Adaptive Bit and Power Allocation for Rate and Margin Maximization in V-BLAST System

[1]Dror Meiri and [2]Irving Kalet

[1] Aelis Photonics, Netanya, Israel (email: dmeiri@netvision.net.il)
[2] Faculty of Electrical Engineering, Technion – Israel Institute of Technology, Haifa, Israel (email: kalet@actcom.co.il)

Abstract— This paper describes the "Water-Pouring" solution for wide-band multitone version of the Vertical Bell Labs Layered Space-Time (V-BLAST) architecture. It is shown that the multitone concept may be combined with the Multiple-Input-Multiple-Output (MIMO) V-BLAST concept for use on a frequency-selective channel. We present an optimal power and bit loading algorithm which attempts to optimize the system performance by enhancing either the data rate or the QoS (error rate), while keeping the other fixed. In both methods, a power constraint exists. Simulation results of the proposed system and algorithm show that adaptive loading enables efficient and reliable communication even with low SNRs. It also shows significant improvement in both methods as compared to a basic OFDM V-BLAST system, which has no a-priori knowledge of the channel characteristics. For example, a system with four transmitters and receivers that uses a 256 multitone symbol doubles the nominal bit rate at SNR of 33dB (for maximum bit rate) and achieves a gain of 19dB at BER of 2x10^{-4} (for maximum QoS).

Index Terms—**fading channels, multi-input-multi-output (MIMO) systems, orthogonal frequency division multiplexing (OFDM), wireless communications.**

I. INTRODUCTION

The demand for high data rate communication systems, and the lack of available bandwidth has led to much research effort into MIMO systems using multiple transmit and receive antennas. It was shown in [1] that MIMO systems can improve the capacity of rich-scattering Rayleigh fading channels, by a factor which is linearly proportional to the minimum of the number of the transmit and receive antennas. The V-BLAST [2] architecture has been proposed for realizing high spectral efficiencies over flat Rayleigh fading indoor wireless channels. Turbo coding in V-BLAST systems was proposed in [17].

Multitone transmission [3,4], or OFDM, has been used in a number of wireline and wireless systems. OFDM eliminates the need of a complex equalizer (in wireless systems) for overcoming ISI caused by delay spread or frequency-selective fading. However, in [3,4] it was shown that for a single-input-single-output (SISO) system which operates over a frequency-selective channel, if the transmitter “knows” the channel characteristics, the “water-pouring“ multitone (MT) technique can be used to optimize the transmitted bit rate and approach the channel capacity. Adaptive bit and power allocation algorithms [11] were shown to achieve efficient use of the "water-pouring" solution in wireline ADSL and VDSL systems.

In [1,12,13,18], the channel capacity for the MIMO system has been analyzed and discussed. Raleigh and Cioffi [7] have developed a coding structure that achieves the capacity and a technique that approaches this structure.

Few works have considered the usage of V-BLAST in MIMO-OFDM systems. Adaptive modulation for such systems has been presented by Ng et al [14]. This work assessed the maximum margin concept only. Meiri and Kalet [8,15,16] have developed an adaptive loading algorithm for the Wide-Band Multitone version of V-BLAST for both maximum rate and maximum margin criteria.

In this paper we present adaptive loading algorithms that optimize either the data rate or the margin (known also as Quality of Service (QoS) maximization), while keeping the other fixed. In both methods, a power constraint exists. Both optimization problems result in (different) power and bit allocations, i.e. each sub-channel carries a different amount of data and transmitted with different power. For the maximum margin approach, we show that for an equal number of antennas on both sides of the link, this algorithm results in improvement of several dBs for BERs of 10^{-3} and 10^{-4} compared to a MIMO system with the best performance that has no channel knowledge at the transmitter, irrespective of the number of antennas. For the maximum bit rate, we investigate two types of error constraints: (a) fixed error rate for all SNRs and (b) error rate figures of a typical OFDM V-BLAST system having the same system parameters (and that does not use adaptive loading). The first constraint results in a practical system that implements the Multi-Tone-Multi-Antenna (MTMA) technique [8]. The second one maximizes the communication efficiency of any given system. We show that for an equal number of antennas on both sides of the link, and a fixed error rate constraint, using the adaptive loading algorithm enables efficient and reliable communication in low SNRs, compared to MIMO systems with the best performance which has no channel knowledge at the transmitter. For the case which there is a nominal error rate constraint, we show that at high SNR values the system more then doubles the bit rate.

The paper is organized as follows: Section 2 describes the system and channel model, Section 3 describes the V-BLAST system, Section 4 presents the wideband multitone version of V-BLAST including the adaptive bit and power allocation algorithm. Section 5 gives the simulation results and Section 6 presents a summary and conclusions.

II. System and Channel Model

A single data stream is split into multiple sub-streams that are transmitted simultaneously from an array of collocated M antennas. All the sub-streams occupy the same (and the entire) bandwidth, and have the same symbol duration. The sum of the powers of all the transmitters is constrained. There are N (N ≥ M) receiving antennas. The complex term h_{ij}(t) represents the independent channel impulse response (with a Rayleigh distributed amplitude) for the signal, s_i(t), transmitted from the ith antenna, and received by the jth receiver antenna. Accordingly, the complex valued signal, r_j(t), received at receiver j is given by

$$r_j(t) = \sum_{i=1}^{M} h_{ij}(t) * s_i(t) + n_j(t) \qquad (1)$$

where * stands for convolution, $i \in 1..M$, $j \in 1..N$ and n_j (t) is a zero-mean complex AWGN signal, with PSD of $N_0/2$ watts/Hz. The channel frequency response may be flat, or frequency-selective (if the channel suffers from ISI [5]). It is assumed that the receiver has perfect channel knowledge. This may be the case for a slowly-changing mobile channel.

III. V-BLAST Overview

The MIMO V-BLAST system [2] has been used in frequency-nonselective channels. The received signals are sequentially decoded using three steps: (a) Nulling the interference from the yet undetected symbols, (b) Symbol detection according to the optimal detection rule, (c) Cancellation of the previously detected symbols. The order of detection is significant and there is an optimal ordering rule.

The Zero-Forcing V-BLAST algorithm [2] is described below:

a. Initialization

$$i = 1 \qquad (2a)$$

$$G_1 = pinv(H) \qquad (2b)$$

$$K_1 = \arg\min_j \left\| (G_1)_j \right\|^2 \qquad (2c)$$

b. Recursion

$$w_{K_i} = (G_i)_{K_i} \qquad (2d)$$

$$y_{K_i} = w_{K_i}{}^T r_i \qquad (2e)$$

$$\hat{s}_{K_i} = slice(y_{K_i}) \qquad (2f)$$

$$r_{i+1} = r_i - \hat{s}_{K_i}(H)_{K_i} \qquad (2g)$$

$$H_{K_1} = H_{K_2} \ldots = H_{K_i} = zeros(1, N) \qquad (2h)$$

$$G_{i+1} = pinv(H) \qquad (2i)$$

$$K_{i+1} = \arg\min_{j \notin \{K_1 \ldots K_i\}} \left\| (G_{i+1})_j \right\|^2 \qquad (2j)$$

$$i = i + 1 \qquad (2k)$$

where H is the channel matrix of size MxN, w is the nulling operator, r the received vector, y the receiver's estimate, i the index of the transmitted signal that is subject to the current detection, and K_i is a permutation of i and refers to the optimal detection ordering. Slice operation implements the maximum likelihood (ML) symbol decoding, *zeros(1,N)* is a vector of length N whose elements have zero value, and *pinv* is the pseudo inverse operator.

IV. A Wideband Multitone Version of V-BLAST

In the Multi-Carrier Modulation (MCM) technique [3,4] a wideband signal is composed of many narrowband QAM signals ("tones" or "frequency-bins"). Hence, each individual tone sees an essentially frequency-nonselective channel, and a simple one-tap equalizer can nullify the channel frequency distortion. MCM can also be used in the system defined in Section Two, and accordingly the many narrowband received MIMO signals can be decoded using V-BLAST. A base-band diagram of this system is shown in Figure 1.

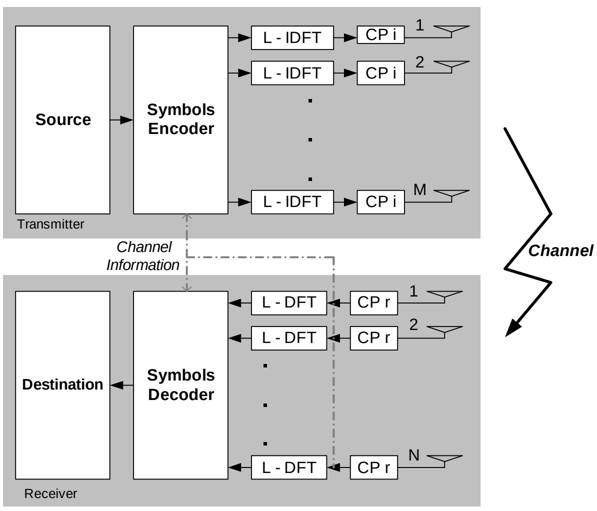

Fig. 1. Block diagram of multitone version of V-BLAST.

This is an extension of the Discrete Multitone (DMT) implementation [11] of the multitone system used in ADSL and VDSL. There are L sub-channels in each L-DFT and L-IDFT. The CP blocks at the transmitter and the receiver represent the introduction and removal of the cyclic prefix, respectively.

If the transmitter has no channel knowledge, the MCM technique becomes a simple OFDM system in which the same modulation is used at each transmitting antenna in each frequency. The total error rate is the same as that of V-BLAST over a frequency-nonselective channel.

Knowledge of the channel characteristics at the transmitter(s) enables the transmitter(s) to adapt the transmitted signal to the channel characteristics in such a way that the system performance will be improved. The improvement can be manifested by enhancing either the data rate or the QoS (error rate) while keeping the other constant. These are the solutions of the following problems:

- The maximum bit rate optimization problem:

$$R = \max_{b_{m,l} \in D} \sum_{l=1}^{L} \sum_{m=1}^{M} b_{m,1}$$

under the total power constraint:

$$\sum_{l=1}^{L} \sum_{m=1}^{M} P_{m,l} \le P_{Total}$$

- The maximum QoS optimization problem:

$$P_{Total} = \min_{b_{m,l} \in D} \sum_{l=1}^{L} \sum_{m=1}^{M} P_{m,l}$$

under the constant bit rate constraint:

$$R = \sum_{l=1}^{L} \sum_{m=1}^{M} b_{m,l}$$

where $b_{m,l}$ and $P_{m,l}$ are the number of bits and the power allocated for the *m*-th antennas at the *l*-th frequency-bin, respectively. D is the set of all possible values of $b_{m,l}$. It is important to note that even though the last problem is formulated to minimize the overall transmit power for a given QoS requirement, the same solution can be applied to maximize the QoS for a given overall transmit power. This can simply be achieved by increasing the power proportionally for all sub-carriers, while using the same set of $\{b_{m,l}\}_{m=1,l=1}^{M,L}$ [6].

In the following, we present an optimal adaptive bit and power allocation algorithm. It is a practical way to implement the MTMA technique [8] and to optimize the system performance under the two criterias given above.

Let *f(b)* denote the single sub-channel required received power (in energy per symbol time) needed for reliable reception of *b* information bits per symbol with a unity channel gain. For a square QAM constellation, *f(b)*, is given by [5]:

$$f(b) \cong \{Q^{-1}(\frac{p_r(e)}{K})\}^2 \frac{(2^b - 1)N_0}{3} \quad (3)$$

where $p_r(e)$ is the symbol error probability, $2 \le K \le 4$ and Q^{-1} is the inverse of the Q-function.

De-Souza [9] proved that a given allocation is an optimal solution to the problems above if and only if any change in the allocation does not require less transmitted energy ("Efficiency") and all resources (power for the maximum bit rate, and bit rate for the maximum QoS criterions) are exploited ("Tightness").

For QAM, *f(b)* is a convex, increasing function of *b* with *f(0)=0*. Hence, the loading algorithm that "puts every increment of the transmitted power where it is most effective" results in an efficient allocation [9].

In V-BLAST each symbol is decoded separately: The symbols that have previously been decoded are already cancelled, and the symbols that have not been detected yet are seen as interferers and are nulled out. This leaves us with a single symbol, which is ML decoded. The other symbols (out of M symbols) are also decoded, in their turn. The conclusion from the above is that the convexity of f(b) holds also in the spatial dimension imposed by V-BLAST, and hence an optimal allocation can be reached as before.

In order to maintain the required error rate or QoS at the receiver, the transmit power allocated to the l-th sub-carrier of the m-th transmitting antenna must be equal to

$$P_{m,l} = G_{m,l}(H) f(b_{m.l}) \quad (4)$$

where G is a function of the channel and implements the reciprocal of the corresponding channel energy gain. Recalling the V-BLAST, G can be given by:

$$G_{m,l}(H) = \|w_{m,l}\|^2 \quad (5)$$

where $w_{m,l}$ for an arbitrary subcarrier index l is given in (2d). Note that for SISO system $w_{m,l}$ becomes $1/|H_l|^2$.

As the power needed to transmit a certain number of bits in a single sub-channel (out of the $M \times L$ sub-channels) is independent of the number of bits allocated to other sub-channels, assigning one bit one at a time to the sub-carrier that requires the least additional power is "efficient". The bit allocation process will be completed when all power is allocated, for the maximum bit rate approach, or when all R bits are assigned for the maximum QoS approach and hence the allocation is "tight". The suggested algorithm is given by:

Step a – Initialization

For every sub-carrier m, and every transmitter l

$$b_{m,l} = 0 \ , \ P_{m,l} = 0 \quad (6a)$$

Step b – Bit and Power Assignment Iterations

While $\sum_{m=1}^{M} \sum_{l=1}^{L} P_{m,l} \le P_{Total}$ *(for maximum bit rate)*

or

While $\sum_{m=1}^{M} \sum_{l=1}^{L} b_{m,l} \ne R$ *(for maximum QoS)*

For every sub-carrier l and every transmitter antenna m,

$$\Delta P_{m,l}(b_{m,l}+1) = \left\| w_{m,l} \right\|^2 * [f(b_{m,l}+1) - f(b_{m,l})] \quad (6b)$$

$$\{\hat{m},\hat{l}\} = \arg\min_{m,l} \Delta P_{m,l} \quad (6c)$$

$$b_{\hat{m},\hat{l}} = b_{\hat{m},\hat{l}} + 1 \quad (6d)$$

$$P_{\hat{m},\hat{l}} = P_{\hat{m},\hat{l}} + \Delta P_{\hat{m},\hat{l}} \quad (6e)$$

Step c – Finish

$b = \{b_{m,l}\}_{m=1,l=1}^{M,L}$ and $P = \{P_{m,l}\}_{m=1,l=1}^{M,L}$ are the bit and power allocation solution.

For the maximum QoS approach, after allocation is finished, the total power should be normalized to accommodate the power budget, as explained before. Also note that for the maximum QoS, the calculation in (6b), can be replaced with a more convenient expression:

$$\Delta \tilde{P}_{m,l}(b_{m,l}+1) = \left\| w_{m,l} \right\|^2 * [2^{b_{m,l}+1} - 2^{b_{m,l}}] \quad (7)$$

where $w_{m,l}$ is the m-th row of the pseudo-inverse of the l-th sub-channel matrix.

As in the V-BLAST reception scheme, the order of the calculation of $w_{m,l}$ for a given sub-channel is of importance. In the V-BLAST receiver the component with the smallest post-detection signal to noise ratio (PDSNR) dominates the error performance of the system, and thus choosing the symbol with best PDSNR at each stage in the detection process leads to the globally optimal ordering [2]. Although the allocation algorithm aims to acheive the same PDSNR for all received sub-channels, optimal ordering at the allocation process should be done in a similar manner to that of the V-BLAST receiver because the integer constraints result in different PDSNR for two sub-channels allocated with the same number of bits. Summarizing, the algorithm for calculating the weight vector $w_{m,l}$ for the lth sub-carrier is a sub-section of V-BLAST algorithm, obtained by using equations (2a),(2b),(2c),(2d),(2h),(2i),(2j) and (2k).

One of the properties of the V-BLAST system is that it exploits the reception diversity in MIMO systems where $M \le N$ to achieve high QoS performance. Note that the algorithm will inherently achieve results that are equal or better than any reception diversity system with $M \le N$, since this solution is a subset of the solution space of the algorithm we propose.

The algorithm is optimal also for bit and power allocation in a MIMO system in which $M < N$. Note, however, that the calculation of *f(b)* changes since the required energy for receiving *b* bits gets smaller because of the diversity enhancement. Naturally, as the ratio between N and M gets larger, the improvement achieved by the loading will get smaller, because of the channel averaging effect.

The algorithm is optimal also for V-BLAST systems that operate over frequency non-selective fading channel. In this case there is a single carrier, accordingly L=1 in all equations. If we take only one transmitter and receiver (M=1), the algorithm becomes the well known "greedy algorithm" [9]

The loading algorithm described so far handles MIMO systems that operate over time invariant channels. Clearly, the same mechanism can be used over time-varying channels. But considering the complexity of the loading algorithm, such a system might be impractical. However, assuming that (a) the time variant channel can be divided into time slots in which the channel can be considered as constant or time invariant, and (b) that the channels corresponding to adjacent time slots have partial correlation, it will be useful taking advantage of the extended "Efficientize" algorithm given in [8] and to use the previous allocation as an initialization for the current channel. Accordingly the bits allocated in every sub-channel will be increased or decreased at every iteration, rather than increased only when the initial allocation is zero.

V. SIMULATION RESULTS

The following examples shows performance gain of three systems: The first is required to transmit a maximum number of bits, with the symbol error rate constrained to be smaller or equal to 2×10^{-3} (maximum bit rate criterion). The second system is required to transmit 4096 bits per symbol with the best error rate (maximum QoS criterion). The third system is required to transmit maximum number of bits, with the symbol error rate constrained to be smaller or equal to the symbol error rate of the OFDM V-BLAST system. All the three systems use a 256 multitone symbol, and there are four transmitting and four receiving antennas. The symbols are chosen from square QAM constellation and thus an even number of bits are Gray mapped onto the symbols. Each simulation run assumes that the channel parameters for that run are known at the receiver and at the transmitter (when relevant). These parameters are sampled from the Rayleigh distribution pertinent to the delay profile. The profile we use for these examples is the DVB-T [10] portable channel. The SNR figures at the abscissa, are relative, and are arbitrarily defined as follows: Each receiving antenna receives the superimposed signal from all M transmitters. This signal has a power of P_{rx} per received symbol. Accordingly the received SNR (at each antenna) is defined as $SNR = 10\log_{10} 2P_{rx}/N_0$. The relation between the total transmitted energy and the received energy is given by $P_{tx} = P_{rx}/E(r)^2$, where r is a Rayleigh distributed random variable. P_{tx} is divided between the M transmitters over the L frequency-bins. The graphs below were obtained by averaging the results over many channel realizations.

Figure 2 refers to the first example (maximum rate at constant error rate constraint) and shows two curves: The first is for equal bit and power allocation and the fixed error rate constraint. The second shows results for our adaptive loading algorithm. In this case the number of bits per antenna per tone varies from zero to eight, and the energy per tone is also variable. The optimized results show significant improvement, compared to the first case. As expected from the water-pouring solution properties, the smaller the SNR is, the greater the gain. As can be seen, at SNR below 15 dB the system with no loading collapses. Adaptive loading, however, enables communication in such conditions. Note also that for SNR of 30 dB the bit rate gain is approximately 1.75.

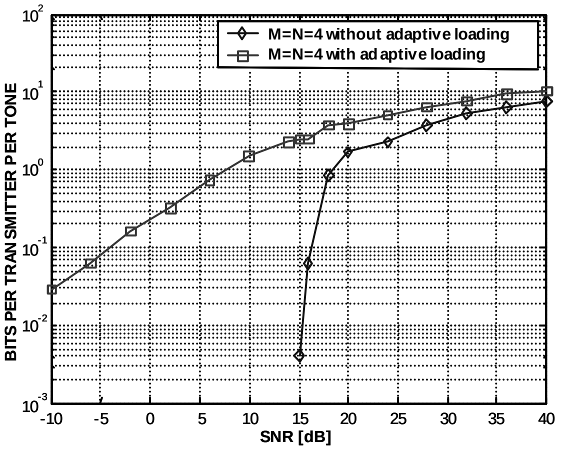

Fig. 2. Bits per transmitter per tone vs, SNR with and without adaptive loading, with 256 multitone symbol over a DVB-T channel, M=N=4, $P_r(e) = 2\text{x}10^{-3}$.

Figure 3 refers to the second example (maximum QoS) and also shows two curves. The first is for a V-BLAST OFDM system with an equal bit and power allocation: four bits per antenna per tone. The second shows results for our adaptive loading algorithm. In this case the number of bits per antenna per tone varies from zero to eight, and the energy per tone is also variable. The optimized results show significant improvement, compared to the first case. For example there are gains of 13 and 19 dB, respectively, at BERs of 10^{-3} and $2\text{x}10^{-4}$. Note also that the higher the SNR is, the greater the gain.

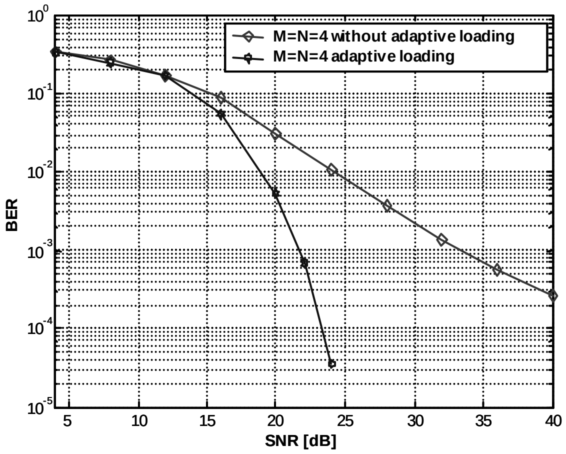

Fig. 3. BER vs. SNR with and without adaptive loading for 4096 bits per 256 multitone symbol (constant bit rate) at s MIMO system with M=N=4.

Figure 4 refers to the third example (maximum rate at OFDM V-BLAST error rate constraint) and we present the potential bit rate gain vs. SNR. The system is required to have at any SNR the same symbol error rate as that of a system that uses no adaptive loading (OFDM V-BLAST). For example at BER=2x10-3, the required SNR in system without adaptive loading is 30 dB. This system's performance can be improved by our algorithm in two senses: (a) lowering the required SNR by approximately 10 dB (as demonstrated in Figure 3) or alternatively (b) enhancing the bit-rate by approximately 1.75 times the original rate (as also shown in Figure 4). Moreover, at SNR of 33dB one can have the same system performance as an equivalent system with 8 transmitters and 8 receivers that does not use adaptive loading. It is important to note that all the results of this section are achieved without coding.

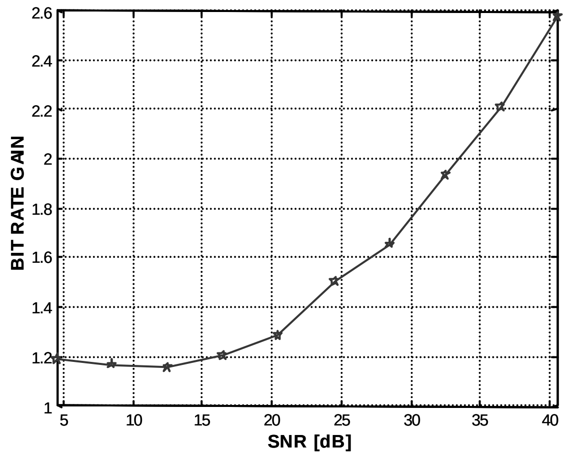

Fig. 4. Potential bit rate gain vs, SNR with adaptive loading compared to OFDM V-BLAST with 4096 bits per 256 multitone symbol over a DVB-T channel, M=N=4.

VI. Summary and Conclusions

We have presented an algorithm for adaptive bit and power allocation in V-BLAST systems operating in any slow fading channel. The loading algorithm is optimal for a maximum bit rate criterion and for maximum QoS (maximum margin) criterion. Simulations of this system show significant improvement for both criteria: By adopting the maximum rate approach it is possible either to achieve efficient and reliable communication with low SNRs (which is not achievable in the original V-BLAST system), or to increase the bit rate. By adopting the maximum QoS approach the power margin is improved with the SNR.

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Dror Meiri (S’00–M’03) was born in Haifa, Israel in 1971. He received BSc. and MSc in electrical engineering from the Technion, Israel Institute of Technology in 1996 and 2003, respectively.
He has been a system engineer and technical project manager at Oren Semiconductors from 1996 to 1999 and R&D team leader at Surf Communication Solutions from 1999 to 2001. On 2002 he joined Aelis photonics, Netanya, Israel as manager of signal processing. His interests include digital communications, adaptive signal processing and MIMO systems.

Irving Kalet was born in The Bronx, NY. He received the B.E.E. degree from the City College of New York, New York, in 1962, and the M.S. and Dr.Eng.Sc. degrees from Columbia University, New York, in 1964 and 1969, respectively.
He taught at the City College of New York from 1964 to 1967. He has been living in Israel since 1970. He was a consultant at Bell Laboratories for many years in the fields of HDSL, ADSL, mobile wireless communications, and on the 56 kbit/s modem. He is a Visiting Associate Professor at the Technion ,in Israe,l for the past six years. He is presently interested in the field of modulation for wireless communications.
Dr. Kalet is a member of Sigma Xi, Tau Beta Pi, and Eta Kappa Nu.