LR2021 CP-FSK Modem Improvements

Application Note

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1 Introduction

The LR2021 integrates a CPFSK (Continuous Phase Frequency Shift Keying) modulator/demodulator specifically designed to provide comprehensive support for FSK (Frequency Shift Keying), GFSK (Gaussian Frequency Shift Keying), MSK (Minimum Shift Keying), and GMSK (Gaussian Minimum Shift Keying) modulation schemes.

A key advantage of the LR2021's FSK modem is that it offers the flexibility to fine-tune and optimize modulation characteristics according to an application's specific requirements. This versatility makes it suitable for a wide range of applications while ensuring physical layer compatibility with various wireless communication standards including Bluetooth® Low Energy (BLE), Wi-SUN FSK, WM-Bus, and Semtech's previous chip families (SX127xx, SX126xx, and LR11xx).

In contrast to previous generations of Semtech radios, the FSK receiver of the LR2021 features some additional, performance enhancing features:

1) **Increased data rates**
2) **Better Rx sensitivity performance**
3) **Frequency and Rx bandwidth tolerance improvement (at low data rates) due to the matched filter**
4) **Improved error immunity with Manchester encoding or whitening for '1' or '0' heavy payloads**

In this Application Note, we discuss these technological improvements to the FSK modem and then present the performance benefits of these new features.

Selecting a Modem: FLRC versus FSK Modulation

The LR2021 contains a wide array of modulation options including LoRa, OQPSK and FLRC in addition to FSK. FSK and FLRC cover similar data rates with similar performance.

Where the designer has the choice **FLRC is the better choice for higher link budget**: Generally, FLRC will give a 2.5 dB improvement in receiver sensitivity compared with the equivalent *effective* bit rate (i.e. real throughput) for a small increase in the current consumption (<1 mA) and provides the benefit of a robust forward error correction (FEC).

FSK is a longstanding communication technology, that is over a century old. For this reason, if a communication link requires compatibility with **existing standards or a long preamble FSK is the better choice**. A long preamble can be useful in the implementation of a preamble sampling MAC (where the radio transmits a long preamble).

2 Recap: Properties of FSK Signals

Before discussing the improvements, it is useful to recap some basic FSK modulation concepts. FSK modulation operates by shifting the carrier frequency between two distinct values representing binary data. This straightforward technique enables reliable data transmission over different distances and through varying channel conditions.

2.1 Modulation Bandwidth

The FSK signal represents the logical '0' and '1' of the modulating digital data as one of two discrete frequencies, with frequencies f_0 and f_1 mapping directly to the modulating signal.

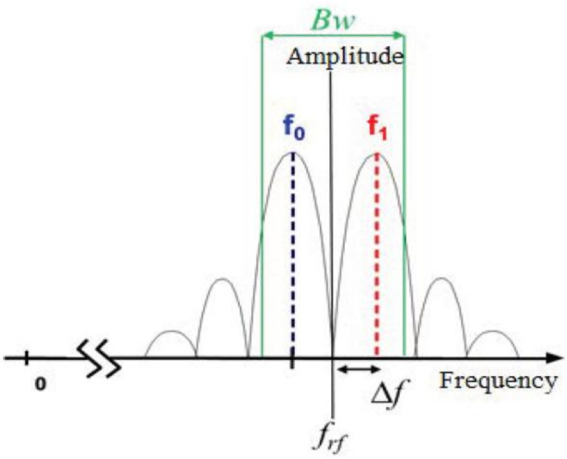

Figure 1. Basic Properties of an FSK Waveform

By convention we refer throughout this document to the double side-band (DSB) occupied bandwidth. In receive mode, the receiver bandwidth is configured to the lowest value that effectively accommodates the FSK signal bandwidth, plus any frequency offset that might be incurred:

$$B_{-20\mathrm{dB}} = 2\Delta f + R_b + \textbf{freqoffset}$$

Equation (1)

Where R_b is the symbol rate, Δf is the single side-band frequency deviation and *freqoffset* represents the RF carrier frequency error between transmitter and receiver - primarily caused by crystal impairments. This frequency error can affect received signal quality and overall communication performance. However, in the LR2021, the matched filter technology employed reduces the impairments to signal reception (see Section 3.3).

2.2 Modulation Index

As seen in Figure 1, as we reduce the frequency deviation (Δf) for a given bit rate (R_b), the closer our two modulating '0' and '1' frequencies become. As we do so, the sensitivity of the demodulator to noise increases, and the harder they become to discriminate between at the receiver.

To quantify this proximity we introduce the modulation index, β, which is given by:

$$\beta = \frac{2\Delta f}{R_b}$$

Equation(2)

Note that the LR2021 supports modulation index values in the range from 0.3 to 8 in FSK (and 6.2 for GMSK).

3 LR2021 FSK Improvements

The LR2021 introduces several new features that enhance the performance of the FSK modem in this section we present each one.

3.1 Increased FSK Data Rates

The LR2021 supports a wider range of receiver bandwidths than previous generations of Semtech radios:

Bandwidth LR2021 **3.4 - 2666 kHz**

Bandwidth SX126x **4.8 - 467 kHz**

As the center frequency of the radio increases, so also does the available transmission bandwidth. To reflect this, both the range of programmable data rates and frequency deviation, scale with the center frequency as shown below:

Table 1. FSK Modulation Parameters Available by Band of Operation

Frequency Range	Data Rate (kbps)		Frequency Deviation (kHz)	
	Min	Max	Min	Max
150 – 433 MHz	0.5	1000	0.6	330
433 – 470 MHz	0.5	2000	0.6	500
470 – 510 MHz	0.5	2000	0.6	500
510 – 863 MHz	0.5	2000	0.6	500
863 – 2500 MHz	0.5	2000	0.6	500

The combination of wider bandwidths, higher data rates, and frequency deviations allows the radios to target higher data rate communication links across both the sub and 2.4 GHz bands including:

- Z-wave up to 300 kbps in the 915 MHz band
- Bluetooth Low Energy at 1 Mbps and 2 Mbps in the 2.4 GHz band

The larger range of data rates is a significant leap in performance from previous generations. As the data rate increase, there is a corresponding increase in receiver consumption as shown below:

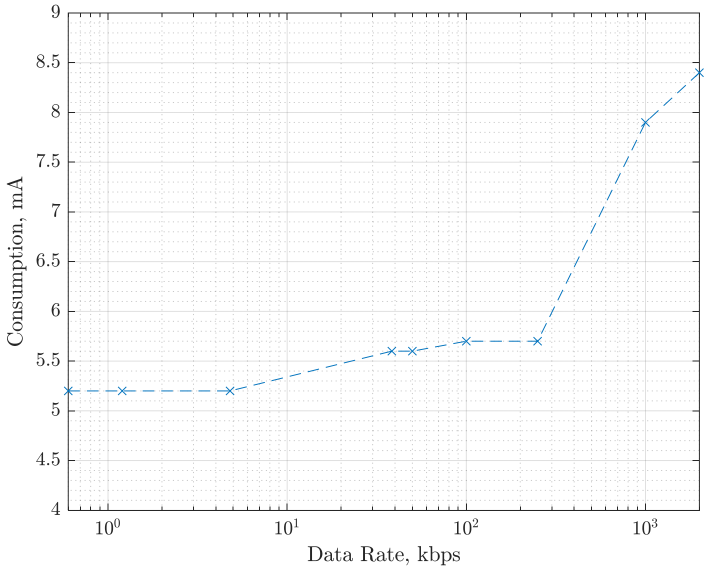

Figure 2. Receiver Consumption of the FSK Receiver Increases with Data Rate

3.2 Receiver Sensitivity Improvement

Today, most FSK modulation uses continuous phase to minimize the spectral emissions that an abrupt change in frequency creates. To further mitigate out-of-band emissions, pulse filtering is also employed to the modulating bit stream. Whilst this filtering has the desirable effect of reducing unwanted emissions – it can induce inter-symbol Interference (ISI). Continuous Phase Frequency-Shift Keying (CPFSK) aims to minimize or eliminate this ISI by exploiting the continuous phase transition between symbols to recover the bit information and mitigate the interference between symbols.

With reduced ISI, the signal-to-noise ratio (SNR) required for a given Bit Error Rate (BER) performance is lower, effectively increasing the link margin. This translates to greater transmission range, better performance in fading conditions, or the ability to use lower transmit power.

The LR20xx has seen significant improvements made from previous generations of FSK modem to receive spectrally efficient, low modulation index and Gaussian filtered signals. The table below shows the measured sensitivity of the LR2021 versus the SX1261. For a fixed data rate of 250 kbps, the influence of varying the modulation index and the presence of Gaussian filtering on the receive sensitivity is investigated.

Table 2. FSK and GSK Modem Sensitivity Performance

Data Rate	Modulation Type	Modulation Index	Sensitivity SX1261 [dBm] (with RF switch)	Sensitivity LR2021 [dBm] (Switchless Ref Design)
250 kbps	FSK	1.0	-102.5	-105
250 kbps	FSK	0.5	-102	-107.3
250 kbps	GFSK BT = 0.5	1.0	-102.5	-105.5
250 kbps	GFSK BT = 0.5	0.5	-100	-106.8

In all cases, substantial sensitivity improvements are seen for LR2021. For a modulation index of 1 the sensitivity gain is 2.5 dB to 3 dB range depending upon the use of Gaussian filtering. The most significant improvement comes for low modulation index (β=0.5) operation. Here a 5.3 to 6.8 dB improvement is observed, again depending upon the presence of Gaussian filtering.

To further appreciate the performance gains over previous generations of product, it is important to consider the hardware configuration of the reference designs of each family. The following diagram shows the concept of a conventional RF-switch based design and the switchless design concept that is also possible in the LR2021.

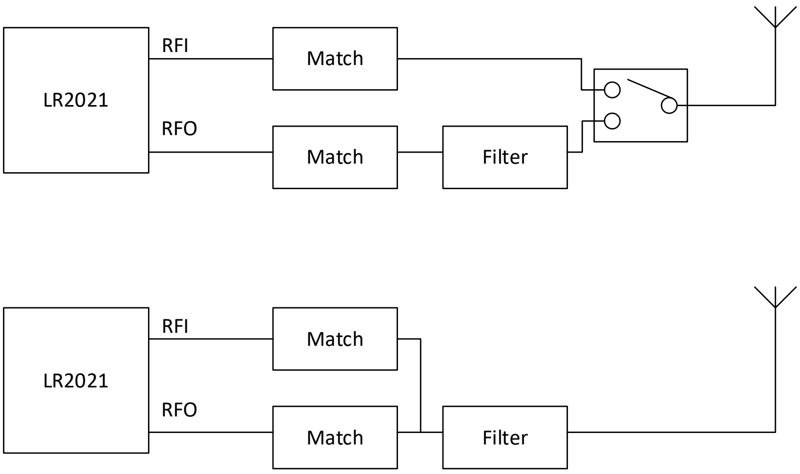

Figure 3. A Simplified Block Schematic of the RF Signal Path of the LR2021: RF Switch (top) and Switchless (bottom)

The RF-switch based design (top) features independent Tx and Rx paths that can be optimised to present optimal impedance for each role of the transceiver with the selection between paths made by the RF switch. In the lower, switchless, case both transmitter and receiver are joined through passive matching networks to a compromise impedance.

Achieving substantial sensitivity gains in a smaller, lower BoM cost format makes the LR2021 the best technical choice for reception of spectrally efficient, low modulation index FSK, GFSK and GMSK modulation.

3.3 Matched Filter Bandwidth and Frequency Tolerance

A matched filter is specifically designed to match the characteristics of the expected signal (in this case, the FSK signal). When the received signal and noise is passed through the matched filter, the filter's output is the result of a correlation between the received signal and the filter's impulse response. This correlation process maximizes the signal's SNR in the presence of noise. In other words, the matched filter makes it easier to distinguish the FSK signal from noise, leading to more accurate detection of the transmitted frequencies and hence the underlying data.

The matched filter's performance is responsible in part for the sensitivity gains seen in the previous section. However, it also imparts another significant benefit to the LR2021 FSK receiver: limited desensitization as the Rx bandwidth increases and improved tolerance of frequency offsets.

The figure below shows the sensitivity of the LR2021 FSK modem versus that of the SX126x measured for 4.8 kbps data rate and 5 kHz frequency deviation (14.8 kHz DSB bandwidth).

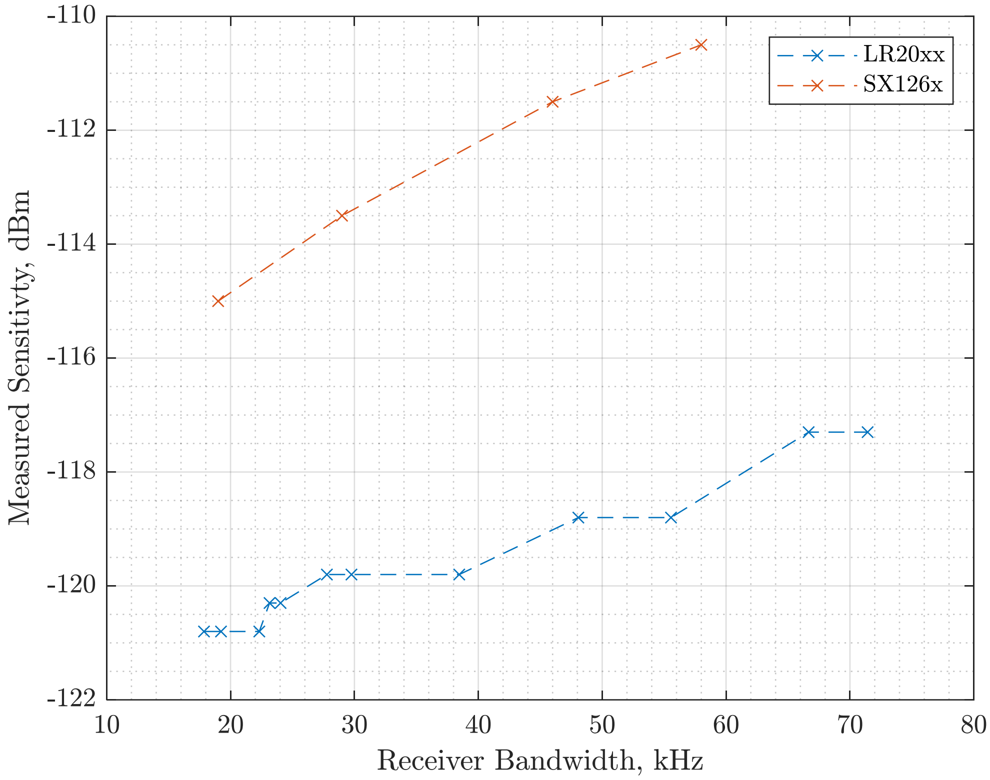

Figure 4. Sensitivity versus FSK Receiver Bandwidth

In this plot we clearly see that for an increasing receiver bandwidth, the LR2021 has a large improvement in sensitivity, and a much reduced gradient in sensitivity degradation.

This trend is easier to see in a plot of the degradation in sensitivity as the BW is increased, as shown in the figure below. Consider that with 46 kHz of frequency offset, the SX126x sensitivity has degraded 3.5 dB (to -111.5 dBm) whereas the LR2021 sensitivity has reduced by only 2 dB to -118.8 dBm.

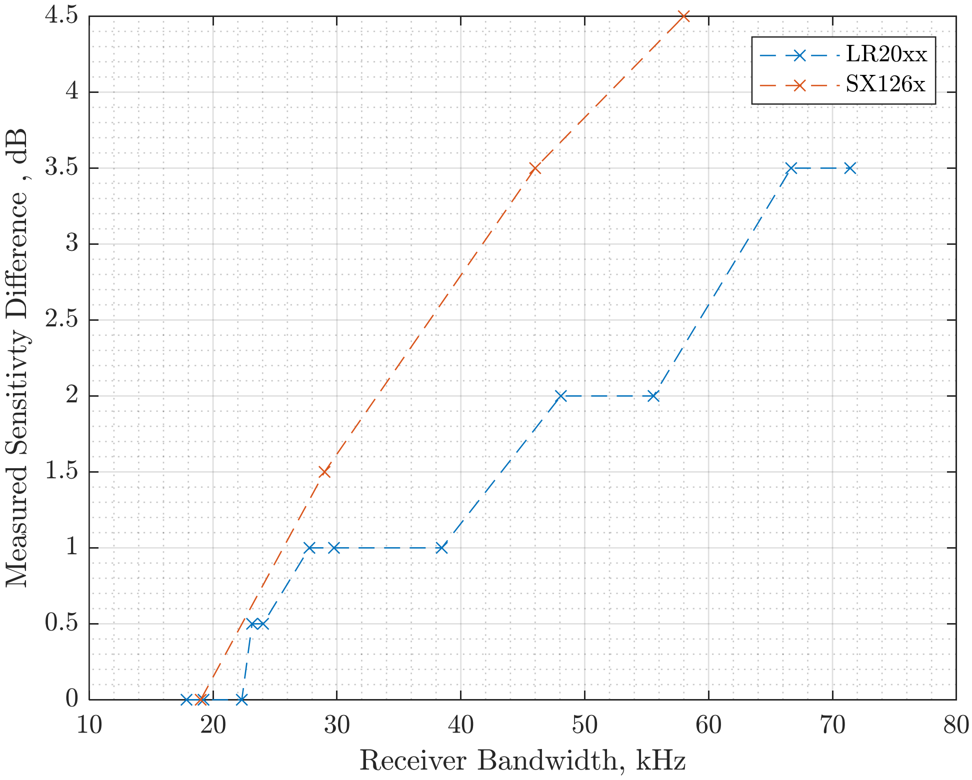

Figure 5. Sensitivity Difference versus FSK Receiver Bandwidth

This behaviour helps to alleviate the issue of desensitisation when seeking an FSK signal with a substantial frequency offset. This can be the case where a narrowband signal is used in conjunction with a low precision reference oscillator.

Instead, with the LR2021, the use of a large bandwidth to accommodate the *freqoffset* of Equation 1 does not incur a substantial reduction in detection sensitivity.

The limit for the frequency error between transmitter and receiver, for <2 dB of sensitivity degradation, is given by the lower of the PPM frequency error, f_{error_PPM}, or bitrate frequency error, f_{error_Rb}, values below:

$$\begin{aligned} f_{error\_PPM} &= 60 \text{ ppm} \qquad & f_{error\_PPM} \le f_{error\_Rb} \\ f_{error\_Rb} &= 16\, R_b \qquad & f_{error\_Rb} < f_{error\_PPM} \end{aligned} \tag{3}$$

3.4 Manchester Encoding and Data Whitening

The LR2021 specifies that the minimum number of consecutive bits which the radio can receive without error is 24. Sensor data is not always predictable and so can sometimes feature long repeating sequences of logical '1 or '0. In these scenarios it is useful, to prevent reception errors, to enable either data whitening or to use Manchester encoding. The two following figures show the process by which they are calculated.

Whitening is generated by the bitwise multiplication of the incoming payload with a pseudorandom bit stream (PRBS). This has the advantage that the DC bias of a long sequence of 1 or 0 is cancelled, without changing the modulation parameters of the link. The use of whitening has no cost to the user and should be used by default. Note that although the probability is reduced, it is still statistically possible to produce input data that will yield a 24-bit sequence without a bit transition.

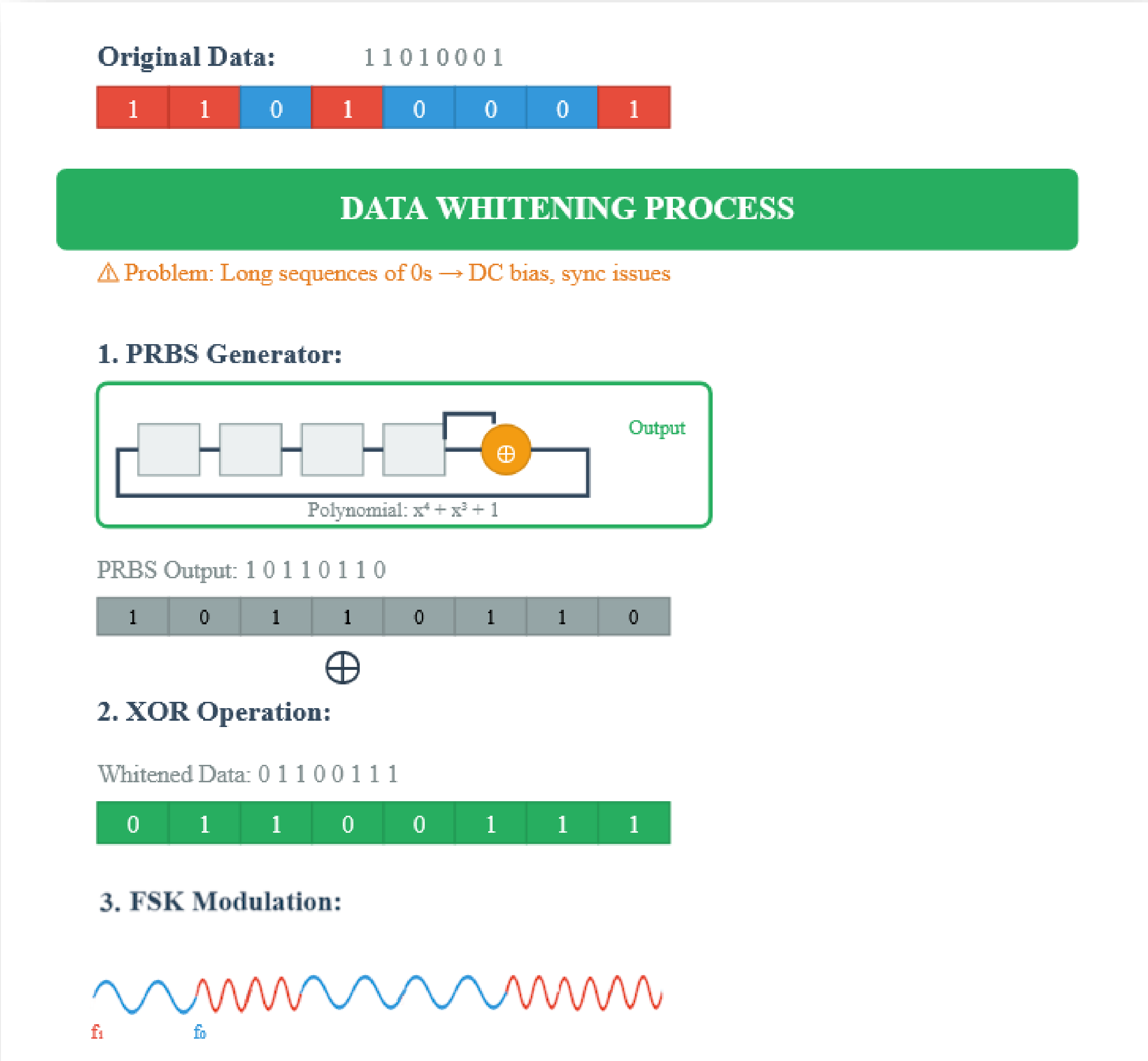

Figure 6. Application of Whitening to Modulating Data of FSK Signal (8 bits shown but real process is 32-bit)

Manchester coding *guarantees* logical transitions by representing logical 1 and 0 with bit transitions from low-to-high and high-to-low transitions respectively. Although the data rate is doubled, the sensitivity of the link with Manchester coding enabled is equivalent to the lower data rate, due to a soft bit decision process made in the LR0221 and the guaranteed bit-transition made during each FSK symbol. However, because the data rate is increased, the use of Manchester coding is best reserved for links where the original modulation index is high.

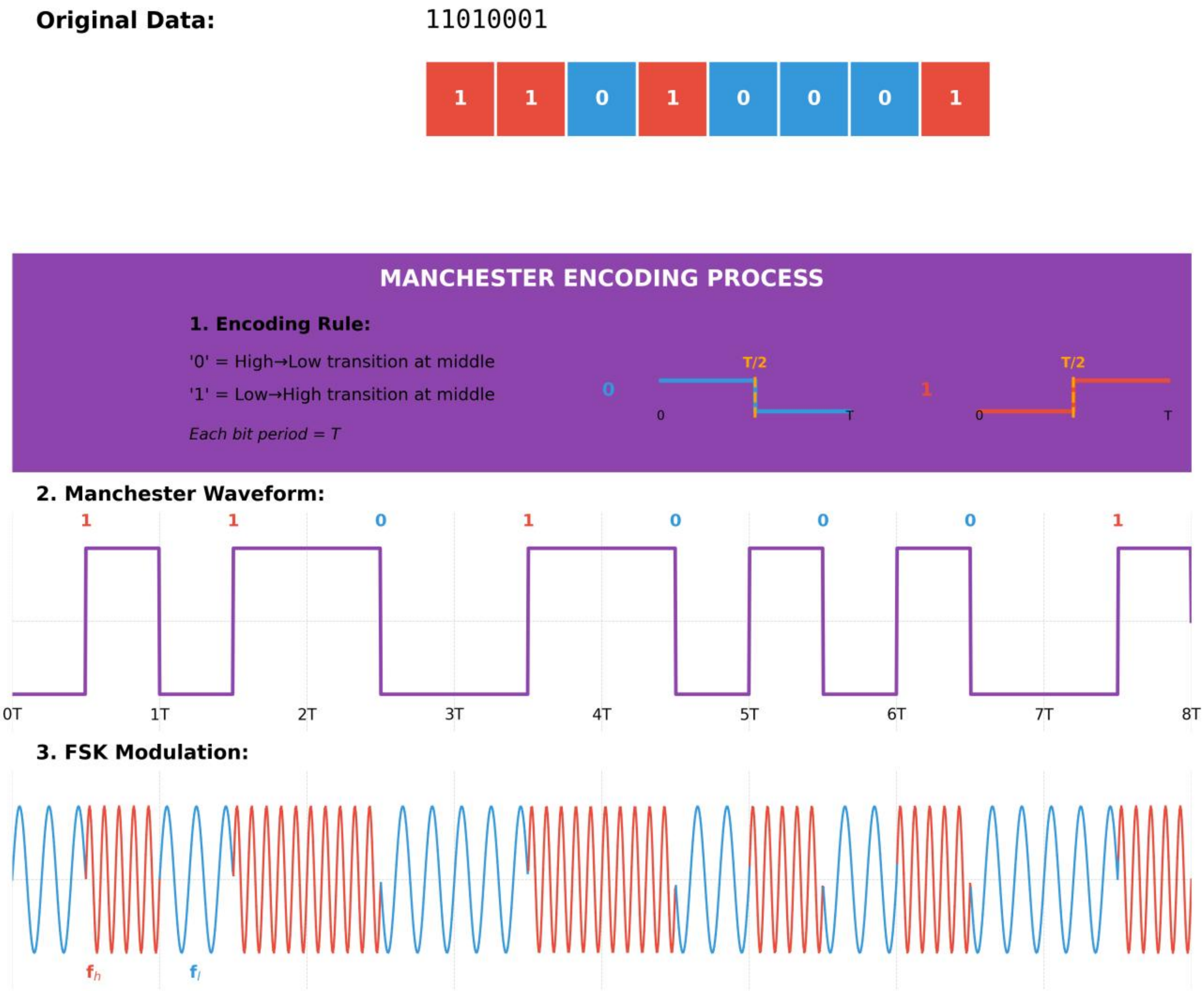

Figure 7. Application of Manchester Coding to Modulating Data of FSK Signal (8 bits shown but real process is 32-bit)

4 Conclusion

A range of enhanced capabilities of the LR2021 FSK modem have been presented. These have shown the capacity of LR2021 to transmit and receive a wider range of FSK data rates, with a higher sensitivity than previous generations of Semtech radio products. The addition of the matched filter has improved the ability of the LR2021 to receive misaligned transmitted signals, providing both improved frequency-offset immunity and higher bandwidth communication; without incurring a sensitivity penalty due to increased noise. Together with improved Manchester coding implementation to tackle sensor data that might contain undesirable DC bias, the LR2021 can meet and exceed the needs of the most challenging FSK applications.

5 Revision History

Version	ECO	Date	Changes and/or Modifications
1.0	ECO-076649	October 2025	Initial version

Important Notice