Implementing the High Speed Modem with Multidimensional Modulation Using the TMS320C542 DSP

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Contents

Figures

Tables

Implementing the High Speed Modem with Multidimensional Modulation Using the TMS320C542 DSP

Abstract

This paper presents the high speed modem with multilevel multidimensional modulation.

The multilevel linear combination of shifted prolate wave spheroidal functions with dual orthogonality is used as information carrying signal. It enables transition from two-dimensional basis (Phase Shift Keying, Quadrature Amplitude Modulation) to more dimensional basis (Multilevel Multidimensional Modulation).

The use of this basis increases information speed and/or noise stability. The shifted prolate wave spheroidal functions are solutions of the special integral equation.

The new features of the Texas Instruments (TI™), TMS320C542 Digital Signal Processor (DSP) make implementation of a high-speed modem, more effective.

This document was part of the first European DSP Education and Research Conference that took place September 26 and 27, 1996 in Paris. For information on how TI encourages students from around the world to find innovative ways to use DSPs, see TI's World Wide Web site at www.ti.com.

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Introduction

The demand for high-speed data communication is increasing. The general switched telephone network (GSTN) is available for data transmission, i.e. for signal/noise ratio (SNR) above 30 dB data rate can be up to 30-50 Kbps according to Shannon theorem.[1]

Nevertheless, the presence of inter-symbol interference prevents a further increase in data rate. It puts forward a complex problem of struggle with inter-symbol interference in high-speed systems of communication, which includes two tasks:

1) The synthesis of signals with finite spectrum for high-speed multi-level system of data transfer through band-limited channels. These signals are optimum in sense of their use in adjusted channels, which eliminates intersymbol interference caused by high-speed transfer of multi-level signals through sharply band-limited channels.

2) The synthesis of adaptive equalizers which enable to compensate all kinds of linear distortions of the frequency response of channels of multi-level communication systems.

The common method for increasing the spectrum using efficiency at the high signal/noise ratio (SNR) is application of quadrature amplitude modulation (QAM) with a large number of quantization levels in each quadrature component. Practically, the achievable number of used signals reach 1024 and requires SNR not worse than 43 dB at error probability of 10^{-3}.

The QAM signal is usually presented by the following expression:

$$S_{QAM} = \sum_{k=0}^{M} a_k \cdot A(t - kT) \cdot \cos(\omega(t - kT) + b_k \cdot A(t - kT) \cdot \sin(\omega(t - kT)) \qquad (1)$$

The pair (a_k, b_k) in this expression determines the position of a signal in the signal space and is a code for an information symbol. Function(s) *sin* and *cos* are orthogonal carriers, T – a duration of an elementary signal. The envelope $A(t)$ is chosen to provide orthogonality of signal carriers on the finite signal interval T and required frequency band of a signal spectrum.

The duration of an elementary signal is limited by a pass-band of a communication channel (Nyquist rate), therefore the only opportunity to increase the throughput of a modem is an increase in the number of used points in the signal space.

It results in a decrease of noise stability through signal distance decreasing at the limited maximum power of the signal. Therefore the modem with QAM signals require high SNR.

In order to permit this contradiction it is offered to use not two, but three and more orthogonal carriers with given time-frequency properties and quantize each of them on levels.

The Functions with Dual Orthogonality Theory Review

The functions having a finite spectrum in the frequency band [*0, Ω*] and the minimum effective duration *T* was found by Landay and Pollak[2] as a solution of integral equation:

$$\lambda_n \cdot \psi_n(t) = \int_{-T/2}^{T/2} \psi_n(\tau) \cdot \frac{\sin \Omega(t - \tau)}{\pi(t - \tau)} d\tau, \tag{2}$$

These functions called prolate wave spheroidal have dual orthogonality

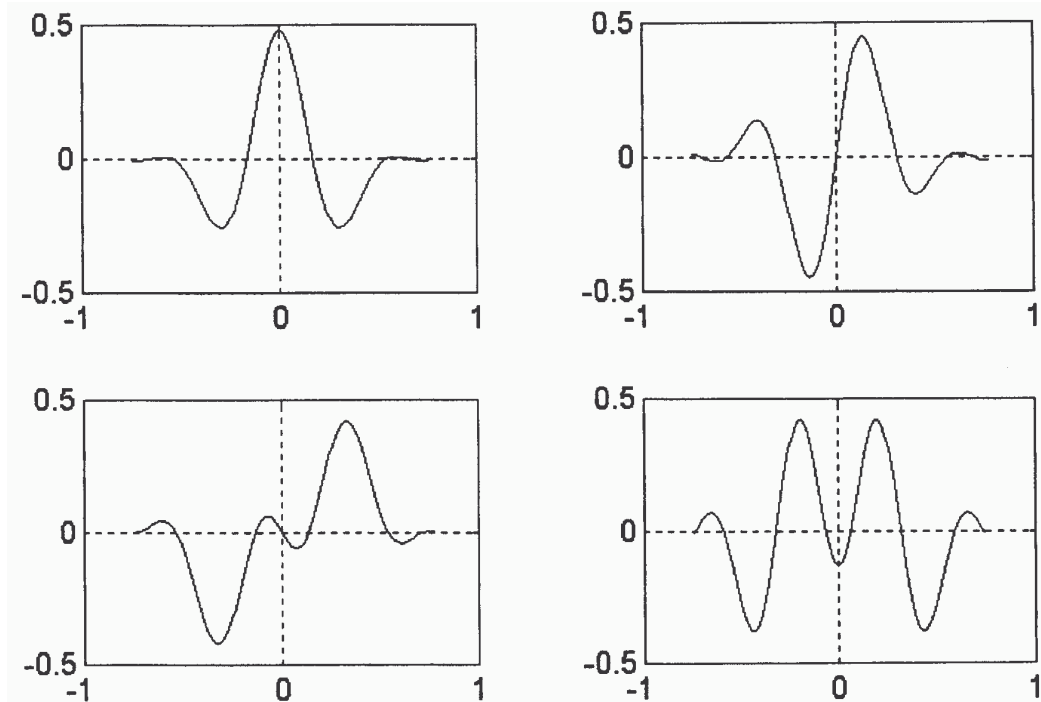$$\int_{-\infty}^{\infty} \psi_i(t)\psi_j(t)dt = \begin{cases} 0, & i \neq j \\ 1, & i = j \end{cases}, \tag{3}$$

$$\int_{-T/2}^{T/2} \psi_i(t)\psi_j(t)dt = \begin{cases} 0, & i \neq j \\ \lambda_{i,} & i = j \end{cases}, \tag{4}$$

However, we need functions with the same properties but having spectrum in frequency band $\left[\omega_0 - \Omega/2, \ \omega_0 + \Omega/2 \right]$.

In this case the integral equation acquires a kind:

$$\lambda_n \cdot \psi_n(t) = \int_{-T/2}^{T/2} \psi_n(\tau) \cdot \frac{\sin((\Omega/2)(t - \tau))}{\pi(t - \tau)} \cdot \cos(\omega_0(t - \tau))d\tau, \tag{5}$$

Figure 1. The Basis Functions for Four Dimensional Space

Where:

$\psi_n(t)$ - the *n*-th eigenfunction of the integral equation;

λ_n - the *n*-th eigenvalue of the integral equation.

They are called as part of the shifted prolate wave spheroidal function. These functions have the duration *T* and are concentrated in the band Ω close to the central frequency ω_0.

From the theory of functions with dual orthogonality it is known, that three basis functions reach 99% energy concentration at $\Omega T/2=7$ and four basis functions at $\Omega T/2=9$.

The basis of the four-dimensional space is shown in Figure 1. as example. The results are obtained by the numerical method solution of the integral equation (5).

The information-carrying signal is the multi-level linear combination of shifted prolate wave spheroidal functions with dual orthogonality and can be described as:

$$S_{MMM} = \sum_{k=1}^{M} \sum_{n=1}^{N} a_{kn} \cdot \psi_n(t - kT), \tag{6}$$

Where:

α_{kn} – information symbol of the *n*-th basis function on the *k*-th signal interval;

N - space dimension.

These functions are used similarly to function(s) *sin* and *cos* in QAM, but do not define two-dimensional space, but space of greater dimensions.

The duration of signal *T* is chosen from a condition of given concentration of $\psi_n(t)$ energy and determines throughput of a modem.

Thus the elementary signal will belong in a three or four dimensional space.

Multilevel Multidimensional Modulation (MMM)

See Figure 2 for functional diagram of MMM model.

The input bit stream is partitioned into symbol vector α, which format defined by space dimension N and the number of quantizing values Q.

The modulator forms the MMM signal according to formula (6). The model of channel imitates the signal transformation in the communication path (band-pass filter and additive white noise).

The correlator calculates the projections of received signal $S'_{MMM}(t)$ to basis functions ψ on the signal interval T:

$$a_i^{'} = \int_0^T s'_{MMM}(t) \cdot \psi_i(t)dt, \tag{7}$$

and forms preliminary symbol estimation vector α'.

Figure 2. The Functional Diagram of the MMM Model
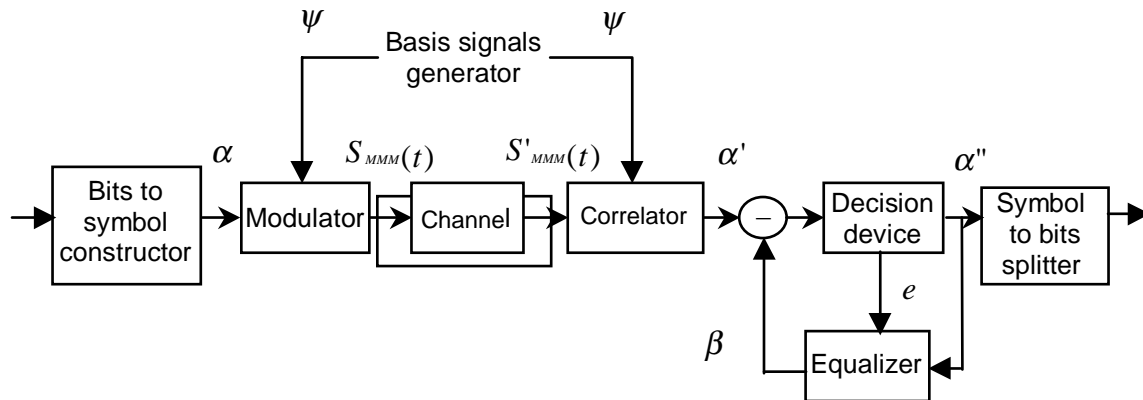
The decision device finds the nearest available signal point from a difference between the preliminary estimation of received symbol α' and the current estimation of inter-symbol interference symbol β and then produces the decision vector α'' and error vector e.

$$\alpha^{'} - \beta = e + \alpha^{''}, \tag{8}$$

Multidimensional Equalizer with Decision Feedback

There are three basic approaches to the design of an adaptive equalizer [3]:

1) T-spaced equalization;

2) Fractional- spaced equalization;

3) Decision feedback equalization.

By the conducted research it is shown that the decision feedback equalizer with a least mean square (LMS) adaptation algorithm is most effective for multi-level multi-dimensional modulation.

The equalizer is multidimensional adaptive FIR filter with least mean square (LMS) algorithm and its functional diagram is represented in Figure 3. It performs forward modelling of a channel in space spanned on the basis functions.

Based on the decision vector α'' and error vector e, the equalizer calculates the new state of filter coefficients B and the current estimation of inter-pulse interference symbol β according to the following expressions:
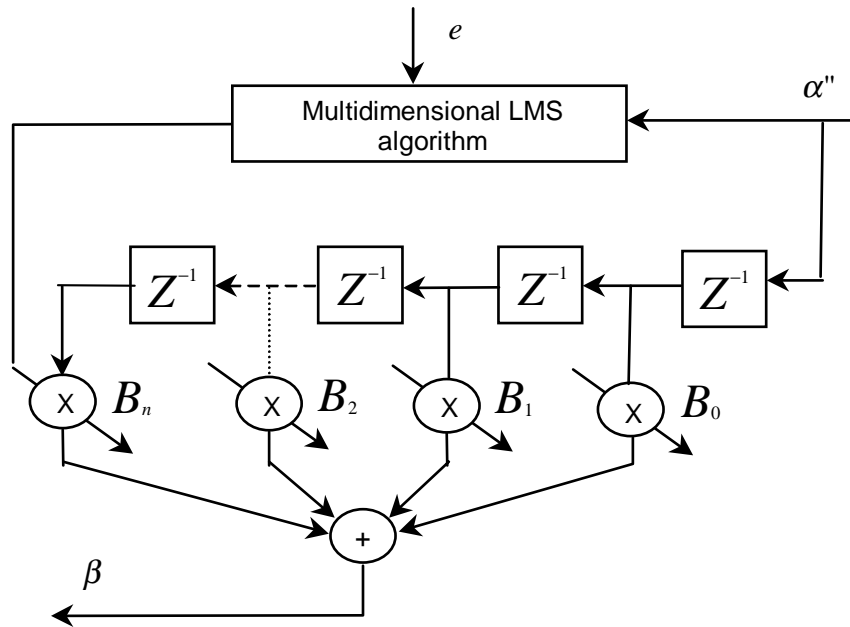
$$B(n) = B(n-1) + \mu \ * \ BC(n), \tag{9}$$

Where:

μ - adaptation constant;

$$\beta(n) = \sum_{k=0}^{M-1} B(k)*a''(n-k), \tag{10}$$

Figure 3. The Functional Diagram of the Multi-dimensional Equalizer with Decision Feedback

The length of FIR filter M depends on the required group delay ripple (channel memory) which must be compensated.

The adaptation constant μ depends on M and rate of channel fluctuation characteristics and is assigned to reach the convergence of the LMS adaptation algorithm.

The channel is identified by equalizer training during one of the connection preamble phases by special training sequence. During information receiving the equalizer is adjusted by α'' decisions.

See Figure 4 for an example of the equalizer training curve.

The structure of a correcting matrix $BC(n)$ is determined by properties of space spanned on the basis functions and has a special form (as an example for four dimensional space):

$$BC = \begin{bmatrix} 2\,e_1\alpha_1'' & e_1\alpha_2''-e_2\alpha_1'' & e_1\alpha_3''+e_3\alpha_1'' & e_1\alpha_4''-e_4\alpha_1'' \\ e_2\alpha_1''-e_1\alpha_2'' & 2\,e_2\alpha_2'' & e_2\alpha_3''-e_3\alpha_2'' & e_2\alpha_4''+e_4\alpha_2'' \\ e_3\alpha_1''+e_1\alpha_3'' & e_3\alpha_2''-e_2\alpha_3'' & 2\,e_3\alpha_3'' & e_3\alpha_4''-e_4\alpha_3'' \\ e_4\alpha_1''-e_1\alpha_4'' & e_4\alpha_2''+e_2\alpha_4'' & e_4\alpha_3''-e_3\alpha_4'' & 2\,e_4\alpha_4'' \end{bmatrix}$$

Figure 4. Equalizer Training Curve
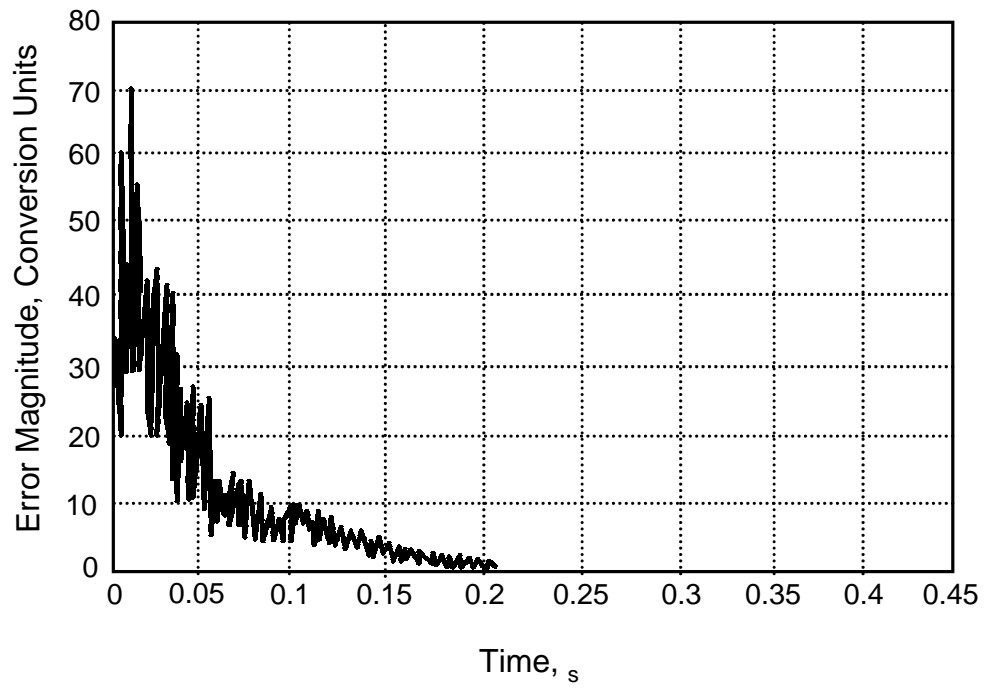
High Speed Modem with MMM

This chapter describes the signal part of the modem only.

At first it needs to choose the dimension of used signal space. The theoretical relationship between required SNR and dimension of space is obtained:

$$h^2 = \frac{2 \arg erfc(p_0)}{c(N)} \cdot 2^{\frac{2C(N)\gamma}{N}},$$ (11)

Where:

h^2 - required SNR for given error probability p_0;

N - dimension of space;

$c(N)$ - the time-bandwidth product (F*T) required for N dimension space generation with given energy concentration.

The required SNR for different space dimensions N, given error of probability $P_0=10^{-3}$ and efficiency of spectrum using $\gamma = 10$ bps/Hz is shown in Table 1.

Table 1.

N	1	2	3	4
c(N)	1.00	1.00	1.115	1.432
h^2 dB	73.22	43.11	34.90	33.01

The high-speed voice band modem with MMM was designed with following basic features:

1) Frequency range   300 – 3400 Hz

2) Data rate   28.800 bps

3) Sampling rate   9600 Hz

4) Symbol rate   1200 boud

5) Signal basis   4 orthogonal vectors

6) Signal points mapping 64 (6 bits) points per dimension

7) Equalizer filter length   21 taps

8) Adaptation constant 10^{-4}

For the observation of modem characteristics the channel filter with the following frequencies responses (Figure 5, Figure 6) is used.

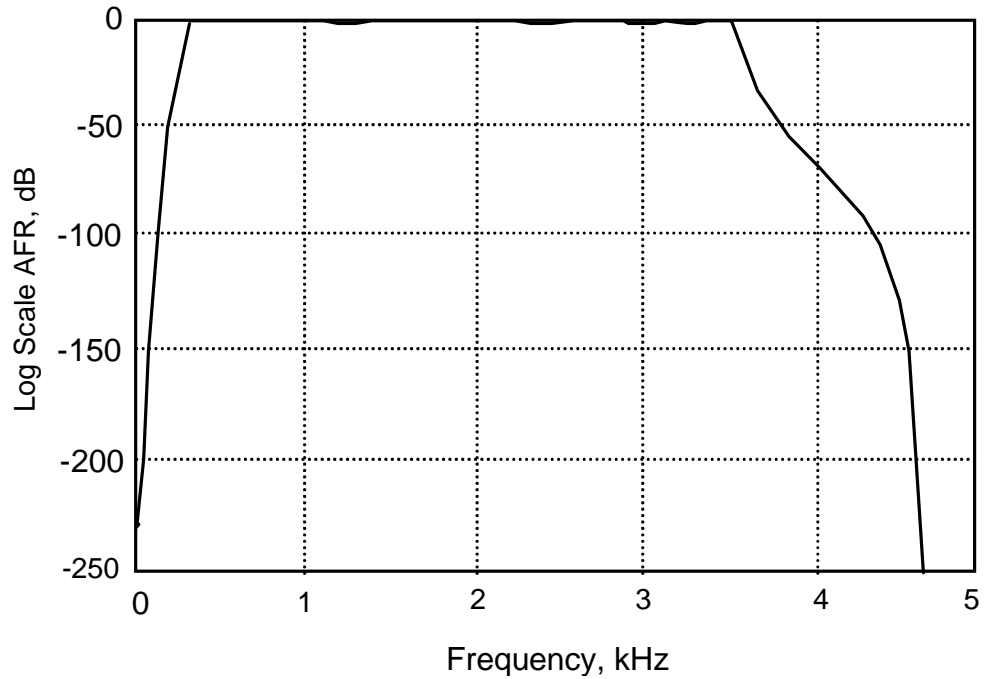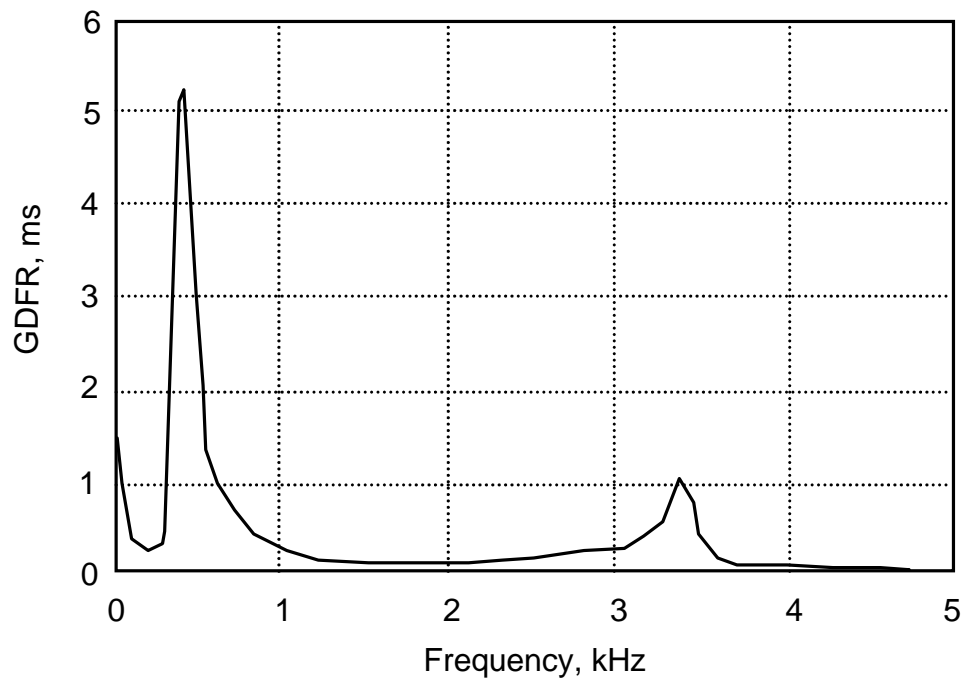Figure 5. Channel Amplitude Frequency Response

Figure 6. Channel Group Delay Frequency Response

There are two models:

1) The channel identification by equalizer training by known sequence.

   The channel identification interval is 250 ms, (see Figure 4) for SNR = 35 dB and remaining error RMS = 0.05 for minimal signal distance equal 1.

2) The information transmission when equalizer has been tuned.

   The bit error rating (BER) character is obtained by MATLAB modeling without any forward error correction (FEC) in shown in Figure 7.

Figure 7. Bit Error Rating
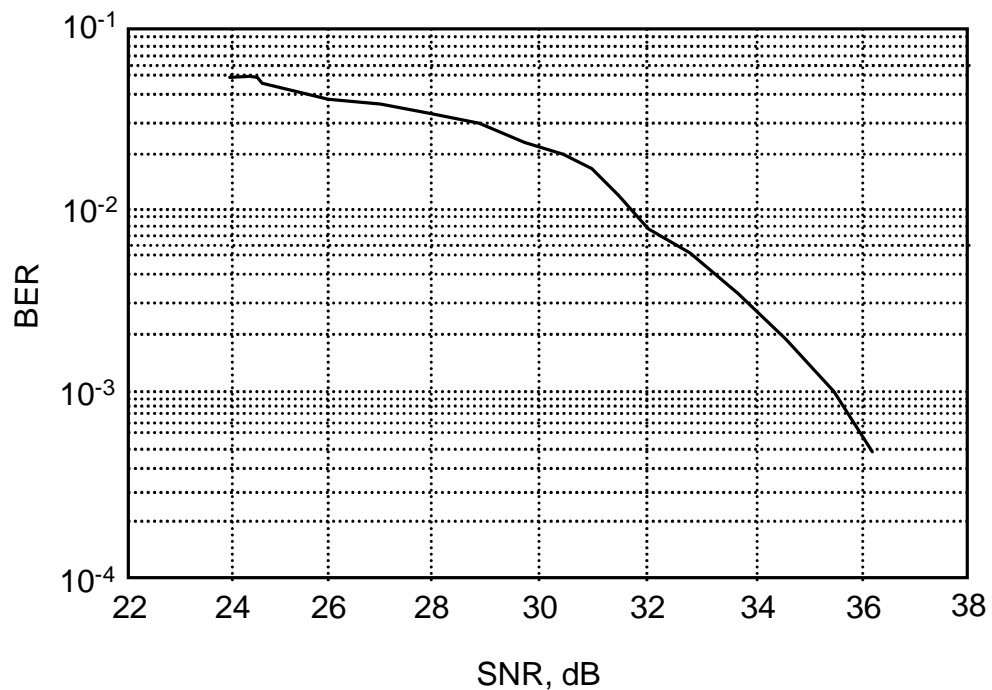
The Modem Implementation on the TM5320C542

The new features of the TM5320C542 make possible an effective implementation of the high-speed modem with multi-level multi-dimensional modulation.

The TMS320C54x generation has superior operational flexibility and speed, a CPU with a high degree of parallelism and application-specific hardware logic, on-chip memory, additional on-chip peripherals, and a highly specialized instruction set [4].

The four internal buses and dual address generators enable multiple operand operations and reduce the number of cycles for operand address preparing.

Example 1. Two Operands Multiplication

```
;for C54x
        MPY  *AR2, *AR3.A

;for C50[5]
        LT   *, AR3
        MPY  *
```

Two independent 40-bit accumulators, 40-bit ALU and 40-bit adder allow to prevent some overflow in iterative computations such as convolution.

Single-cycle normalization and exponential encoding support floating-point arithmetic.

Example 2. Accumulator Normalization[4][5]

```
;for C54x
        EXP  A            ;TREG = exp(A)
        ST   T, EXP       ;store exponent
        NORM A            ;A=A<<TREG


;for C50
        LAR  AR1,#0h       ;clear out exponent
                           ;counter
loop:   NORM *+            ;one bit is
                           ;normalized
        BCND loop,NTC      ;if TC=0,
                           ;magnitude not
                           ;found yet
```

The double precision instructions (DLD, DADD, DSUB etc.) reduce cycle consumption for 32-bit operand processing.

Example 3. Two 32-bit operands addition

```
;for C54x
        DLD   *AR2,A
        DADD  *AR3,A


;for C50
        LACC  *-,l6
        ADDS  *,AR3
        ADD   *-,l6
        ADDS  *
```

A 17x17 multiplier in multiplier/adder (MAC) block allowing 16-bit signed or unsigned multiplication, with rounding and saturation control - all in one instruction cycle.

Example 4. The 32-bit fractional multiplication [7]

```
;for C54x
        LD        #0,A
        MACSU     *AR2+,*AR3-,A
        MACSU     *AR3+,*AR2,A
        LD        A,#-16,A
        MAC       *AR2,*AR3,A
        DST       A,*AR4

;for C50
        BIT       *,#0
        LT        *+,AR3
        MPY       *-,AR2
        LTP       *,AR3
        MPY       *+
        MPYA      *
        BSAR      16
        XC        1,TC
        ADD       *-
        BIT       *,0,AR2
        APAC
        XC        1,TC
        ADD       *,AR4
        SACL      *+
        SACH      *
```

New special instructions produce effective code:

FIRS – for symmetric FIR filters,
LMS - for adaptive FIR filters with LMS adaptation algorithm,
SQDST - for Euclidean distance calculating,
ABDST - for distance based on the absolute value computing,
POLY - for polynomial evaluation.

Example 5. The Euclidean Distance Calculating

```
;for C54x
        SUB         *AR2+,*AR3+,A
        RPTZ        B,N-1
        SQDST       *AR2+,*AR3+

;for C50
        LACC        #N-1
        SAMM        BRCR
        RPTB        loop
        LACC        *+,AR3
        SUB         *+,AR2
        SACL        TMP
        ZAP
        SQRA        TMP
        ADDB
loop:   SACB
```

A software stack and compiler direct addressing mode simplify-C interface and operations with temporary variables.

A host port interface (HPI) provides an effective exchange with host controller through on-chip shared memory which is accessible to both processors.

The use of all mentioned features allows to implement developed modem algorithms at low processor loading. Free resources of processor can be utilized to perform algorithms :voice coding, FEC, echo and noise cancellation, protocols and interfaces.

References

[1] Shannon C.E. *Bell Syst. Tech. J.*, 1948, v.27.

[2] Landay H.J., Pollak H.O. Prolate spheroidal wave functions, Fourier analysis and uncertainly., I, II, III, *Bell Syst. Tech. J.*, 1961, 1063 v.40, v41.

[3] Cowan C.F.N., Grant P.M. *Adaptive filters* Prentice-Hall, Inc., Englewood Cliffs, 1985.

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[5] *TMS320C5x User's Guide*, Texas Instruments Inc., 1993.