<u>Jim Thomas</u> (7/20/23)

Jim Thomas, Labs from 1970, retired just after LM purchase in 2001

Preface – sent to COMARA on 11/3/2025

I was born in Olney, MD, and have lived almost my entire life here in Sandy Spring, MD. I had my first job at Sandia National Laboratories starting in 1966. When I traveled home from Albuquerque, NM, in 1970 to look for a job close to home in Maryland, I saw a distinctive building just south of Clarksburg, but with no sign indicating what it was. Out of curiosity, I got off I-270 and found my way to the building and discovered Comsat Labs!

I went in with no appointment, and asked if I could interview for a job. I was welcomed enthusiastically, and interviewed by two managers who both offered me a job on the spot! :-) In addition, personnel offered to pay for my trip even though nothing had been prearranged!!

I accepted a job immediately, and thus began my career at Comsat :-)

The Labs was the building that started it all!

Introduction

Beginning in the early 1980s, the Modem Department of the Communications Technology Division (CTD) of COMSAT Laboratories in Clarksburg, Maryland, became heavily committed to the implementation of digital modem structures using digital signal processing (DSP) techniques realized in pipelined parallel digital hardware. This is in contrast to other implementations employing DSP Microprocessors, which took place in other departments within the Labs, but were necessarily limited to lower data rates.

This paper will briefly describe these efforts as they applied to the first Digitally Implemented Modem (DIM), the NASA Programmable Digital Modem (PDM), two generations of On Board Processing (OBP) designs, including the Multi-Channel Demodulator ASIC (the MCD-1), and the realization of a non-shared version of the MCD-1 in FPGA hardware. In addition, there will be a very brief description of the MSP-10, another non-shared digital modem ASIC which preceded the MCD-1.

Also described are Detection-Transition Sample Estimation (DTSE), and RAM- based Sharing methods, COMSAT patented digital techniques which significantly reduced expected power consumption in On Board applications.

Digitally Implemented Modem [1]

In the early 1980s work began in the CTD Modem Department on the Digitally Implemented Modem. Based on extensive simulations and theoretically work, this equipment used RAM lookup tables to directly generate QPSK, BPSK, and advanced modulated waveforms, a Finite Impulse Response digital filter for receive side Nyquist filtering, and the COMSAT patented Concurrent Clock and Carrier Synchronization (CCCS) [2][A] method implemented in discrete digital hardware (primarily multipliers, adders, and registers) to complete the demodulation and detection of received signals.

This modem used a conventional analog back end in the modulator, and front end in the demodulator. In other words, D/A and A/D conversion were performed at baseband, and up- or down-converted to RF by analog means. Direct sampling at IF or RF, as found in "digital radios", which have become quite common today, was not employed.

Software to generate the Modulator RAM and FIR Filter coefficients was developed and simulated. As part of this work, the feasibility of incorporating various kinds of pre-distortion and equalization into the applicable coefficients was demonstrated. This powerful technique is presumed to be common in most subsequent digitally implemented modems wherever developed.

The DIM worked as designed and proved the concept of digitally implemented modems of this kind sufficiently well to provide the basis for almost all following related work in COMSAT Labs CTD.

1st Generation Shared Multi-Carrier On Board Processing Demonstration of Concept [3]

In the mid-1980s, work was undertaken to demonstrate the feasibility of using time-shared hardware to demultiplex and demodulate a group of independent carriers in a single piece of equipment with the intention of eventually migrating the methods developed to hardware capable of being placed on board future satellite systems. The objective of using a single piece of equipment rather than replicating a large number of individual demodulators was to minimize mass and power consumption on board the satellite. The objective of demodulating individual carriers on board the satellite was to allow recombination of signals for retransmission in selectable spot beams, thereby improving satellite bandwidth utilization, for example for satellite based internet access. In addition, demodulation and remodulation on board the satellite provides a significant effective improvement in signal to noise ratio on the link.

Specifically in this case, the equipment developed was intended to handle multiple carriers conforming to Intelsat IBS/IDR specifications. One defining characteristic of these carriers, other than not being particularly high in data rate taken individually, is the fact that due to variations in coding techniques and overhead rates, their symbol rates are not integer multiples of one another. This meant that sampling the composite baseband stream with a single A/D could not provide digital samples for all carriers such that they were simultaneously sampled at an integer number of samples/symbol. Since conventional digital demodulator structures typically rely on integer sampled data, this presented a problem.

The problem of non-integer sampled data was solved in the 1st generation OBP equipment by means of building a shared multi-carrier interpolating filter, a type of FIR digital filter capable of effectively resampling data originally sampled at non-integer sampling rates, and outputting data sampled at integer sample rates (e.g. 2 samples/symbol). This portion of the equipment proved to be very complex and power hungry, a fact which led to development of the DTSE technique described later.

The interpolating filter was fed by an FFT-based demultiplexer, equipment which separated the composite data stream, sampled at baseband, into time domain multiplexed data consisting of groups of samples from each carrier separated by dummy samples corresponding to the guard bands between the original carriers in the frequency domain. This stream was ideally suited for processing by the shared interpolating filter and shared demodulator since the dummy samples allowed time for the shared equipment to switch contexts between carriers.

The baseband sampler and its high speed A/D converter were fed by a bank of conventional analog IBS/IDR modulators used to simulate the Intelsat composite upstream. A simple channel simulator inserted Gaussian noise in the RF path between the subsystems.

The output of the interpolating filter was fed to a shared digital demodulator which was largely designed based on lessons learned from the DIM. The pipelined parallel digital hardware was shared amongst carriers by means of swapping practically every register in the device in and out of static memory that was distributed throughout the equipment. Again, the time required for this swapping (actually only a few cycles) was provided by the dummy samples already mentioned.

This equipment worked as designed, suffering only from an unusual digital (systematic) noise problem which, ironically, occurred when testing with a single carrier and no channel noise. This problem was eventually attributed to the use of two's complement digital arithmetic and the fact that having a large number of near zero samples passing through the system resulted in a high percentage of the registers alternating between all zeros and all ones with attendant heavy current spikes on the power busses. With an actual signal composed of many carriers and noise there was no problem.

Another, bigger, problem was the fact that the equipment occupied an entire eight foot equipment rack and handled only 8 carriers. A more practical approach for

actual on board application would require a solution to the interpolating filter problem, and the use of much higher levels of digital circuit integration, such as ASICs.

NASA Programmable Digital Modem (PDM) [4, 5, 6]

Whereas the DIM was a not a particularly high data rate modem, advancements in digital technology allowed COMSAT to bid for and win a contract to produce a very high speed digitally implemented modem for NASA around 1990-1992 using the lessons learned from the original project.

The PDM was capable of being programmed for 2, 4, 8, 16-PSK, 16-QAM, MSK, and Offset-QPSK modulation schemes over a range of data rates from 2.34 to 300 Mbps with programmable spectral occupancy from 1.2 to 1.8 times the symbol rate. These operational parameters were executable in burst or continuous mode. All of the critical processing in both the modulator and demodulator was done at baseband with very high-speed digital hardware and memory. Quadrature analog front-ends were used for translation between baseband and the IF center frequency. The modulator was based on the table lookup approach, where precomputed samples were stored in memory and clocked out according to the incoming data pattern. The sample values were predistorted to counteract the effects of the other filtering functions in the link as well as any transmission impairments. To expedite and provide for more reliable synchronization, initial estimates for these loops were computed in a parallel acquisition processor. The heart of the demodulator realization was the pre- averager received data filter which allowed operation over a broad range of data rates without any hardware changes, greatly simplifying the implementation complexity.

Emulation results confirmed tracking loop operation over the entire range of operational parameters listed above, as well as the capability of achieving and maintaining synchronization at BERs in excess of 10-1. The emulation results also showed very close agreement with the tracking loop analysis, and validated the resolution apportionment of the various hardware elements in the tracking loops.

MSP-10 ASIC Modem [7] In the early 1990s, a single channel burst and continuous mode digital modem

capable of data rates up to 10 MS/s was developed as an ASIC, CTD's first foray into this technology. This modem, capable of handling BPSK, QPSK, and MSK modulation techniques, was successfully demonstrated around 1992.

2nd Generation OBP and the MCD-1 ASIC [8]

Beginning in the mid-1990's, work began on an effort, funded by Intelsat, to produce a shared multi-carrier demultiplexer/demodulator that would actually be feasible for on board applications. This work required the development of a shared multi-carrier demodulator ASIC, the MCD-1, using DTSE to obviate the need for an interpolating filter.

The demultiplexer was built by Alenia-Spazio in Rome, Italy, including the development of a special purpose FFT ASIC of their own. Eventually, in the late '90s, the two systems were successfully integrated to produce a shared demux/ demod capable of handling 189 carriers in a volume about 50 times smaller than the original 8 carrier system built with 1980s technology.

At COMSAT CTD, extensive theoretical and simulation work led to the development of the COMSAT patented DTSE method [B] for handling non- integer sampled data without an interpolating filter. The patent also included the sharing methods developed for the 1st generation OBP system and applied in the MCD-1. As described in the patent, sharing, and processing in general, was complicated by the use of gated clocks in the system.

DTSE used a set of specialized lookup tables, multipliers, and adders to estimate the values of the samples that would have been obtained had the data been originally sampled at integer sample rates. This was done entirely within and as part of the demodulation process, eliminating the interpolating filter altogether. Note that the Nyquist filtering originally done by an interpolating filter in the first generation OBP is done in the demultiplexer in this implementation. Simulations and subsequent measurements showed that the degradation attributable to this technique was negligible.

The MCD-1 was a shared multi-carrier demodulator ASIC capable of simultaneously demodulating up to 24 channels consisting of continuous mode QPSK carriers of mixed rates from 64 kBit/s (in which case the full 24 channels were available) to 8.448 MBit/s (in which case only 1 channel was available). In shared mode, the actual number of channels depended on the mix of carriers in use and the corresponding total composite bandwidth. Provision was made to link multiple MCD-1s together to handle larger numbers of carriers and provide for flexible, reconfigurable frequency plans. The demodulator structure was based on the original DIM design with the sharing and DTSE circuitry overlaid. Provision for burst mode, with additional external circuitry, was also made. A board about 8x10 inches in size was constructed containing 10 MCD-1 ASICs, which was tested in-house with a demux emulator, and eventually integrated with the Alenia-Spazio equipment mentioned above. As with most of the systems described in this paper, the MCD-1 produced soft decision output samples suitable for application to Viterbi FEC decoders.

Subsequently, COMSAT CTD built their own FFT-based demultiplexer using commercially available FFT chips that were not available earlier. This demultiplexer was also successfully integrated with the MCD-1 board, and the combined system delivered to a US Government customer.

FPGA Implementation

In the late 1990s, an unshared demodulator based on the MCD-1 technology was implemented in an Altera FPGA for a modem being developed on another contract. This work was successful and was delivered to the customer. It was also shown that implementation of a shared version in an FPGA was readily achievable.

Conclusions

This paper has endeavored to show how digital modem technology using digital signal processing techniques implemented in pipelined parallel hardware progressed at COMSAT Labs CTD over the period from 1980 to the acquisition of COMSAT by Lockheed Martin Corporation around the year 2000. Methods developed at each stage of the work were carried over into subsequent stages in an evolutionary manner. Some equipment, and the corresponding reports, were delivered to NASA, Intelsat, and other customers, and the personnel who worked on this equipment have moved on to such companies as Lockheed Martin, Hughes Network Systems, Viasat, and The Aerospace Corporation, among others, hopefully taking with them the lessons learned during this exciting period of intellectual development at COMSAT Laboratories.

Credits

The following individuals, among others, contributed to the work described: Chris Cronin, Mike Eng, Russell Fang, Faris Faris, Gil House, Mark Hutchins, Greg Jividen, Mark Kappes, David Layer, John J. Poklemba, Michael Saginaw, Soheil Sayegh, John Snyder, Mark Steber, James Thomas, Chester Wolejsza, Peter Wyckoff.

References

[1] John J. Poklemba and F.R. Faris, "A Digitally Implemented Modem: Theory and Results", COMSAT Technical Review, Spring 1992

[2] John J. Poklemba, "A Joint Estimator Detector for QPSK Data Transmission", COMSAT Technical Review, Fall 1984

[3] M. Eng, G. House, M. Kappes, J. Poklemba, S. Sayegh, M. Steber, J. Thomas, "On Board Demux Demod", NASA Accession Number: 92N14221; Document ID: 19920005003, 1991

[4] John J. Poklemba, " Programmable Digital Modem", NASA 2nd Space Communications Technology Conference: On Board Processing and Switching, Cleveland, OH, Nov. 1991, Proceeding. pp 263-271, NASA Conference Pub. 3132

[5] John J. Poklemba, "Dual Overlapping, Weighted Preaveragers", NASA Accession Number: 94B10426; Document ID: 19940000426; Report Number: LEW-15166, 1994

[6] John J. Poklemba, "Digital Tracking Loops for a Programmable Digital Modem", NASA Accession Number 93N27014; Document ID: 19930017825; Report Number: E-7273, NAS 1.26:189219, NASA-CR-189219, 1992

[7] D. Layer, "Burst Mode ASIC-Based Modem", NASA Contractor Report 202315, 1997

[8] J. Thomas, S. Sayegh, "A Multi-Carrier Demodulator ASIC for On-Board Applications", proceedings, Fifth ESA DSP Conference, 1996

Hardware DSP Modem Implementation at COMSAT Laboratories 1980-2001 Author: James R. Thomas, COMSAT Labs, 1970-1973, 1979-2001

Patents

[A] J.J. Poklemba, "Concurrent Carrier and Clock Synchronization for Data Transmission Systems", U.S. Patent No. 4,419,759, Dec. 6, 1983

[B] S. Sayegh, J. Thomas, "Demodulation of asynchronously sampled data by means of detection-transition sample estimation in a shared multi-carrier environment", U.S. Patent No. 6,278,754

J.J. Poklemba, "Rate synchronized symbol timing recovery for variable rate data transmission systems", U.S. Patent No. 4,849,998, July 18, 1989

J. Poklemba, J. Thomas, "Coherent phase and frequency recovery method and circuit", U.S. Patent Number 4,987,386, January 22, 1991

J.J. Poklemba, "Programmable noise bandwidth reduction by means of digital averaging", U.S. Patent No. 5,052,027, September 24, 1991

J.J. Poklemba, J. Thomas, C. Wolejsza "Programmable noise bandwidth reduction by means of digital averaging", U.S. Patent No. 5,216,696, June 1, 1993

J.J. Poklemba, "Continuously variable if sampling method for digital data transmission", U.S. Patent No. 5,696,796, December 9, 1997

J. Thomas, "Method and apparatus for zero overhead sharing for registered digital hardware", U.S. Patent Number 6,006,293, December 21, 1999

J. Thomas, "DTSE at less than two complex samples per symbol", U.S. Patent Number 7,154,971, December 26, 2006