Throughput of Broadcast Digital Subscriber Lines

Keang-Po Ho† and Walter Y. Chen‡

†Dept. of Informational Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong
‡Texas Instruments, 13510 North Central Expressway, Dallas, Texas 75243

Abstract:

Broadcast Digital Subscriber Lines (BDSL) can provide a cost effective architecture to deploy digital broadcast services in the near future by utilizing the in-place unshielded twisted-pairs. In BDSL system, all broadcasting channels can share the same transmitter to reduce the cost. Because all twisted-pairs transmit same BDSL signal in the same direction, both near-end crosstalk and far-end crosstalk can be eliminated. While HDSL and ADSL signals are carried at low frequency band, BDSL signals can be transmitted at higher frequency band. To increase the efficiency of BDSL, a discrete multitone based modulation method is proposed. Compared to scheme employing identical modulation for all subchannels, we can increase the channel though-put of low frequency subchannels for their smaller channel losses and utilize the high frequency subchannels which are otherwise unable to use for their small signal-to-noise ratio. The combination of HDSL, ADSL, and BDSL can provide subscribers many digital one-to-one and broadcasting broadband services.

1. Introduction

The communication and entertainment industries want to provide broadband services to the home. In addition to plain old telephone service (POTS) that carries voice signals to almost every household, other broadband services build upon the ability to transmit high-quality still or moving pictures and high fidelity audio on demand, using modern communication technologies. These broadband services include high-speed.Internet access, digital video, video dial tone, video library, tele-commuting, tele-retailing, multimedia transmission services, etc.

A broadband trunking and switching network and high-speed subscriber lines are essential to support these services. One way to build the subscriber loop is to bring fiber all the way to the home. Fiber-to-the-home (FTTH) has long held the promise of being the ultimate vehicle for the delivery of broadband services. However, in spite of significant industry effort that has produced dramatic reduction in the cost of fiber and related components, there remain serious near term barriers in cost, standards, and technologies to the wide-spread installation of dedicated fiber to each subscriber residence.

The Asymmetrical Digital Subscriber Lines (ADSL) is designed to transmit digital information via unshielded twisted pair telephone loops to telephone subscribers [1]-[3]. The main advantage of the ADSL technology is the utilization of existing twisted-pair loop plant for delivering high-speed digital signal with the only addition of transceivers at each end of the subscriber loop. To make the ADSL a viable technology, the transceiver cost should be further minimized. On the other hand, if we can deliver digital broadcast video programs also through the same twisted pair loop and share the same transmission and decompression hardware, the impact of digital video services introductory cost can be minimized.

The adoption of ADSL technology in conjunction with the Broadcast Digital Subscriber Lines (BDSL) [5] in this paper could provide a cost effective solution for the introduction of digital video services in the near term. More effective for short twisted-pair loops, BDSL can provide digital broadcast video programs to all subscribers through existing twisted-pair telephone loops.

2. Digital Subscriber Line Systems

Although the telephone voice channel has a limited bandwidth of 3 kHz, the twisted-pair telephone subscriber loop connecting subscriber to central office has a much wider bandwidth limited only by loop attenuation and noise environment. The Digital Subscriber Line (DSL) used for the Integrated Services Digital Network (ISDN) basic rate access channel has a transmit signal bandwidth of 40 kHz (see Fig. 1). The High-bit-rate Digital Subscriber Line (HDSL) developed mainly for the repeater-less T1 service has a transmit signal spectrum of 200 kHz. Both DSL and HDSL usable bandwidth are limited by near-end crosstalk (NEXT) due to the bidirectional nature of both ISDN and HDSL.

The usable bandwidth can be expanded by use the concept of ADSL. For the compressed digital video information delivery, the ADSL receiver only experiences far-end

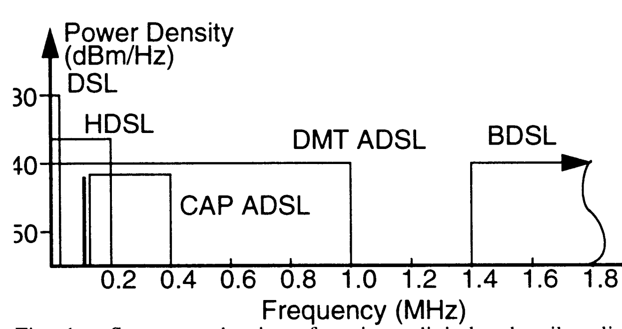

Fig. 1 Spectrum density of various digital subscriber line systems.

crosstalk (FEXT) because each direction of ADSL utilizes different frequency band and only one of the direction transmits high-rate digital information. Since the magnitude of FEXT is relatively lower compared with that of NEXT, more throughput can be achieved via subscriber loops. The DMT ADSL has a transmit signal bandwidth of 1.1 MHz. The full duplex POTS service is located at below 10 kHz and the upstream, from subscriber to central office, digital telephony channels are located at between 10 kHz and 100 kHz.

The concept of ADSL can also be carried out by other passband modulation schemes such as QAM or CAP 6.. The passband QAM or CAP transmit signal spectrum can be located between 140 kHz and 400 kHz. The QAM or CAP upstream channel can be located at around 100 kHz. For this arrangement the spectrum below 100 kHz can be used by POTS and ISDN basic rate access channel services. The passband ADSL spectrum can be moved closer to the POTS channel if the inclusion of ISDN basic rate access channel is not required.

If the effect of NEXT and FEXT can both be avoided, the usable bandwidth of the subscriber loop can be further expanded. This can be achieved through the concept of BDSL by broadcasting compressed video information to all subscribers. Under the concept of BDSL, the usable bandwidth also depends upon the transmit signal strength. To also accommodate the need of providing symmetrical and asymmetrical switched digital services, the broadcasting channels can be allocated at a spectrum above those constrained by NEXT and FEXT noise as shown in Fig. 1.

Fig. 2 shows the architecture of the BDSL transmission system. The same signal is sent to all subscriber loops occupied the higher frequency band. Because the signal in all twisted-pairs are identical and the transmission is unidirectional in the BDSL frequency band, both NEXT and FEXT can be eliminated. In BDSL, the same mechanism that induces FEXT in ADSL enhances the signal power instead of causing interferences. Only the receiver thermal noise degrades the performance of the transmission system. As shown later, receiver noise is much smaller than both NEXT and FEXT, a large improvement may be expected by using BDSL technique.

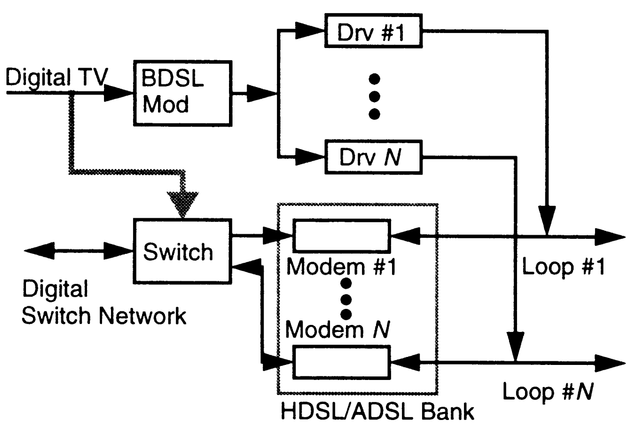

Fig. 2 The architecture of the central office modem bank of the BDSL systems.

3. Subscriber Loop Plant Noise Environment

Due to the structure of twisted pair cable, there exists crosstalk between different wire pairs. The noise level caused by crosstalk at voice frequency is very small and can be simply ignored. However, crosstalk noise at high frequency is the major limitation for providing high speed digital communication through the twisted pair loop plant. Crosstalk experienced by a receiver from adjacent transmitters is called Near End Crosstalk (NEXT) while a receiver of an one directional transmission system, such as ADSL, only experience Far End Crosstalk (FEXT) in addition to possible NEXT from other full duplex systems.

It is interesting to examine copper loop usable bandwidth according to a certain Signal-to-Noise Ratio (SNR) under NEXT, FEXT, and white noise environments. According to 7., the SNR under NEXT can be expressed as

$$SNR_n \approx \frac{e^{-2d\zeta\sqrt{f}}}{\chi f^{3/2}}, \tag{1}$$

where d is the loop distance in feet, $\zeta = 9\times10^{-7}$ for 26 gauge loop, f is frequency in Hz, and $\chi = 8.8\times10^{-14}$ for the 49 disturber 1% worst case NEXT model. The SNR under FEXT 7. can be expressed as

$$SNR_\phi = \frac{1}{\psi f^2 d}, \tag{2}$$

where $\Psi = 8\times10^{-20}$ for the 49 disturber 1% worst case FEXT model. In addition, the SNR bandwidth limited by a receiver background white noise (AWGN) can be expressed as

$$SNR_w \approx 1\times10^{10} e^{-2d\zeta\sqrt{f}} \tag{3}$$

where a -40 dBm/Hz transmitted power density level and a -140 dBm/Hz receiver background noise power density level are assumed.

As shown in [5], NEXT limited data rate mostly for high-rate systems, FEXT degrades the system less than NEXT, and AWGN limited systems the least. Because of this situation, if we are to accommodate all of these technologies, the best trade-off will be achieved by placing the spectra of full duplex digital subscriber line systems whose throughputs are limited by NEXT such as DSL and HDSL in the lower frequency band, half duplex systems such as ADSL whose throughputs are related to FEXT at the next higher frequency band, and BDSL whose throughputs are only limited by background white noise beyond these full and half duplex systems.

It should be noted that NEXT and FEXT usable bandwidths are defined by cable and crosstalk losses while the AWGN bandwidth is expandable by raising transmitter power density. The BDSL sends the same information on every subscriber loop in only one direction. NEXT is eliminated because of unidirectional transmission. For BDSL, FEXT will only enhance signal strength but not cause any interferences.

4. Multitone Techniques for BDSL

All modulation schemes may be employed for BDSL. In 5., OQAM, CAP, and digital Vestigial Side Band (VSB) are considered to transmit digital signal for BDSL. Each BDSL subchannels employ 16-point constellation. With a data rate of 1.6 Mb/s, each BDSL subchannel occupies a bandwidth of 400 kHz for OQAM without guard band, and 450 kHz for CAP or VSB scheme with guard band. It is shown that forty BDSL channels can be provided through a distance of 2 kft with a voltage level suitable for the 5-volt VLSI technology.

Multicarrier transmission methods 8.-9. can be utilized to optimize the performance of data transmission on band-limited dispersive communication channels. In multicarrier modulation, the transmission channel is partitioned into bank of orthogonal, memoryless subchannels. Data are transmitted independently through each subchannels, allowing the flexibility to change modulation scheme (allocated different number of bits) and power in each subchannel. One form of multicarrier transmission, known as discrete multitone modulation (DMT) 3., is particularly attractive for its ability to be implemented using efficient digital signal processing techniques.

The DMT technique is employed for the ANSI ADSL standard [3] and also proposed for the return path of CATV networks [10]. Obviously, the same technique can be applied to BDSL. In the transmitter, the whole bandwidth is partitioned into many subchannels, say N subchannels. Depending on the bit-allocation, each broadcasting TV channel can occupy some of those subchannels in consecutive order, for example, the i-th TV channel utilize n_i subchannels. In each individual BDSL receiver, the demodulation of all subchannels is not required. Obviously, each receiver only requires to receive $M > \max(n_i)$ subchannels to select one of the all TV channels.

As shown in Fig. 2, a single BDSL transmitter is shared by all BDSL receivers. A complicate, expensive, and computational intensive BDSL transmitter is allowed because its expensive is shared by many subscribers. Therefore, it is expected that the total number of subchannels can be large, for example, $N = 512$, 1024,.... In contract, each receiver should be as simple as possible, small number of subchannels is required to demodulate, for example, $M = 16$, 32, or 64. The sampling rate of the receiver can also be reduced if a down converter is employed to select the proper subchannels before demodulation.

Fig. 3 shows the simplified block diagram of the DMT based BDSL transmitter. All digital TV channels are combined into a single bit stream. The combined bit stream is partitioned into block of size $b = RT$ bits, where R is the combined bit rate of all digital TV channels, T is the DMT symbol period, and b is the number of bits contained in each DMT symbol. The bits are allocated to N subchannels. Note that the bits from the same digital TV channel are allocated

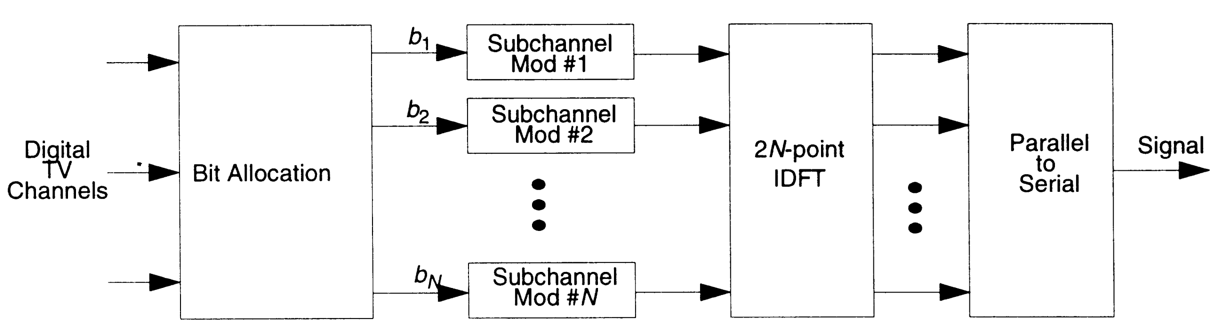

Fig. 3 The DMT transmitter of BDSL.

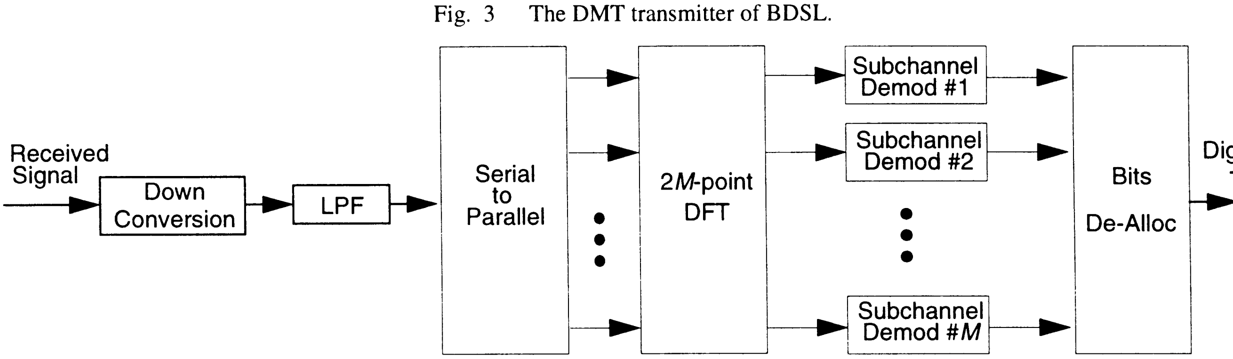

Fig. 4 The DMT receiver of BDSL.

to adjacent subchannels. Each digital TV channel may have different bit-rate. Real-time changing of bit-rate of each TV channel is possible, but complicate controlling mechanism may be required.

After the bit allocation, bits of each subchannel are mapped to the constellation points of each subchannel by a modulator. The signals of all modulators are collected and serve as the input to a $2N$-point inverse discrete Fourier transform (IDFT) block. The IDFT block provides the time-domain signal which is converted to serial data and transmitted one by one after a digital-to-analog (D/A) converter. Depending on the scheme, an upconverter may be required after the D/A converter to convert the signal to a frequency band higher than 1.4 MHz. Alternatively, the upconverter can be implemented digitally before the D/A converter.

Fig. 4 shows the simplified block diagram of a DMT based BDSL receiver. After the signal is received at the receiver front-end, it is down-converted and passed through a low-pass filter. The down-conversion and filtering may be implemented either by analog or digital techniques. If the down-conversion is implemented by digital technique, down-sampling can be employed to reduce the number of signal points after the low-pass filtering. The channel tuning is accomplished by the down-conversion process. By down-converting the subchannels of a specific digital TV channel into the low-frequency band, the receiver can select the specific digital TV channel.

The low-passed signal is followed by a serial-to-parallel converter. The DFT block is employed to demultiplex each subchannel in the DMT symbol. The bits of each subchannel are demodulated by the demodulator of each subchannel. The bit selector collects bits from all M subchannels, combines those bits to a single bit-stream for a specific digital TV channel. The digital TV signal can be sent to a video decoder after the BDSL receiver.

Because the BDSL receiver is not required to demodulate all subchannels in the combined DMT signal, BDSL receiver can select only the required subchannels for a specific digital TV channel. The BDSL receiver is much simpler than an ordinary DMT receiver that is required to demodulate all subchannels.

5. Channel Capacity of BDSL

In BDSL, because all twisted-pair loops transmit identical broadcasting signal, both NEXT and FEXT are eliminated. In the BDSL receiver, the signal is only contaminated by thermal noise. The frequency depending SNR is shown in (3). In the study of [5], by assuming that each channel occupies 400 kHz and requires a SNR of 30 dB, the number of channel is estimated by finding the maximum frequency f_{max} such that $SNR|_{f_{max}} \geq 30\,\text{dB}$ for a fixed transmitter output power. If each 400 kHz channel has a data rate of 1.6 Mb/s, the overall date rate of the OQAM scheme is equal to

$$C_{QAM} = 4\,(f_{max} - f_L)\,. \tag{4}$$

where f_L is the beginning frequency of the BDSL channel. In this paper, $f_L = 1.4$ MHz is assumed.

From (3), the SNR is exponential fall off as frequency increase, the subchannels at low frequency can achieve a much higher SNR than those at high frequency. To take this advantage, more complicate modulation scheme (utilizing constellation with higher number of points) can be employed for the low-frequency band. DMT is the modulation scheme that can fully utilize the bandwidth and SNR of each frequency band to achieve the optimal system performance.

The channel capacity of the BDSL channel, i.e., the theoretical maximum transmission throughput, for the system can be calculated according to:

$$C_{max} = \int_{f_L}^{\infty} \log_2(1 + SNR_w)\, df. \tag{5}$$

The maximum capacity of the channel is usually very difficult to achieve, however, it is a good comparison with respect to the practical system performance.

The number of bits in each DMT subchannel is equal to [8], [11]

$$b_i = \log_2\left(1 + \frac{SNR_w}{\Gamma}\right), \tag{6}$$

where $\Gamma = 9.8$ dB for uncoded DMT systems. The value of Γ can be lowered to 5-6 dB with coding gain [11]. In this paper, for simplicity, uncoded DMT system with $\Gamma = 9.8$ dB is considered.

The total number of bits in each DMT symbol is

$$b = \sum_{i=1}^{N} b_i \tag{7}$$

and the overall data rate is $R = b/T$, where T is the DMT symbol period.

Fig. 5 shows the channel capacity and maximum data rate of the DMT based BDSL systems. The maximum data rate of the OQAM modulation scheme considered in [5] is also shown for comparison. The spectrum density of the DMT signal is -40 dBm/Hz or -30 dBm/Hz. The OQAM modulation scheme is system with $SNR|_{f_{max}} \geq 30\,\text{dB}$, 400 kHz bandwidth and 1.6 Mb/s per channel, and employed 5 volt VLSI technology.

In Fig. 5, the number of bits in each subchannel is determined by (6). To evaluate the theoretically maximum data rate of DMT system, fractional number of bits per subchannel is allowed. In practical system, it is possible to map bits to multiply subchannels such that fractional number of bits

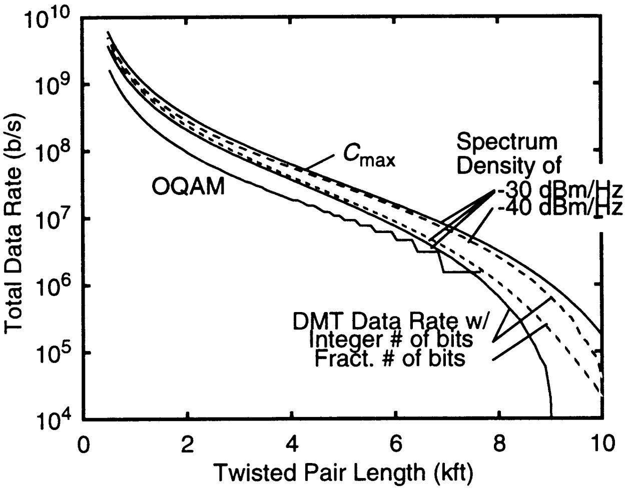

Fig. 5 Channel capacity and DMT maximum data rate of BDSL systems as a function of twisted-pair length. The maximum data rate of OQAM scheme is also shown for comparison.

per subchannel can be implemented, for example, if 4 bits are mapped to 3 subchannels equally, each subchannel has 4/3 bits. For simplicity, integer number of bits per subchannel is assumed and the maximum number of bits per subchannel is less than 14. Fig. 5 also shows the maximum data rate under the assumption $0 < b_i \leq 14$, b_i is integer, with spectrum density of either -40 dBm/Hz and -30 dBm/Hz.

The channel capacity and maximum data rate in Fig. 5 are provided with a 6 dB of SNR margin. The 6 dB SNR margin is included to account of any unexpected noise in the system, for example, impulse noises, large resistance,... The total number of subchannels in the DMT scheme is 1024. In another scheme, we also consider system in which each DMT subchannel occupies a bandwidth of 20 kHz and the total number of subchannels is 512. All different DMT schemes yield almost identical maximum data rate.

Table I summarized the maximum data rate of the DMT based BDSL system compared with OQAM system. It is shown that the overall maximum date rate of DMT based system is about twice the maximum data rate of OQAM system. For a twisted-pair length of 2 kft, with spectrum density of -40 dBm/Hz, the DMT scheme can support an overall data rate of 210 Mb/s, which corresponding to more than 100 MPEG-1 video channels, each with 1.5 Mb/s data rate, or more than 30 MPEG-2 video channels, each with 6 Mb/s data rate.

TABLE 1. Maximum Data Rate (Mb/s) of Various Twisted-Pair Length

Length	1 kft	2 kft	3 kft	4 kft
DMT (-40 dBm/Hz)	897	210	82	38
DMT (-30 dBm/Hz)	1204	286	116	57
OQAM [5]	413	98	40	19

When the noise of the system is limited by either NEXT or FEXT, the increase of transmitter power does not increase the receiver SNR proportionally. In BDSL system, the limiting noise is the receiver thermal noise. The receiver SNR is directly proportional to the transmitter power. As shown Fig. 5 and Table I, if the transmitted spectrum density increases from -40 dB/Hz to -30 dB/Hz, the overall data rate can increase about 35 to 50%.

6. Conclusion

The combination of HDSL, ADSL, and BDSL can provide telephone subscribers many useful services. For a short distance, in addition to the conventional HDSL/ADSL, more than 200 Mb/s of digital TV signal can be transmitted. The 200 Mb/s corresponds to more than 100 MPEG-1 and 30 MPEG-2 video channels. The combination of HDSL, ADSL, and BDSL can provide subscribers many digital one-to-one and broadcasting broadband services.

7. References

1. W. Y. Chen and D. L. Waring, "Applicability of ADSL to support video dial tone in the copper loop," *IEEE Commun. Mag.*, May 1994, vol. 32, No. 5, pp.102-109.
2. P. S. Chow, J. C. Tu, and J. M. Cioffi, "Performance evaluation of a multichannel transceiver system for ADSL and VHDSL services," *IEEE J. Select. Areas in Commun.*, Vol. 9, No. 6, pp. 909-919, August 1991.
3. "Telecommunications - Network and customer installation interface -Asymmetric digital subscriber line (ADSL) metallic interface (ATIS)," ANSI T1.413, 1995.
4. A. K. Aman, R. L. Cupo, and N. A. Zervos, "Combined trellis coding and DFE through Tomlinson precoding," *IEEE J. Select. Areas in Commun.*, Vol. 9, No. 6, pp. 876-884, August 1991.
5. W. Y. Chen, "Broadcast digital subscriber lines," *IEEE J. Select. Areas in Commun.*, vol. 13, pp. 1550-1557, 1995.
6. K. Kerpez and K. Sistanizadah, "High-bit-rate digital communication over telephone loops," *IEEE Tran. Commun.*, Vol. 9, No. 6, pp. 876-884, May 1995.
7. J. J. Werner, "The HDSL environment," *IEEE J. Select. Areas in Commun.*, Vol. 9, No. 6, pp. 785-800, August 1991.
8. J. A. C. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Commun. Mag.*, vol. 28, no. 5, pp. 5-14, May 1990.
9. I. Kalet, "The multitone channel," *IEEE Tran. Commun.*, vol. 37, pp. 102-109, 1989.
10. K. S. Jacobsen, J. A. C. Bingham, and J. M. Cioffi, "Synchronized DMT for multipoint-to-point communications on HFC networks," *Proc. GLOBECOM '95*, p, 963, 1995.
11. J. S. Chow, J. C. Tu, and J. M. Cioffi, "A discrete multitone transceiver system for HDSL applications," *IEEE J. Select. Areas in Commun.*, vol. 9, pp. 895-908, 1991.