# Real-Time MIMO
# Discrete Multitone Transceiver Testbed

Alex G. Olson, Aditya Chopra, Yousof Mortazavi, Ian C. Wong, and Brian L. Evans
Embedded Signal Processing Laboratory
The University of Texas at Austin, Austin, TX USA
http://www.ece.utexas.edu/∼bevans

***Abstract*—Given a wireline transmitter/receiver pair with fixed parameters (modulation and coding methods, transmission, bandwidth, receiver noise floor, etc.) that achieves a certain bit rate on a single pair of wires, one might expect that using two pairs of wires (and two sets of transceivers) would double the bit rate. However, the presence of crosstalk induced by the coupling of the energy across the wire pairs may cause significant reduction in the expected bit rate. In this paper, we present a multiple-input multiple-output (MIMO) discrete multitone (DMT) system that achieves double the bit rate of a traditional single transmitter-receiver system when using 2 transmitters and 2 receivers operating over two wires. The improvement has been achieved both in desktop simulation and in a real-time testbed. The testbed also allows rapid exploration of many design tradeoffs in a DMT system.**

## I. Introduction

Discrete Multitone (DMT) modulation uses multiple orthogonal subcarriers to transmit data over a wideband channel. The wideband channel is thus transformed into a set of narrowband channels with magnitude responses that become more flat as the number of subcarriers increases. By using proper training sequences, the frequency response of the channel is measured as well as the noise levels across subchannels. This allows the transmitter to allocate different number of bits on each subcarrier depending on their Signal to Noise Ratio (SNR) levels. Bit allocation ensures that a DMT system could avoid using subcarriers that fall into nulls of the channel. Using the measured frequency response of the channel a DMT receiver can perform frequency domain equalization more easily on the narrowband channels individually than on the entire wideband channel directly.

Given a fixed set of transceiver parameters/constraints such as modulation and coding schemes, bandwidth, receiver noise floor and transmitted energy, a maximum achievable bit rate exists. One way to increase the bit rate beyond this limit is to use multiple pairs of wires to transmit the bit stream. Ideally, a system using two pairs of wires (and two sets of transceivers) would double the bit rate over a single transceiver system assuming that the pairs of wires result in two identical wideband channels.

When using multiple pairs of wires in close proximity (i.e. in a bundle), the achievable bit rate could be significantly lower than ideal due to near-end echo, near-end crosstalk (NEXT) and far-end crosstalk (FEXT). As shown in Fig. I, echo is introduced by hybrid circuits that are required for bidirectional transmission on a single wire pair. NEXT is due to coupling between the transmitter and receiver of different pairs of wires on the same end of the cable bundle (e.g. TX A → RX D). FEXT is due to the coupling between transmitters and receivers of different pairs of wires on opposite ends of the cable (e.g. TX A → RX B). Echo cancellation is achieved by removing the known locally-transmitted signal from the locally-received signal on the same transceiver. Cancellation of NEXT can be achieved using the same means as the cancellation of echo if the transceivers at each end are coordinated. The challenging problem is FEXT cancellation where the data on both pairs of wires are unknown.

In this paper, we present our 2×2 MIMO Discrete Multitone (DMT) testbed, i.e. with 2 transmitters and 2 receivers operating over 2 wires. The testbed permits rapid implementation, and comparison of communication performance vs. implementation complexity tradeoffs. The software for the testbed is a MIMO extension of our 1×1 ADSL2 Simulator [1]. The rest of the paper is organized as follows. Section II describes the testbed including the communication system design, as well as the hardware and software solutions implemented as part of the testbed. Section III presents experimental results. Section IV draws conclusions on some of the tradeoffs in the system design choices.

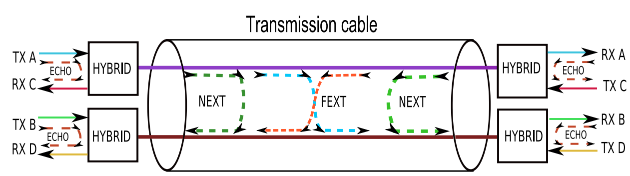


Fig. 1. System model for the 2x2 MIMO DMT Testbed

## II. MIMO DMT Modem Implementation

This section reviews the structure of a MIMO DMT modem and describes the design of the 2×2 MIMO DMT testbed. Finally, we discuss the method we adopted for FEXT cancellation based on a design matrix that compares various implementations on the merit of their achievable bit rate vs. implementation complexity.

### *A. Modem Structure*

The receiver in the testbed is designed to compensate the effects of the channel. Upon startup, the DMT transmitter and receiver execute a training phase that allows the receiver to estimate the frequency response of the direct channel and the various crosstalk components. These estimates allow the receiver to design equalizer(s) to combat the effect of the channel. DMT systems use a cyclic prefix that allows the channel to be equalized in the frequency domain via the fast Fourier transform (FFT) [2], [3]. However, this is only possible when the channel impulse response is shorter than the cyclic prefix length (plus one). In wireline DMT systems, the channel impulse response is usually significantly longer in duration than the cyclic prefix. The cyclic prefix must be kept short so that it does not negatively impact the maximum achievable bit rates. Thus, increasing the length of the cyclic prefix to match the channel response is generally inefficient.

We have implemented a classic DMT equalization approach that filters the samples received from the analog-to-digital (A/D) converter with an finite impulse response (FIR) filter commonly called a time-domain equalizer (TEQ) [2], [3]. After the TEQ, the cyclic prefix is discarded and an FFT operation is performed on the symbol. After the FFT, the frequency domain equalizer (FEQ) scales each FFT output (tone) by a complex value (which was estimated during training). Alternate equalization structures, such as dual-path TEQ and per-tone equalization, were not considered here [2], [3].

During training, the receiver also estimates the noise power on each subchannel and performs bit/gain loading. Bit/gain loading is the process where the receiver determines the bit rate on each subchannel and the allocation of transmitter power. All subchannels need not be used nor do they need to have equal transmitter power. These operations allow the receiver to make effective use of the channel for high-speed data transmission. A block diagram of the DMT transmitter and receiver implemented is shown in Fig. 2.

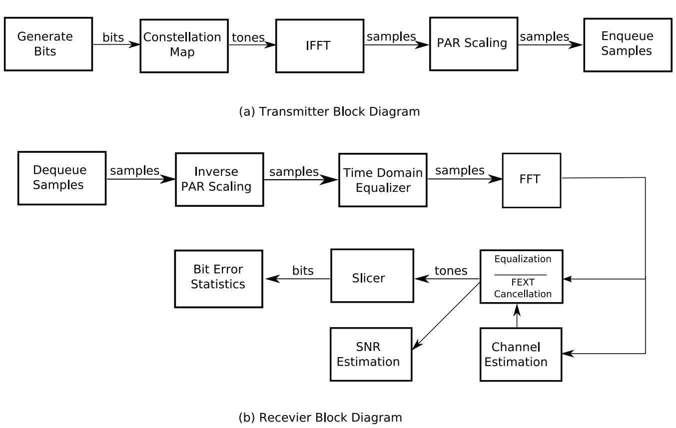


Fig. 2. System model for the 2x2 MIMO DMT Testbed

## B. Hardware

The hardware used in the testbed consisted of commercial off-the-shelf components from various vendors. Briefly the following components (depicted in Fig. 3) were used to form our modem.

- National Instruments (NI) hardware, consisting of data acquisition (digitizer) and arbitrary waveform generation (AWG) boards and real-time embedded computer, all on a single chassis
- Custom built analog low-pass filters from TTE, Inc., for anti-aliasing and noise reduction
- Texas Instruments hybrid circuit for analog cancellation of near-end cross-talk (NEXT)
- Spool of 1000 ft CAT-5e cable for the channel (with four pairs of wires)
- External computer for visualization/control (connected to the embedded controller via Ethernet)

Two of the four twisted pairs of wires in the CAT-5e were used. To achieve maximum crosstalk, one differential signal was applied to the two ground wires and the other differential signal was applied to the positive wires, instead of applying of the differential signals on the two pairs of wires as per usual. Our approach resulted in the crosstalk power to be only 10 dB lower than that of the direct channel.

## C. Software

The system is composed of the following software components:

- Software/hardware running on the Realtime (RT) Target:
  - LabVIEW Virtual Instruments (VIs)
  - DMT Physical Layer Processing as a C++ Dynamically Linked Library (DLL)
- Software running on a Desktop PC.

The RT target contains LabVIEW VIs that access the NI hardware and make calls to the DLL to initialize the C++ routines. All physical layer processing is done in `Transceiver.DLL` (for execution speed). This DLL generates and processes samples that are eventually sent/received to/from the NI hardware. These samples are exchanged via a circular queue. This design allows the computation and transmission of samples to be somewhat decoupled. For visualization, a desktop PC runs another set of LabVIEW VIs that receive and display data generated by the DMT modem. This data is received via a TCP link that is established by the desktop PC.

## D. Bit Loading Algorithms

Bit Allocation is performed at the transmitter and is the procedure of deciding how many bits are to be transmitted on each tone. In a DMT communication system, each individual tone has different level of noise and interference. The SNR needed to transmit $b$ bits on a given tone is calculated as $\Gamma(2^b - 1)$ where $\Gamma$ is the gap which decides the probability of error in transmission. Since the total amount of energy available per DMT symbol is fixed, the transmitter has to compute how much energy to allocate to each tone in order to maximize the total number of bits transmitted per symbol, under the constraint of the total allocated energy has to be lower than the available energy. Bit allocation algorithms can be divided into two families - Rate Adaptive and Margin Adaptive [10]. Rate Adaptive algorithms use a fixed $\Gamma$ or gap

TABLE I
COMPLEXITY OF THE VARIOUS FEXT CANCELLATION METHODS

| Algorithm | Complexity (Training) | Complexity (Symbol decoding) |
|---|---|---|
| V-DMT | $O(KN^3 + KNI)$ | $O(KN^2)$ |
| OSB | $O(I_{sg}KN^3B^N)$ | $O(KN)$ |
| SSA | $O(KNI)$ | $O(KN)$ |
| ESA | $O(KNI)$ | $O(KN)$ |

and maximize the total number of bits allocated across all tones resulting in the maximum data rate possible, whereas Margin Adaptive algorithms distribute a fixed total number of bits across all tones so as to maximize the gap resulting in low probability of bit error. The two types of bit allocation algorithms implemented in the testbed are:

*1) Uniform Gain Bit Loading:* The uniform gain method of bit allocation is a trivial non-optimal method of bit allocation in DMT. Each tone gets equal amount of energy and depending on the consequent SNR in the tone, the number of bits to be allocated on the tone are decided. This method is highly sub-optimal, but has the least design and implementation complexity.

*2) Hughes-Hartog Bit Loading [11]:* The Hughes-Hartog bit gain algorithm is an optimal bit loading algorithm. In this algorithm the energy needed by each tone to add one more bit on that tone is calculated across all tones as a table. Then the tone with the minimum energy cost of adding a bit gets the next bit allocated to it and the table is updated. This iteration continues until all the bits have been allocated in the case of Margin Adaptive or until no more energy is available in the case of Rate Adaptive mode.

### *E. FEXT Cancellation*

FEXT is the single most important cause of degradation of communication performance in multi-cable DMT systems. In desktop simulation, we considered the following methods to combat FEXT: Vectored DMT [4], Optimal Spectrum Balancing (OSB) [5]–[9], Static Spectral Allocation (SSA), and Exclusive Spectrum Allocation (ESA). (SSA and ESA are suboptimal.) Table 1 gives the complexity of different algorithms considered. $K$ is no. of tones, $N$ is no. of pairs of wires, $I$ is number of iterations for Hughes-Hartog algorithm, $I_sg$ is no. of iterations for subgradient search, and $B$ is no. of bit levels. Iterations are only necessary during training. Because of low complexity during training and better communication performance than SSA and OSA algorithms, we evaluated only Vectored DMT (V-DMT) methods in the real-time testbed.

Simulations were performed for the four FEXT cancellation methods for N = 2 wire pairs. Roughly 10-20 iterations were needed for Hughes-Hartog and subgradient search algorithms. In high crosstalk environments, based on our simulations, huge performance gains (around 100%) of V-DMT vs. the other methods can easily justify the increase in complexity of training and decoding, and is thus the recommended method. In low cross-talk environments, OSB outperforms V-DMT while having lower per-symbol processing requirements. Thus, if training complexity is not an issue, OSB is recommended in these environments. Finally, if computational complexity is the primary concern, then ESA is recommended in low cross-talk environments, and SSA is recommended in high cross-talk environments.

Using our 2×2 MIMO DMT testbed, we implemented V-DMT using QR decomposition and V-DMT using Successive Interference Cancellation. The crosstalk occurring in a MIMO DMT system can be modeled mathematically as a matrix multiplication of the received signal vector by a channel matrix H. Crosstalk cancellation involves removing the effect of H to get back the original transmitted signal vector. Both V-DMT methods are based on inverting the channel matrix H. This inversion is performed on a per-subcarrier (i.e. per-tone) basis. The QR-Decomposition operation is computed by using a series of Givens Rotations, which is a computationally efficient and more importantly, numerically stable technique. Successive Interference Cancellation slices the received symbol at the ith receiver and uses the sliced symbols received at the 1st to ith receivers to remove the interference terms at the (i + 1)st receiver.

## III. EXPERIMENTAL RESULTS

The 2×2 MIMO DMT modem was tested with the parameters listed in Table 2. The transmission media was a 1000ft CAT-5 cable where two twisted pairs of wires were utilized in order to have significant crosstalk, such as to mimic realistic crosstalk levels in longer transmission lines.

TABLE II
PARAMETERS USED IN EXPERIMENTS WITH THE REAL-TIME TESTBED

| | |
|---|---|
| Number of complex subcarriers (real FFT) | 256 |
| One-side bandwidth | 156.26 kHz |
| Tones used for data transmission | 3-255 |
| Number of pilot tones | 1 |
| Oversampling factor | 2 (625 kHz hardware sampling rate) |
| NI Hardware analog input and output impedance | 50 |
| Bit allocation style | Rate adaptive (maximize bit rate) |
| Margin for bit allocation | 0 dB |
| Target Bit Error Rate (uncoded) | 10-7 |
| Maximum bits per subcarrier (tone) | 15 |
| Time-domain equalizer design method | Maximum Shortening SNR [2][3] |

Fig. 4 shows the results. Note that switching from single-channel to two-channel operation without FEXT cancellation significantly reduces the overall bit rate. With V-DMT however, the bit rate increases to 1.99X of the single channel case, which is close to the ideal (2X).

## IV. CONCLUSIONS

The maximum bit rate in single-channel wireline communications systems is inherently limited by the channel's available bandwidth. For high data-rate applications, a single-channel communication system may not be sufficient. A natural solution is to use multiple transceivers communicating over multiple channels (pairs of wires) which are usually in close

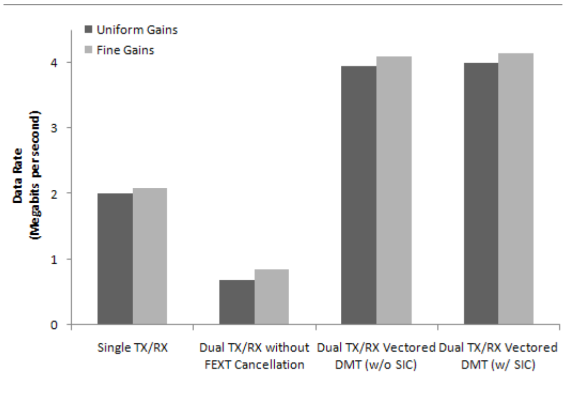


Fig. 3. Experimental results obtained on the testbed

proximity (bundle). However, such systems are limited by crosstalk. If not canceled, far-end crosstalk (FEXT) can lead to significant degradation in communication system performance.

In this paper, we show that the "Vectored DMT" method can effectively cancel FEXT. We have constructed a 2×2 MIMO DMT prototype communication system using commercial off-the-shelf (COTS) hardware. Experimental tests on a 1000ft cable with strong crosstalk (FEXT) show that the Vectored DMT method used on a 2×2 MIMO DMT system can provide 1.99x the bit rate of a similar single-channel DMT transceiver.

Vectored DMT is highly effective in canceling FEXT with low computation and memory requirements. Experimental tests involving strong FEXT with Vectored DMT yielded bit rates very close to a crosstalk-free scenario. We canceled FEXT using two methods. One method simply inverts the channel matrix, and the other method was successive interference cancellation (SIC). In our experiments, SIC yielded improvements of up to 100kbit/s or 2.5% in bit rate over the channel matrix inversion method, while still maintaining a similar level of computational complexity at the receiver.

## References


[1] A. G. Olson, D. Wang, I. C. Wong, and B. L. Evans, "ADSL2 Simulator", Version 1.1, May 24, 2006. Available at http://www.ece.utexas.edu/~bevans/projects/adsl/simulator/index.html.

[2] R. K. Martin, K. Vanbleu, M. Ding, G. Ysebaert, M. Milosevic, B. L. Evans, M. Moonen, and C. R. Johnson, Jr. "Unification and evaluation of equalization structures and design algorithms for discrete multitone modulation systems", *IEEE Transactions on Signal Processing*, vol. 53, no. 10, pp. 3880-3894, Oct. 2005.

[3] R. K. Martin, K. Vanbleu, M. Ding, G. Ysebaert, M. Milosevic, B. L. Evans, M. Moonen, and C. R. Johnson, Jr. "Implementation complexity and communication performance tradeoffs in discrete multitone modulation equalizers", *IEEE Transactions on Signal Processing*, vol. 54, no. 8, pp. 3216-3230, Aug. 2006.

[4] G. Ginis and J. Cioffi, "Vectored transmission for digital subscriber line systems," *IEEE J. Select. Areas Commun.*, vol. 20, no. 5, pp. 1085-1104, Jun. 2002.

[5] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Trans. Commun.*, vol. 54, no. 7, pp. 1310-1322, Jul. 2006.

[6] P. Tsiaflakis, J. Vangorp, M. Moonen, J. Verlinden, and K. Van Acker, "An efficient search algorithm for the Lagrange multipliers of optimal spectrum balancing in multi-user xDSL systems," in *Proc. IEEE Int. Conf. on Acoust., Speech, and Sig. Proc.*, Apr. 2006.

[7] P. Tsiaflakis, J Vangorp, M. Moonen, and J. Verlinden, "A low complexity branch and bound approach to optimal spectrum balancing for digital subscriber lines," in *Proc. IEEE Global Telecom. Conf.*, Nov. 2006.

[8] R. Cendrillon, W Yu, M. Moonen, J. Verlinden, and T. Bostoen, "Optimal multi-user spectrum balancing for digital subscriber lines, " *IEEE Trans. Commun.*, vol. 54, no. 5, May 2006.

[9] I. C. Wong and B. L. Evans, "Optimal OFDMA resource allocation with linear complexity to maximize ergodic rates," *IEEE Trans. Wireless Commun., submitted*.

[10] Leke, A.; Cioffi, J.M., "A maximum rate loading algorithm for discrete multitone modulation systems," *Global Telecommunications Conference, 1997. GLOBECOM '97., IEEE* , vol.3, no., pp.1514-1518 vol.3, 3-8 Nov 1997

[11] D. Hughes-Hartog, "Ensemble modem structure for imperfect transmission media." U.S. Patents Nos. 4,679,227 (July 1987), 4,731,816 (March 1988), and 4,833,706 (May 1989).