MX•COM, INC. MiXed Signal ICs

APPLICATION NOTE

GMSK **Practical GMSK Data Transmission**

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Introduction

The proliferation of computers in today's society has increased the demand for transmission of data over wireless links. Binary data, composed of sharp "one to zero" and "zero to one" transitions, results in a spectrum rich in harmonic content that is not well suited to RF transmission. Hence, the field of digital modulation has been flourishing. Recent standards such as Cellular Digital Packet Data (CDPD) and Mobitex* specify Gaussian filtered Minimum Shift Keying (GMSK) for their modulation method.

GMSK is a simple yet effective approach to digital modulation for wireless data transmission. To provide a good understanding of GMSK, we will review the basics of MSK and GMSK, as well as how GMSK is implemented in CDPD and Mobitex systems.

GMSK modems reduce system complexity, and in turn lower system cost. There are, however, some important implementation details to be considered. This paper will cover some of these details, focusing on interfacing a single chip baseband modem to the IF/RF section of a "typical" FM radio topology.

Background

If we look at a Fourier series expansion of a data signal we see harmonics extending to infinity. When these harmonics are summed, they give the data signal its sharp transitions. Hence, an unfiltered NRZ data stream used to modulate an RF carrier will produce an RF spectrum of considerable bandwidth. Of course, the FCC has strict regulations about spectrum usage and such a system is generally considered impractical. But if we start to remove the high frequency harmonics from the Fourier series (i.e. pass the data signal through a lowpass filter), the transitions in the data will become progressively less sharp. This suggests that pre-modulation filtering is an effective method for reducing the occupied spectrum for wireless data transmission. In addition to a compact spectrum, a wireless data modulation scheme must have good bit error rate (BER) performance under noisy conditions. Its performance should also be independent of power amplifier linearity to allow the use of class C power amplifiers.

The academic field of “Data Transmission” is loaded with modulation strategies that attempt to meet the above criteria. Most involve translation of data bits or patterns into a particular combination of phase, frequency or amplitude. Some of the more notable techniques are listed in Table 1.

MODULATION TECHNIQUE	COMMON ACRONYM
Frequency Shift Keying	FSK
Multi-level Frequency Shift Keying	MFSK
Continuous Phase Frequency Shift Keying	CPFSK
Minimum Shift Keying	MSK
Gaussian Minimum Shift Keying	GMSK
Tamed Frequency Modulation	TFM
Phase Shift Keying	PSK
Quadrature Phase Shift Keying	QPSK
Differential Quadrature Phase Shift Keying	DQPSK
Pi/4 Differential Quadrature Phase Shift Keying	Pi/4 DQPSK
Quadrature Amplitude Modulation	QAM

Table 1: Modulation Formats

** Mobitex is a trademark owned by the Telia Corporation.*

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Each of the modulation formats listed in Table 1 is suited to specific applications. In general, schemes that rely on more than two levels (e.g. QAM, QPSK) require better signal to noise ratios (SNR) than two-level schemes for similar BER performance. Additionally, in a wireless environment, multi-level schemes generally require greater power amplifier linearity than two-level schemes. The fact that GMSK uses a two-level continuous phase modulation (CPM) format has contributed to its popularity. Another point in its favor is that it allows the use of class C power amplifiers (relatively non-linear) and data rates approaching the channel BW (dependent on filter bandwidth and channel spacing).

GMSK Basics

Prior to discussing GMSK in detail we need to review MSK, from which GMSK is derived. MSK is a continuous phase modulation scheme where the modulated carrier contains no phase discontinuities and frequency changes occur at the carrier zero crossings. MSK is unique due to the relationship between the frequency of a logical zero and one: the difference between the frequency of a logical zero and a logical one is always equal to half the data rate. In other words, the modulation index is 0.5 for MSK, and is defined as

$$m = \Delta f \times T$$

where,

$$\Delta f = |f_{\text{logic } 1} - f_{\text{logic } 0}|$$

$$T = 1/\text{bit rate}$$

For example, a 1200 bit per second baseband MSK data signal could be composed of 1200 Hz and 1800 Hz frequencies for a logical one and zero respectively (see Figure 1).

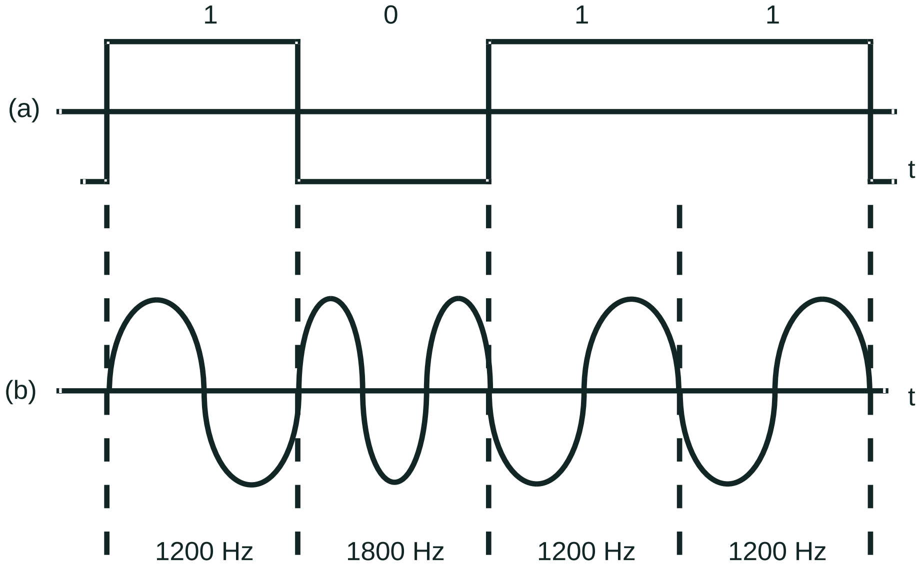


Figure 1: 1200 baud MSK data signal; a) NRZ data, b) MSK signal.

Baseband MSK, as shown in Figure 1, is a robust means of transmitting data in wireless systems where the data rate is relatvely low compared to the channel BW. MX-COM devices such as the MX429 and MX469 are single chip solutions for baseband MSK systems, incorporating modulation and demodulation circuitry on a single chip.

An alternative method for generating MSK modulation can be realized by directly injecting NRZ data into a frequency modulator with its modulation index set for 0.5 (see Figure 2). This approach is essentially equivalent to baseband MSK. However, in the direct approach the VCO is part of the RF/IF section, whereas in baseband MSK the voltage to frequency conversion takes place at baseband.

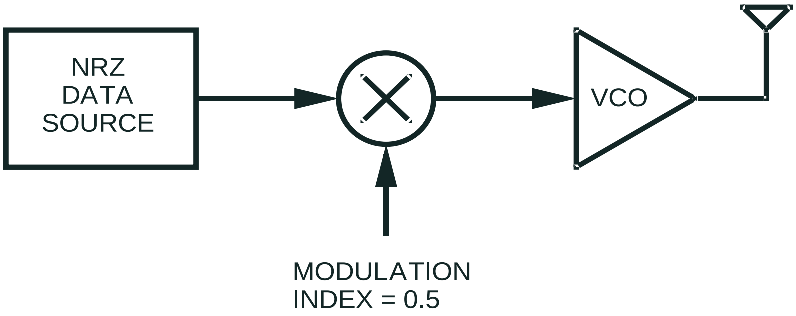


Figure 2: Direct MSK modulation

The fundamental problem with MSK is that the spectrum is not compact enough to realize data rates approaching the RF channel BW. A plot of the spectrum for MSK reveals sidelobes extending well above the data rate (see Figure 4). For wireless data transmission systems which require more efficient use of the RF channel BW, it is necessary to reduce the energy of the MSK upper sidelobes. Earlier we stated that a straightforward means of reducing this energy is lowpass filtering the data stream prior to presenting it to the modulator (pre-modulation filtering). The pre-modulation lowpass filter must have a narrow BW with a sharp cutoff frequency and very little overshoot in its impulse response. This is where the Gaussian filter characteristic comes in. It has an impulse response characterized by a classical Gaussian distribution (bell shaped curve), as shown in Figure 3. Notice the absence of overshoot or ringing.

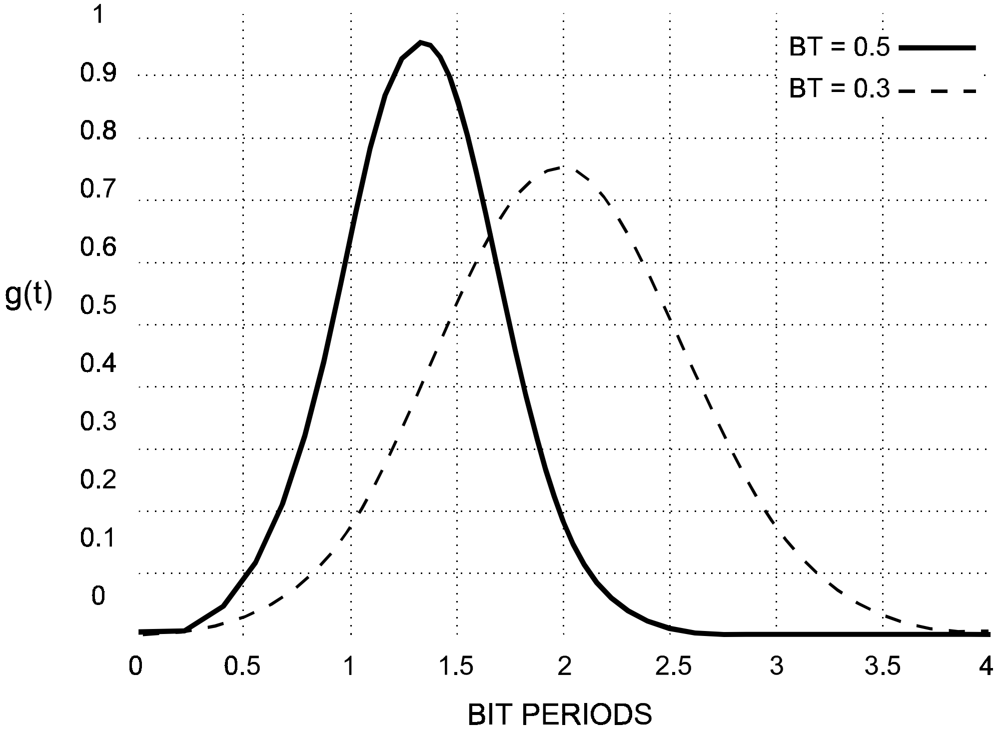


Figure 3: Gausssian filter impluse response for BT = 0.3 and BT = 0.5

Figure 3 depicts the impulse response of a Gaussian filter for BT = 0.3 and 0.5. BT is related to the filter's -3dB BW and data rate by

$$BT = \frac{f_{-3dB}}{\text{BIT RATE}}$$

Hence, for a data rate of 9.6 kbps and a BT of 0.3, the filter's -3dB cutoff frequency is 2880Hz.

Still referring to Figure 3, notice that a bit is spread over approximately 3 bit periods for BT=0.3 and two bit periods for BT=0.5. This gives rise to a phenomena called inter-symbol interference (ISI). For BT=0.3 adjacent symbols or bits will interfere with each other more than for BT=0.5. GMSK with BT=∞ is equivalent to MSK. In other words, MSK does not intentionally introduce ISI. Greater ISI allows the spectrum to be more compact, making demodulation more difficult. Hence, spectral compactness is the primary trade-off in going from MSK to Gaussian pre-modulation filtered MSK. Figure 4 displays the normalized spectral densities for MSK and GMSK. Notice the reduced sidelobe energy for GMSK. Utlimately, this means channel spacing can be tighter for GMSK when compared to MSK for the same adjacent channel interference.

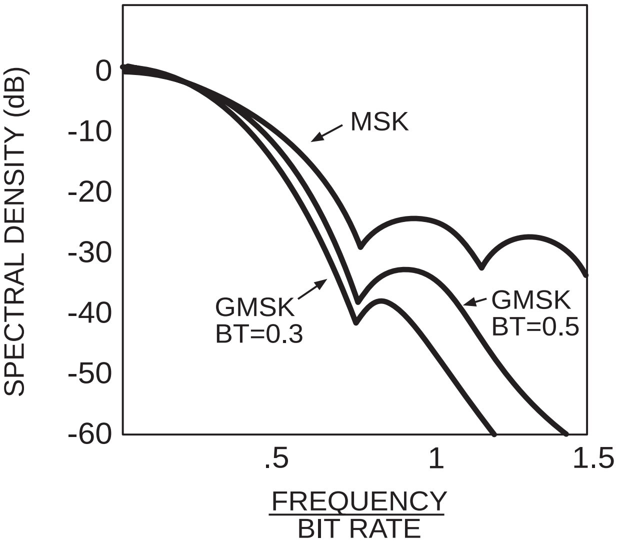


Figure 4: Spectral density for MSK and GMSK

Performance Measurements

The performance of a GMSK modem is generally quantified by measurement of the signal-to-noise ratio (SNR) versus BER. SNR is related to E_b/N_0 by

$$\frac{E_b}{N_0} = \frac{S}{RN_0} = \frac{S}{N}\left(\frac{B_n}{R}\right)$$

where,
S = signal power
R = data rate in bits per second
N_0 = noise power spectral density (watts/Hz)
E_b = energy per bit
$B_n \text{ x } N_0 = N$ = noise power
B_n = noise BW of IF filter

Recent Standards

GMSK has been adopted by many wireless data communication protocols. Two of the systems specifying GMSK modulation are Cellular Digital Packet Data (CDPD) and Mobitex.

CDPD uses the dead air time on cellular systems by sending data packets on idle cellular voice channels. Data is transmitted at 19.2kbps using a BT of 0.5. This high data rate is facilitated by the 30kHz channel spacing of the cellular network and the spectral conservation of GMSK. Voice has priority over data and will interrupt data transmission, forcing the CDPD system to seek a new idle cellular channel. This could prove to be an obstacle to the throughput promised by its 19.2kbps data rate when implemented in a highly congested area where dead time is limited.

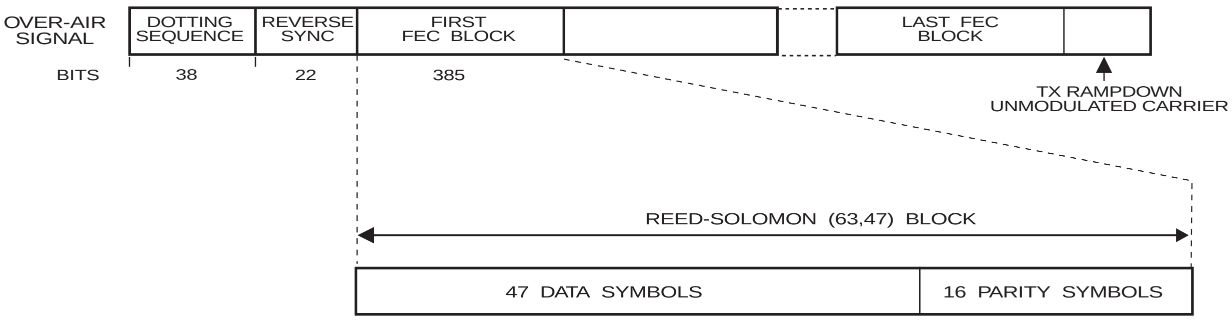
CDPD is being added to the existing cellular infrastructure and therefore promises to offer widespread coverage. The coverage and ease of adaptation appear to be the greatest strengths of the CDPD system.

The slower-than-expected deployment of CDPD has many people anxious and perhaps a bit nervous about its potential.

Competition from dedicated data systems such as Mobitex is not insignificant. While Mobitex has a lower data rate than CDPD (8kbps), it is not sharing its channels with cellular voice transmissions. Several subtleties such as this will make it more difficult for end users to select the system best suited to their needs by obscuring the actual throughput potential of the systems. Mobitex’s choice of 8kbps and a BT of 0.3 afford it a much tighter channel spacing (12.5kHz) than CDPD, but the greater inter-symbol interference for BT=0.3 limits the system’s tolerance to noise and distortion. The narrower channel also limits Mobitex's tolerance to frequency offsets between units.

Both CDPD and Mobitex employ forward error correction in their packetting of data. Figure 5 shows the typical packet structures of these two systems for comparison. Forward error correction (FEC) helps improve the systems' throughput when less than ideal channel conditions exist.

CDPD Reverse Channel Frame Transmission Structure



Mobitex Frame Structure

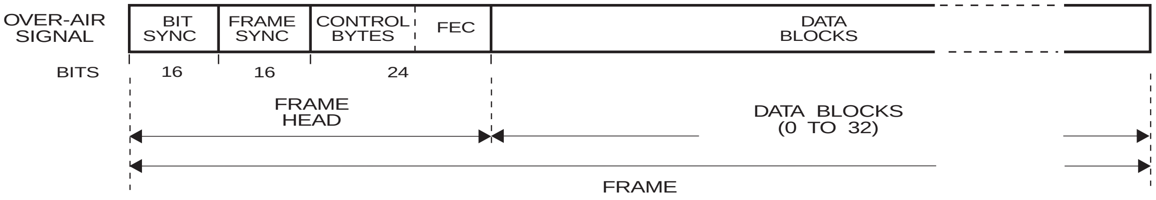


Figure 5: Typical packet structures for CDPD and Mobitex

Implementation Considerations

The design of a GMSK modulator/demodulator appears to be a straightforward task. Most textbooks present the modulator as a “simple” Gaussian filter cascaded with a VCO. However, in practice it is generally not that simple. Many of the sections in a typical radio such as the synthesizer, IF filter, power amplfier, etc. have far from ideal behavior. In particular, the synthesizer presents a unique problem for GMSK modulation. Data patterns consisting of several consectutive ones or zeros have a spectral response extending down to near DC. Most frequency synthesizers will not respond to this low frequency signal (a typical synthesizer effectively has a highpass filter characteristic).Two of the most common modulation methods, which help considerably where the non-ideal behavior of the synthesizer is concerned, are "Two-point modulation" and "Quadrature modulation."

Two point modulation

Two point modulation (see Figure 5) circumvents this synthesizer problem by splitting the Gaussian filtered signal; one portion is directed to the VCO modulation input, the other portion is used to modulate the TCXO. The TCXO is not in the frequency control feedback loop. Hence, the TCXO can be modulated by the low frequency portion of the signal, and its output is effectively summed with the signal modulating the VCO in the synthesizer. The composite signal has a spectral response extending down to DC.

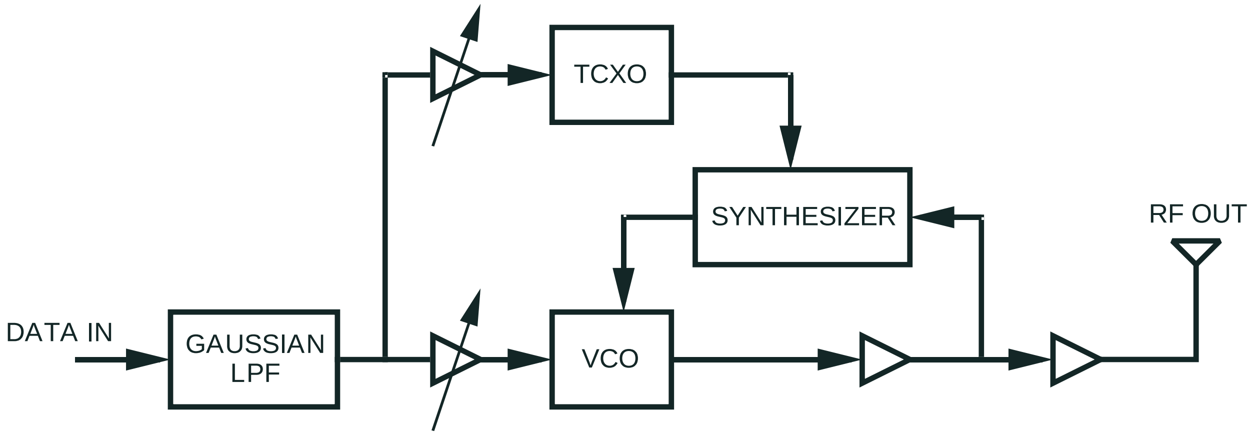


Figure 6: Two point modulation radio block diagram

I and Q modulation

Quadrature (I and Q) modulation can also be effective in eliminating synthesizer shortcomings. In I and Q modulation, the Gaussian filtered data signal is separated into in-phase (I) and quadrature phase (Q) components. The modulated RF signal is created by mixing the I and Q components up to the frequency of the RF carrier, where they are summed together. The role of the synthesizer has now been reduced to merely changing carrier frequency for channel selection. The key to optimum performance with quadrature modulation is accurate creation of the I and Q components.

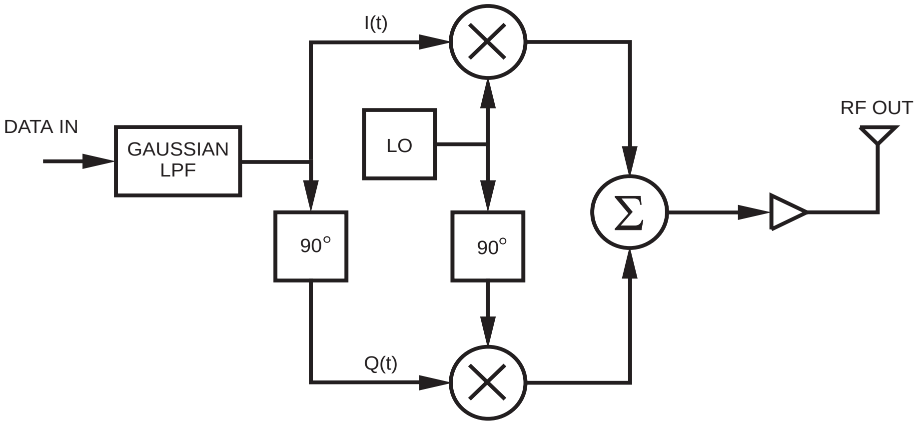


Figure 7: I and Q radio block diagram

Baseband I and Q signals can be created by using an all-pass phase shifting network. This network must maintain a 90 degree phase relationship between the I and Q signals for all frequencies in the band of interest.

Demodulation

Demodulation of the GMSK signal requires as much attention to the preservation of an unadulterated wave form as does modulation of the signal. The choice of a Gaussian shaped pre-modulation filter was made for three main reasons[1]:

1) narrow bandwidth and sharp cutoff
2) lower overshoot impulse response
3) preservation of the filter output pulse area.

The first condition gives GMSK modulation its spectral efficiency. It also improves its noise immunity when demodulating. The second condition affords GMSK low phase distortion. This is a major concern when the receiver is demodulating the signal down to baseband, and care must be taken in the design of the IF filtering to protect this characteristic. The third condition ensures the coherence of the signal. While this is quite strict and not realizable with a physical Gaussian filter, the phase response can be kept linear and therefore sufficient for coherent demodulation.

In most systems the constraints on the above goals also include

- Data Rate
- Tx filter bandwidth (BT)
- Channel Spacing
- Allowable adjacent channel interference
- Peak carrier deviation
- Tx and Rx carrier frequency accuracy
- Modulator and Demodulator linearity
- Rx IF filter frequency and phase characteristics.

These constraints are all part of the balance that must be struck to provide a robust GMSK system. The data rate, Tx BT, peak carrier deviation, and carrier frequency accuracy between receiver and transmitter all contribute to the necessary width of the IF filter. The IF filter should have sufficient width to accommodate the maximum variations in the above parameters so that the received signal will not run into the skirts of the filter. The skirts of the IF filter can introduce excessive amounts of group delay (phase distortion) in the higher frequency components of the received data. The passband of the IF filter should have little or no group delay. The more group delay introduced, the more degraded the bit error rate (BER) performance of the receiver will become. Rules of thumb for group delay dictate less than 10% of a bit time is tolerable. How happy you are with this level of performance is very dependent on the other factors that influence the BER of your system: BT, signal strength, fading, etc. Phase equalization measures can also be taken to help reduce group delay, but if there is control over the IF filter's design these steps can be avoided.

The CDPD and Mobitex standards mentioned earlier are addressed by two devices manufactured by MX-COM: the MX589 and the MX909. Both devices are designed to interface to the transmitter and receiver of a system at baseband. The MX589 is a versatile device capable of operating at data rates from 4kbps-40kbps and at BT's of 0.5 or 0.3. The device is implemented in a CMOS process that allows it to operate at low supply voltages (3.0-5.0 volts) and draw little current (1.5mA @ 3.0V). The digital data interface is a synchronous serial bit stream for both receive and transmit.

The MX909, also fabricated in a CMOS process, is specifically intended for Mobitex type systems, and has a corresponding BT of 0.3. Its data rate can be varied from 4kbps-19.2kbps, but should be set to 8kbps to achieve Mobitex compatibility. It can be operated from a supply voltage of 4.5-5.5 volts and typically draws 3.0mA. The data interface is a parallel microprocessor I/O compatible bus, and the MX909 contains all the circuitry needed to implement the forward error correction encoding and decoding of the Mobitex format.

The demodulation of the baseband GMSK signal presented to these devices is accomplished using a Gaussian shaped lowpass filter, clock extraction and reference level compensation circuitry in concert with data extraction circuitry. The signal first goes through a Gaussian lowpass filter similar to that used by the transmit section. The signal's zero crossing reference and clock timing are then extracted using peak detection circuitry and a phase lock loop in coordination. This cooperative effort helps improve both section's immunity to noise. Once "lock" has been achieved accurate demodulation of data from the data extraction circuitry can be expected.

The peak detection circuitry can adjust to large changes in DC level of the signal within 1.5 bit periods. This "clamping" mode is used when the carrier is first detected by the receiver. The PLL has a wideband acquire mode that can lock onto a signal in less than 8 zero crossings. Using these two modes allows the devices to start decoding data very shortly after the receiver senses carrier. Both the phase lock loop and the peak tracking circuitry have less aggressive modes that afford better noise immunity once the initial acquire modes have obtained lock. The nature of the GMSK signal at baseband requires good response of the system near DC as mentioned in the section on modulation. A more random data pattern does not have as large a DC component and is less sensitive to the highpass characteristics of any AC coupling that might need to be used to interface the baseband signal to the GMSK modulator or demodulator. The bit error rate (BER) performance of the MX589 is shown in Figure 8. The figure shows the effect of various highpass characteristics on the BER profile of the device.

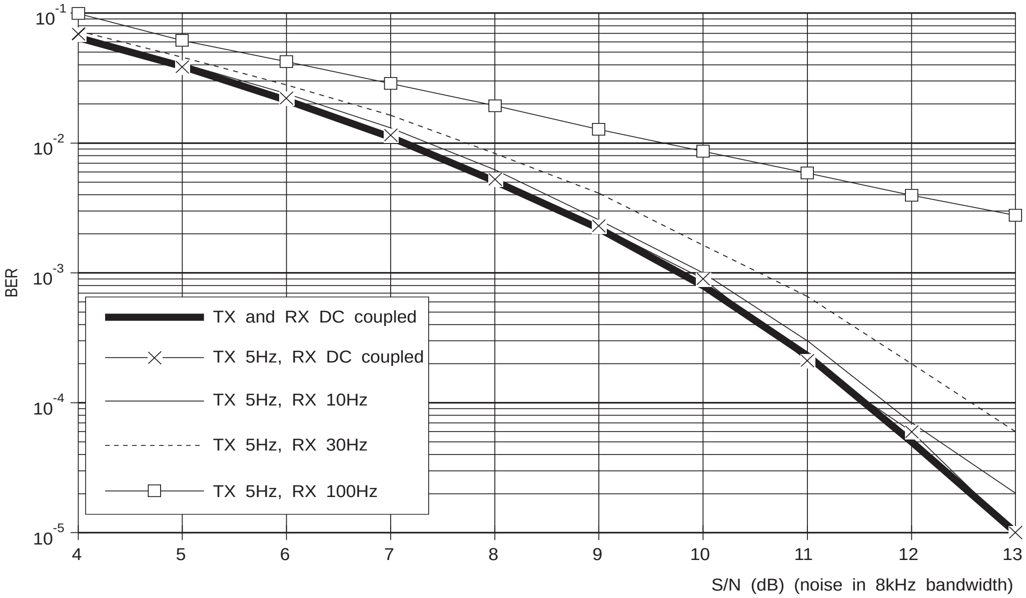


Figure 8: BER performance of the MX589

This figure represents data taken from a static system running at 8kbps with a BT of 0.3 and a noise bandwidth equal to the bit rate. With the noise bandwidth equal to the bit rate, and assuming the noise spectrum at baseband is flat, the x-axis is in essence E_b/N_0. As an alternative to a full DSP implementation, these two devices offer cost-effective and space conservative solutions to the modulation and demodulation requirements of the CDPD and Mobitex GMSK based systems.

Summary

GMSK provides a straightforward, spectrally efficient modulation method for wireless data transmission systems (e.g. CDPD and Mobitex). MX-COM's MX589 and MX909 baseband GMSK modems offer single-chip solutions, facilitating the implementation of a GMSK system using standard FM radio topologies.

Although the MX-COM baseband modems integrate the majority of the modulation signal processing requirements, some key aspects of system design must not be neglected. For instance, the modulator configuration must have a flat spectral response down to DC. In addition, the receiver's phase response must be linear across the BW occupied by the data with special attention focused on the IF filters. Following these recommendations in conjunction with a single-chip baseband modem insures excellent BER performance, low power consumption and low cost.

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