}\right) \tag{3}$$

where, $f_{symbols}$ is the symbol rate in Hz.

Mode 2 is the recommended mode due to its more robust operation against frequency offsets. Note that Mode 2 does not support the DSSS=1 setting.

5 Recommended Operating Limits

In a K=7 convolutional code, the decoding algorithm keeps track of 64 possible states. For each state, there are at least two symbol metrics and two accumulated metrics to add: compare and select. For further explanation of the Add-Compare-Select algorithm, see Bernard Sklar, *Digital Communications – Fundamentals and Applications*, 2nd Edition. Internally, in order to keep digital complexity within reasonable limits, the K=7 decoder is implemented serially in time. Table 3 indicates the maximum and minimum data rates and symbol rates for each of the configurations allowed in the CC13xx Long Range Modes. The limits in Table 3 apply to both Mode 1 and Mode 2.

Table 3. LRM Minimum and Maximum Rates

	Symbol Rate		Data Rate	
DSSS	**Max**	**Min**	**Max**	**Min**
1 (1)	100 kbps	10 kbps	50 kbps	5 kbps
2	100 kbps	10 kbps	25 kbps	2.5 kbps
3	100 kbps	10 kbps	12.5 kbps	1.25 kbps
4	100 kbps	10 kbps	6.25 kbps	625 bps

(1) Only available for Mode 1.

Note that these values do not assume anything of the modulation kernel used to transmit the binary symbols. The tradeoff between symbol rate, modulation index (or its equivalent term, frequency deviation) and receiver's bandwidth should follow the same general rules as in standard, uncoded GFSK transmission.

6 Usage

SmartRF™ Studio supports three different CC13xx Long Range modes:

- 625 bps, Legacy Long Range (Mode 1), 10 ksps, DSSS = 8
- 2.5 kbps, SimpleLink Long Range (Mode 2), 20 ksps, DSSS = 4
- 5 kbps, SimpleLink Long Range (Mode 2). 20 ksps, DSSS = 2

The *rfPacketErrorRate* and *EasyLink* examples in the SDK (SimpleLinkTM Sub-1 GHz CC13x0 Software Development Kit and SimpleLinkTM Sub-1 GHz CC13x2 Software Development Kit) support two different CC13xx Long Range modes:

- 625 bps, Legacy Long Range (Mode 1), 10 ksps, DSSS = 8
- 5 kbps, Simple Link Long Range (Mode 2). 20 ksps, DSSS = 2

For performance figures, see *CC1310 SimpleLink™ Ultra-Low-Power Sub-1 GHz Wireless MCU Data Sheet* and *CC1312R SimpleLink™ High-Performance Sub-1 GHz Wireless MCU Data Sheet*.

Using one of the above Long Range Modes as a starting point the code examples can be modified to support other symbol rates and/or data rates within the limits in Table 3.

The deviation should be changed if the symbol rate is changed. Mode 1 uses FSK with h=1 and Mode 2 uses GFSK with h=0.5. The receiver's filter BW needs be wide enough to fit the transmitted signal BW.

Data whitening should always be enabled when using CC13xx Long Range Modes. Set .formatConf.whitenMode = 0x1 in CMD_PROP_RADIO_DIV_SETUP.

Selection of the DSSS is performed by a hardware override. Table 4 lists these overrides which are valid for both Mode 1 and Mode 2.

Table 4. DSSS Overrides

DSSS	Hex Value
1	HW_REG_OVERRIDE(0x505C,0x0000) (1)
2	HW_REG_OVERRIDE(0x505C,0x0100)
4	HW_REG_OVERRIDE(0x505C,0x0303)
8	HW_REG_OVERRIDE(0x505C,0x073C)

(1) Only valid for Mode 1.

The *rfPacketTx* and *rfPacketRx* examples in the SDK can also be used for testing. In this case, the *smartrf_settings.c* file needs to be replaced with the one exported from SmartRF Studio.

Example: Running *rfPacketErrorRate* or *EasyLink* with “2.5 kbps, SimpleLink Long Range (Mode 2), 20 ksps, DSSS = 4”. In the *smartrf_settings_predefined.c* file there is a CMD_RADIO_DIV_SETUP SIMPLELINK LONGRANGE override list. Change HW_REG_OVERRIDE(0x505C,0x0100) to HW_REG_OVERRIDE(0x505C,0x0303). The new override sets DSSS = 4.

Example: For 4 kbps, SimpleLink Long Range (Mode 2) and DSSS = 4. Use “2.5 kbps, Simple Link Long Range (Mode 2), 20 ksps, DSSS = 4” in SmartRF Studio as a starting point. Change the symbol rate to 32 ksps (.*symbolRate.rateWord* = 0x51EC), deviation to 8 kHz (.*modulation.deviation* = 0x20), and RX filter BW to 78 kHz (.rxBw = 0x23). Generate a new *smartrf_settings.c* file.

NOTE: Symbol rate, deviation, and RX filter BW can be entered in SmartRF Studio and the new settings will automatically be included in the generated *smartrf_settings.c* file. The DSSS override needs to be set manually either by modifying the *smartrf_settings.c* file or using the override editor.

7 References

- Bernard Sklar, *Digital Communications – Fundamentals and Applications*, 2nd Edition.
- PER vs BER
- Texas Instruments: *CC13x0, CC26x0 SimpleLink™ Wireless MCU Technical Reference Manual*
- Texas Instruments: *CC13x2, CC26x2 SimpleLink™ Wireless MCU Technical Reference Manual*
- SimpleLinkTM Sub-1 GHz CC13x0 Software Development Kit
- SimpleLinkTM Sub-1 GHz CC13x2 Software Development Kit
- Texas Instruments: *CC1310 SimpleLink™ Ultra-Low-Power Sub-1 GHz Wireless MCU Data Sheet*
- Texas Instruments: *CC1312R SimpleLink™ High-Performance Sub-1 GHz Wireless MCU Data Sheet*

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