A DSP GMSK Modem for Mobitex and Other Wireless Infrastructures

Appliation Report

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Abstract

Mobitex is a packetized wireless 900-MHz wide area network (WAN) that allows mobile/portable subscribers to transfer data, including e-mail, through the growing national and international network infrastructure. The network operates with an 8-kbps data rate using GMSK.3 modulation. User terminals are typically sophisticated portable or mobile devices that encompass one or more applications and all additional OSI protocol layers necessary to send and receive data on the network. Within the user terminal, the interface between the radio (physical layer) and other layers is a high-performance Gaussian minimum shift-keying (GMSK) modem. During transmission, the modem converts packets of network data into transmit baseband. For receiving, it demodulates similar waveforms into data decisions. The typical Mobitex modem produces at least part of the physical-layer processing necessary for radio interface.

The cellular industry solution for packetized data is called cellular digital packet data (CDPD). The modem waveforms used for Mobitex are similar (GMSK), though CDPD uses 19.2 kbps. Core GMSK concepts, however, still apply; therefore, the modem design described herein can also be used as a basis for CDPD modem development in the future.

Synetcom Digital Incorporated has developed a DSP-based Mobitex modem that accomplishes the radio interface. Transmit data in packet form is level shifted and Gaussian filtered digitally within the modem algorithm so that it is ready for transmitter baseband interface, either via D/A converter or by direct digital modulation. Receive data at either baseband or intermediate frequency (IF) from the radio receiver is digitized and processed by the modem—nearly optimally—into data decisions. Packet synchronization is also handled by the modem, assuring that the next layer sees only valid Mobitex packets. Received signal degradation from frequency offsets, multipath (Rayleigh) fading, and other effects is anticipated and addressed in the modem design.

Introduction

About Mobitex

Mobitex is a packetized narrow-band data service operating near 900 MHz (450 MHz in the United Kingdom), originally conceived by Swedish Telecom and further developed by Eritel, a joint venture of Swedish Telecom and Ericsson. The service is being offered in the United States by RAM Mobile Data/Bell South. Base stations, which typically cover 5–15 mile radii, are arranged in a cellular-like fashion. Network roll-out has proceeded to the extent that coverage within the top 200 U.S. metropolitan areas is advertised. At Synetcom Digital Incorporated's Redondo Beach, California office, five base stations are audible on an indoor cellular whip, four of which have usable signals.

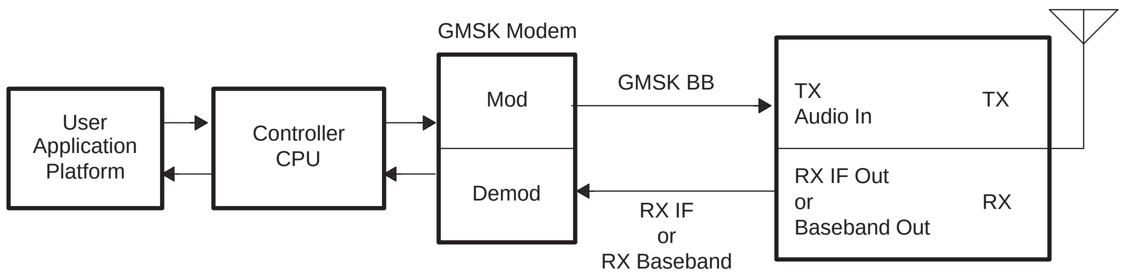
Other Networks

Mobitex falls into the class of wireless WANs. There is at least one other operational infrastructure, called Ardis (IBM/Motorola), and several more are anticipated, including CDPD from McCaw Cellular and its partners.

Mobitex Terminal Hardware Architecture

Figure 1 shows a typical terminal architecture. Controller CPU functions typically handle higher OSI layers, which form packets, provide error coding and scrambling, handle acknowledgments, and control transmitter and receiver operation.

Figure 1. Typical Mobitex Terminal Architecture



WAN Modems and the Radio Channel

WAN modems are designed to operate with signal distortions produced by multipath frequency offsets and nonideal radio IF filters. Multipath distortion occurs when a signal reflection causes propagation along several paths across the link. Different path lengths and reflections produce signal components with unequal amplitude and delay, which vector sum at the receiver. For fixed links, the vector sum looks like a superposition of comb filters in the frequency domain. In the time domain with long delays, symbol energy is *smeared*; this smearing is known as intersymbol interference (ISI). A null (cancellation) or significant slope at or near the carrier frequency causes severe distortion to the received signal, which can degrade bit error rate (BER) performance.

The actual multipath parameters vary spatially for mobile links. The receiver sees time-varying comb functions with nulls that traverse the spectrum and momentarily align with the signal frequency, causing deep fades. Under these conditions, the received carrier-envelope amplitude has been shown theoretically and experimentally to conform to a Rayleigh distribution. Based on this model, it has been shown that 99.9% of fluctuation occurs within a dynamic range of 40 dB [1].

Typical radio systems allow for some frequency error (tight frequency tolerance is expensive), which may degrade modem receive performance. Receiver IF and baseband filtering is also never ideal and can introduce additional waveform distortion from ISI.

The Mobitex modem design described herein anticipates these and other distortions and has been shown to operate satisfactorily in laboratory simulations of the degradations. Mobile field tests are anticipated to further qualify modem performance.

Advantages of DSP Modems

Modem DSP code is written to closely approximate the ideal modem architecture—typically, more closely than an analog implementation approximates it — potentially realizing outstanding modem performance that is repeatable over time and temperature. The approach is flexible because all modem parameters can be trimmed in software.

A DSP can assume other chores in the user terminal and may become the platform for additional protocol layers required for a given network, assuming enough spare MIPS are available, and it may even be reconfigured to interface with other networks on multiple layers.

DSP chips are on the same fast track as CPUs, with smaller feature size, higher speed, lower power, and lower voltage required with each new generation. Competition among several major corporations has brought pricing down to levels that compete favorably with discrete analog and ASIC implementations.

Mobitex DSP Modem Characteristics

Code Size and DSP MIPS Requirement

The Mobitex modem code is actually two distinct algorithms associated with half-duplex transmit and receive functions. The receive (digital demodulator) algorithm is more complex and embodies most of the important features necessary for a successful modem design. As with all modems, receiver code requires more processor power, as shown in Table 1.

Table 1. Receiver-Code Processor Power Requirements

Function	Code Size	TMS320C25 MIPS Requirement
Transmit GMSK Modulator	256 words	3
Transmit PN Generator	128 words	1
Receiver Digital Demodulator	500 words	6
Receiver Discriminator†	128 words	4

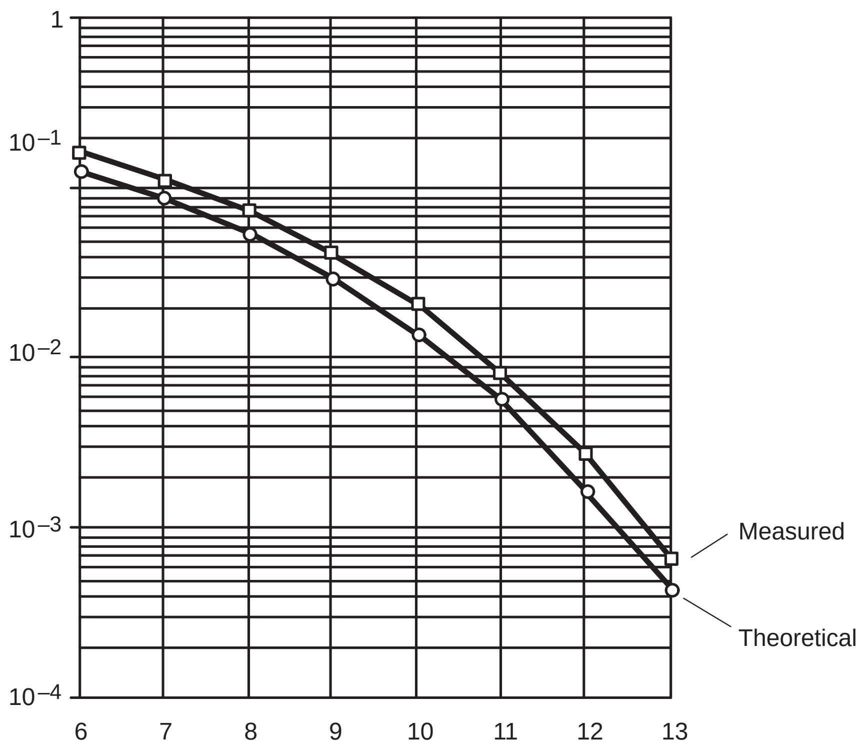
† Discriminator code is required if the A/D interface is receiver IF.

Bit-Error-Rate Performance

The BER performance of a pair of the Mobitex modems was measured in the laboratory. GMSK IF and Gaussian noise are summed to create an approximation of the noisy radio channel, representative of weak receive signals. Signal and noise power levels are calibrated relative to each other and converted to E_b and N_o values through bit rate and equivalent bandwidth normalization. The test scenario increments noise in 1-dB steps and captures BER data.

Results are plotted against theoretical performance in Figure 2. Performance is quite close to ideal (< 0.5 dB) over the range of data shown. Transmit GMSK is a continuous 2^9–1 pseudorandom noise (PN) code.

Figure 2. Bit Error Rate Versus E_b/N_o Modem Performance



Modulator Design

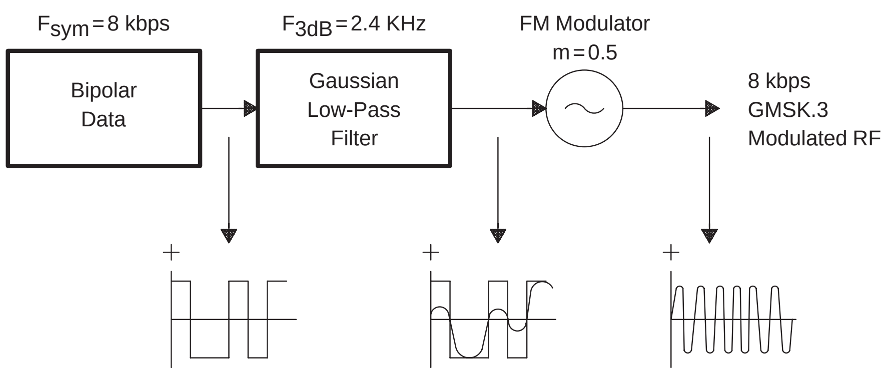
GMSK.3 Modulation

GMSK has been widely proposed and utilized for mobile radio data communications. In addition to Mobitex, GMSK is used for GSM (European digital cellular) and CDPD in the U.S. Several characteristics that make it especially attractive for these applications are:

- Spectral efficiency (12.5-kHz channels for 8-kbps GMSK.3)
- Constant RF envelope (efficient class-C amplifiers and hard-limiting receivers)
- Compatibility with analog FM techniques
- Reasonable performance (assuming proper modem techniques) in multipath environment

As illustrated in Figure 3, GMSK.3 is generated with Gaussian low-pass filtered bipolar data, applied to a DC coupled FM modulator, set to a modulation index of 0.5.

Figure 3. Idealized GMSK.3 Generation



The .3 suffix on GMSK refers to the BT, or bandwidth, symbol time product. Alternatively, BT can be expressed as the ratio:

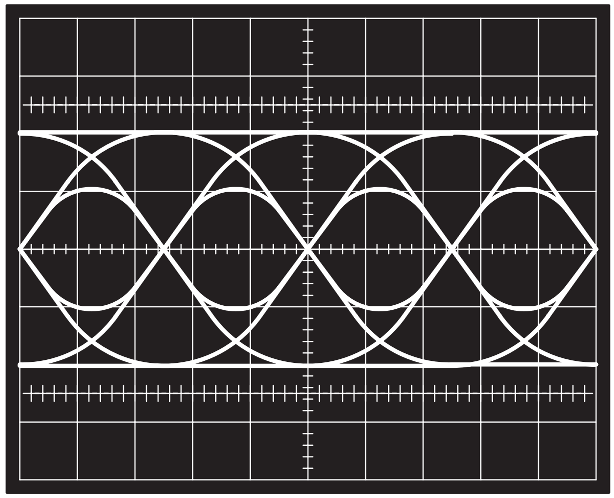
$$F_{tx} / F_s = 0.3 \text{ for GMSK.3}$$

where F_{tx} is the transmit filter with a 3-dB bandwidth and 2.4-kHz frequency, and F_s is the symbol rate.

As the ratio increases, more energy at higher frequencies is transmitted, occupying more radio spectrum. A decrease in ratio below 0.2 attenuates higher frequencies significantly, compromising obtainable performance.

The eye pattern for GMSK.3 baseband signals is shown in Figure 4. An eye pattern conveys every possible trajectory in the transmit/receive data baseband waveform synchronized to symbol timing. It is useful because it can very quickly convey the *fidelity* of transmit and receive data and is a strong diagnostic tool in the wireless development environment.

Figure 4. Eye Pattern for 8-kbps GMSK.3, 2^{15}–1 Length Pseudorandom Transmit Data†

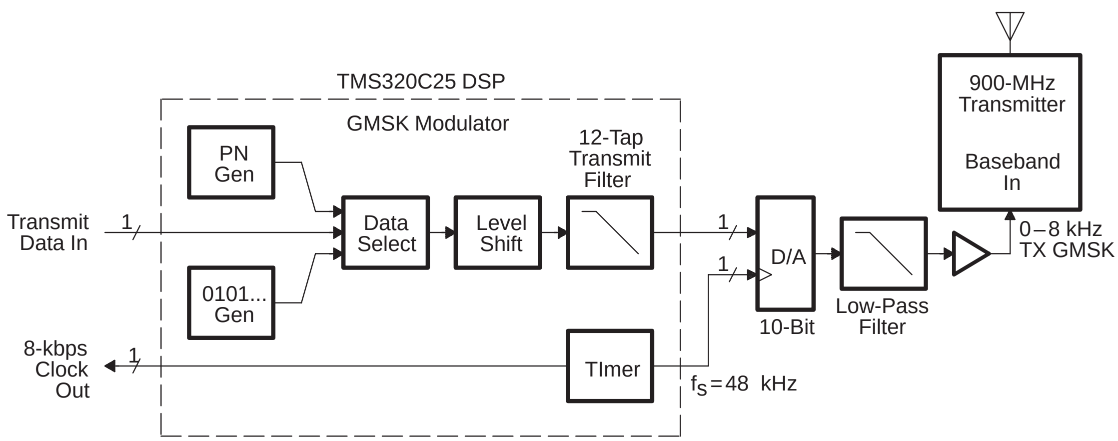


† Signal observed at the output of the transmit filter

GMSK Modulator Architecture

A block diagram of the modulator DSP implementation is shown in Figure 5.

Figure 5. GMSK Modulator DSP Implementation



The present GMSK modulator algorithm accepts data from upper OSI layers that has been packetized, error encoded, and scrambled according to Mobitex specifications. In most systems, this is accomplished on a CPU in the application computer or in a separate microcontroller. Ultimately, these functions can occur on the DSP.

The modulator algorithm either accepts external data or can generate pseudorandom (PN) data with 2^7–1, 2^9–1, and 2^{15}–1 length codes for transmit test purposes. This feature enables easier bit-error-rate measurements, eye-pattern checks, and other system measurements during integration with radio gear.

The DSP algorithm implements a level shift and digital low-pass filter function on the square data provided by the other OSI layers or the algorithmic PN generator. A 12-tap (two symbol length) linear-phase FIR structure forms the transmit filter, which is designed to approximate the ideal Gaussian transmit filter very closely. The FIR 3-dB point is set to 2.4 kHz for BT = 0.3. The modulator sample rate is 48 kHz, producing a baseband bandwidth with significant energy out to approximately 5 kHz and virtually no energy beyond 10 kHz.

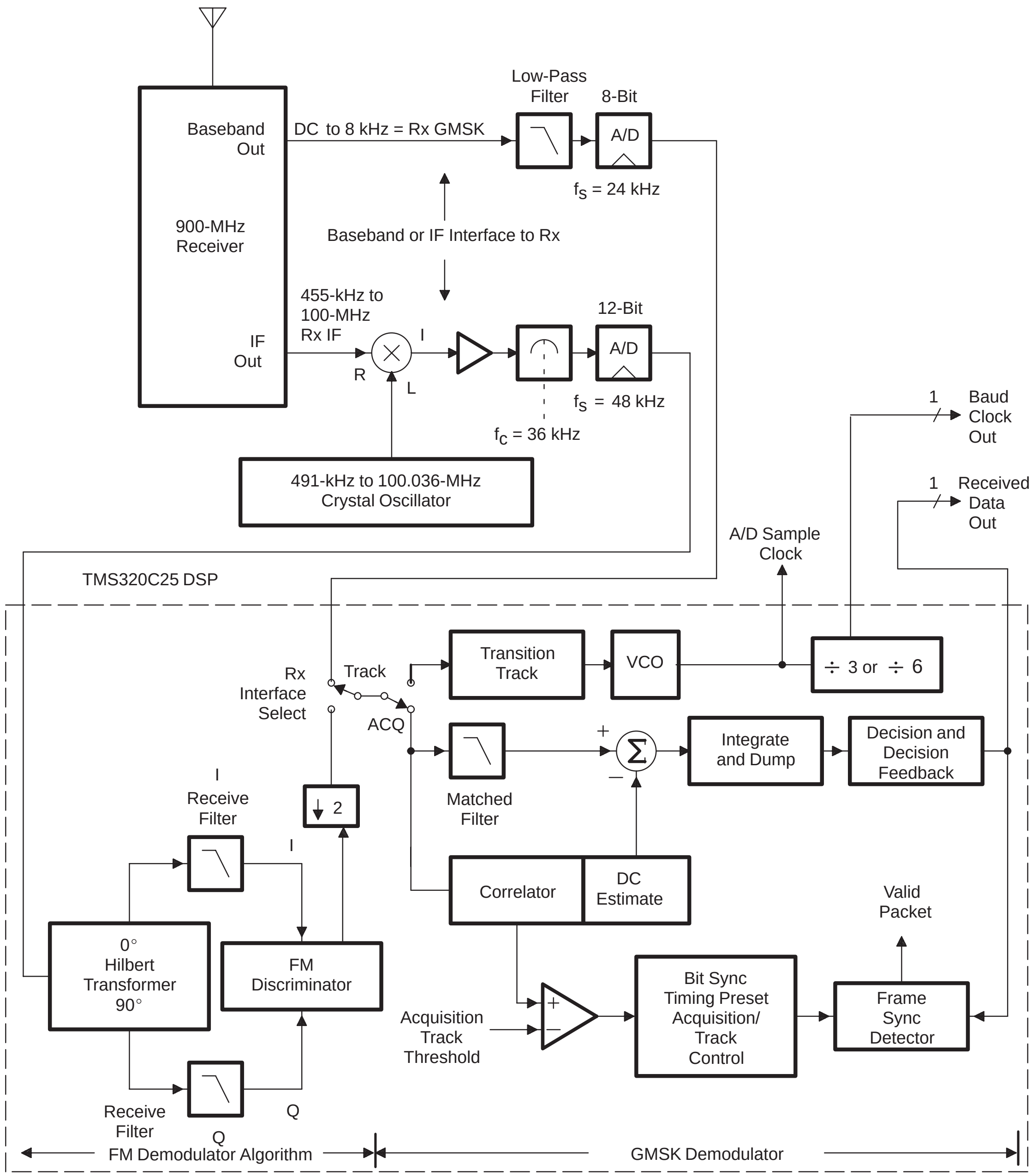
The modem exists on an evaluation board that contains a 16-bit D/A converter and low-pass reconstruction filter that attenuates digital spectra beyond $f_s/2$ (24 kHz) to levels near the noise floor. Other implementations can exploit the latest single-chip CODEC or analog interface circuits, which combine several D/A and reconstruction filter blocks with A/D converters. A single chip can thus furnish the entire radio-analog interface. Ten-bit precision D/A converters are adequate for this application.

GMSK Demodulator Design

GMSK Demodulator Architecture

A block diagram of the demodulator structure is shown in Figure 6. The upper half of the figure shows an external interface to a 900-MHz radio receiver. Either a baseband or an IF interface is possible with this algorithm. The IF interface includes an FM discriminator function in the DSP code.

Figure 6. GMSK Demodulator DSP Implementation



The demodulator algorithm employs noncoherent techniques to arrive at each data decision. Two entry points for digitized data from the receiver are shown in Figure 6.

Digitized IF Processing

As the cost and power consumption of DSP MIPS and associated A/D converters decrease, it will make sense to locate the A/D converter closer to the antenna, somewhere in the radio IF strip. Traditionally, digital processing at IF has been applied to expensive military systems in which the highest possible receiver performance is required. As DSP costs decrease and techniques improve, IF processing may become standard in wireless applications, where both benefits—cost and performance—are possible. In anticipation of this next step, a radio IF interface to the DSP demodulator algorithm was created.

Band-limited radio IF (presumed to be at 36 kHz center, 12.5 kHz wide for Mobitex) is digitized at a sample rate of 48 kHz, realizing a digital down-conversion to a center frequency of 12 kHz. The DSP algorithm then implements a close approximation of a 0°/90° splitter that feeds a pair of identical, 7-tap low-pass FIR receive filters, carefully bandwidth optimized under noise conditions for best overall demodulator performance.

Digital FM Discriminator

The FM discrimination algorithm maps the frequency of complex IQ samples to a voltage using a differential estimation technique. Sample-rate decimation by a factor of 2 is also used, yielding subsequent processing that executes only on every other input IF sample. After decimation, the discriminator normalizes each sample by $I^2 + Q^2$ to wipe off any IF energy variation, due to radio channel fades that fall out of the receiver's hard limiting or AGC range. The dynamic range of the normalization algorithm approaches 40 dB when used with a 12-bit A/D converter.

Normalization becomes a significant issue if the receiver RF/IF chain must have linear or AGC loop-controlled gain. Certain modulation types require linear receiver performance. In a multinetwork/infrastructure environment, linearity may be a requirement. The normalization algorithm exists to cover that eventuality, even though most implementations to date have used hard limiting and traditional FM receiver techniques.

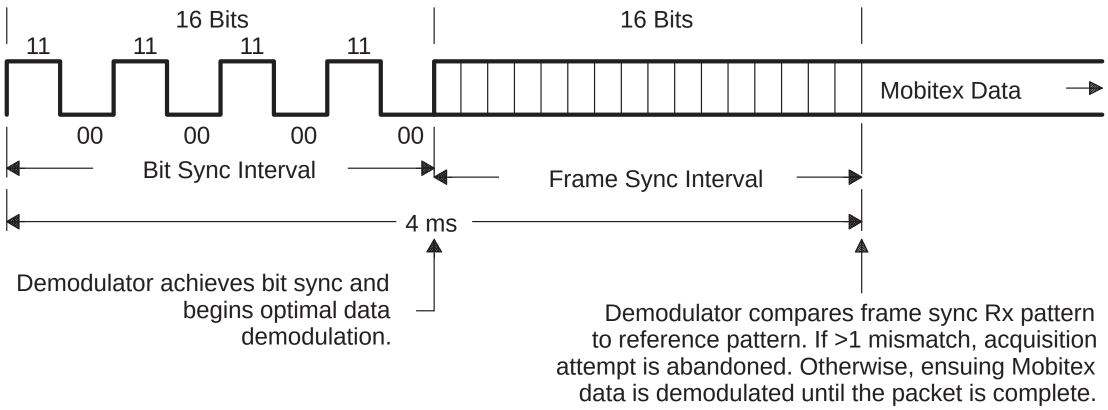
Baseband Processing

A second entry point to the demodulator algorithm can be selected just after the digital FM discriminator of Figure 6. The receiver baseband (audio DC to 8 kHz) that carries the data waveform is digitized by at least an 8-bit A/D converter at a sample rate of 24 kHz. Less precision is required because the receiver hard limiting and discriminator mitigate most of the envelope fluctuation due to flat signal fading. Processing beyond this point is identical regardless of which input is selected.

Packet Acquisition

All received Mobitex packets are qualified by an acquisition process that recognizes and exploits information in the first two data structures of the Mobitex packet, which is shown in Figure 7.

Figure 7. Mobitex Packet Structure



When the demodulator is not tracking and demodulating a qualified packet, an FIR filter-based structure that implements pattern specific correlation is executed. The correlator searches for the bit sync pattern. When correlator output exceeds a preset threshold, demodulation begins and frame sync, which is a fixed, country-specific pattern 16 bits long, is expected. If frame sync does not occur within the next 16 bits with one bit error or less, the packet acquisition attempt is abandoned and the correlation process is begun again. In this manner, probability of false acquisition is kept very small, and higher OSI layers in the user terminal receive data only when qualified packets are present.

Simultaneous to successful correlation, a low-bandwidth tracking-loop algorithm is invoked. Data transitions (zero crossings) are extracted, and the algorithm attempts to keep crossings aligned by adjusting the DSP timer register, which ultimately generates sample pulses to the A/D converter. The resulting servo loop is invoked as long as the qualified packet data is present. This feature is especially important for long packets and operates reliably even with very weak receive signals.

Also, after each successful correlation, a DC estimate (which is proportional to receiver frequency offset relative to base station) is extracted from the bit sync sequence and is used to cancel DC offsets in the baseband demodulation (track) path. The modem performance is made tolerant of frequency offsets in this manner.

Finally, the correlator triggers an A/D sample timing preset. Correlator output information is examined, and a precise estimate of correct initial A/D sample phase and frequency is made. The preset timing is subsequently updated very slowly at each zero crossing with the aforementioned servo loop.

Data Demodulation

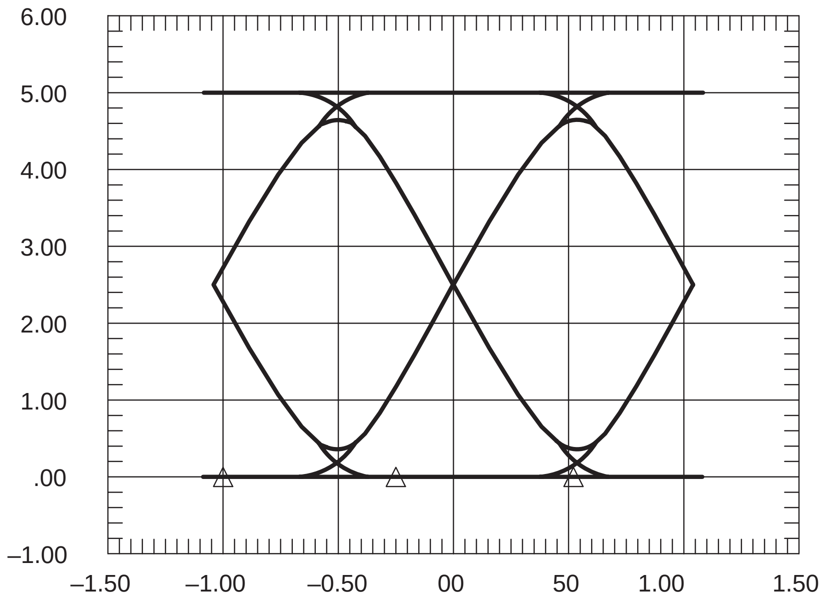
After correlation to the packet bit sync pattern occurs, the data demodulation/decision process begins. Conceptually, the goal of the decision process is simple: every three samples (at 24 kHz) produce either a zero or one data decision such that the original packet data, prior to modulation, is recovered.

The decision process employs matched filtering (which is identical to transmit filtering), integrate-and-dump, and decision feedback techniques to minimize the probability of bit errors. The integrate-and-dump and decision feedback algorithms are especially effective under disturbed conditions, such as with either fixed or time-varying multipaths, and they also reduce modem sensitivity to ISI induced by receiver filters.

Design Adaptations for CDPD

The CDPD modem requirement is for GMSK.5 radio waveforms at 19.2 kbps. CDPD utilizes cellular channels that are full-duplex; the packetized protocol can use this characteristic, though a half-duplex CDPD implementation is also possible. A computer simulation of the transmit eye pattern for GMSK.5 is shown in Figure 8.

Figure 8. Computer-Simulated Eye Pattern for 19.2 kbps GMSK.5 (Amplitude Versus Time)



As compared to Mobitex, the higher baud of CDPD dictates use of a more powerful DSP chip, such as one from TI's TMS320C5x family, to support the modem function. Generally speaking, a good estimate for half-duplex CDPD MIPS required for the GMSK demodulator can be obtained by simply scaling the 6-MIPS benchmark for the baseband-interfaced Mobitex demodulator. A conservative approximation is based on the ratio of bauds (19.2 / 8 = 2.4). CDPD, therefore, can require up to 14.4 MIPS peak for the receive modem function.

Digital demodulators can operate with fewer samples per baud than were assumed above. The Mobitex modem uses an A/D converter to sample IF at 48 kHz or baseband at 24 kHz. The algorithm ultimately uses three samples per 8-kHz symbol in the data-decision section.

For CDPD, it is estimated that if two samples per baud are used, approximately 0.7 dB of performance is sacrificed. The associated baseband sample rate is 38.4 kHz, and the corresponding MIPS requirement is approximately 10 (33% less than the 3 samples-per-baud case).

CDPD's GMSK.5 uses a higher BT factor (0.5). The immediate result is an eye pattern that is less filtered than shown in Figure 4. Overall modem receive performance is correspondingly improved. Adjustments of constants in the current decision feedback algorithm are necessary to optimize performance, though the current constants (based on GMSK.3) will operate surprisingly well.

CDPD transmit baseband eye pattern has been simulated and is shown in Figure 8. The Gaussian transmit filter 3-dB frequency is 9.6 kHz. The transmit and receive Gaussian digital filter is adjusted for the new bandwidth.

Transition of GMSK Modem to TMS320C5x

Work has begun to translate the existing ’C2x code to a ’C5x processor. The GMSK modulator and portions of the demodulator algorithm are currently able to execute successfully on TI’s EVM system. The translation is very straightforward, using TI’s DSP assembly conversion utility (DSPCV.EXE), and the utility is able to convert ’C2x source code (.ASM) files directly to ’C5x source code files. A minor amount of manual intervention is necessary after running the utility. This intervention is associated with memory directives that do not have exact equivalents between the two processor families.

Conclusions

Packet networks such as Mobitex or CDPD generally operate with a sophisticated protocol that allows for error detection, limited error correction, and, if all else fails, packet retransmission. All data is eventually received successfully across the link. High-performance modem techniques are employed to meet overall network performance requirements because inferior modems can generate unnecessary traffic, requiring repetition of missed data.

The Mobitex modem code exists on a 16-bit fixed-point TMS320C25, which is an entirely adequate platform for the core modulation/demodulation algorithms implemented. No issues associated with the 16-bit fixed-point precision were encountered. In general, no applications are envisioned in which floating-point processors or wider fixed-point registers are necessary for wireless modems anticipated for future implementation.

The existing code is portable to the Texas Instruments TMS320C5x family, which will ultimately offer 3.3-volt, 40-MIPS operation, suitable for battery-powered portable operation. The fully implemented IF interface Mobitex modem algorithm requires 10 MIPS for demodulation. The ’C5x family and similar processors from other manufacturers open prospects for other layers of wireless protocol executing on the same DSP, with ultimate partitioning of DSP and controller-processing responsibilities dictated by DSP/processor cost, memory requirements, speed and power consumption, and interface issues. All new designs should weigh these issues carefully.

The DSP chip offers flexibility beyond Mobitex. Multiple wireless infrastructures, including CDPD, can ultimately be accommodated on the same processor, which, in fact, may be necessary for long-term product survival. As wireless/PCN industries take shape, the emphasis will likely be on flexibility. Systems that are incompatible starting at the lowest link/physical layers will dictate that user radio/modem devices be capable of loading and executing new modem and control (protocol) code as needed. A single user terminal can thus interface with multiple infrastructures.

Code Availability

The associated software is available for licensing from Synetcom Digital Incorporated, 1426 Aviation Boulevard, Suite #203, Redondo Beach, California 90278.

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