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Discrete Wavelet Multi-Tone Transmission for Digital Subscriber Line

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Abstract

Multi-Carrier Modulation (MCM) is an attractive technique for copper wire access technology in high-performance communication networks (e.g. Asymmetric and Very-high-rate Digital Subscriber Line). In digital implementations of MCM, subcarrier generation and data modulation are accomplished digitally using orthogonal transformations of data blocks called Discrete Multi-Tone (DMT). These implementations are efficient with regard to bandwidth utilization and transceiver complexity.

In this article, a variant high-performance digital MCM was used, the Discrete Wavelet Multi-Tone (DWMT) transmission. The standard asymmetric digital subscriber line modems use DMT line code and are able to deliver up to 8 Mbps. The computer simulation test results of the systems show that an improved performance can be achieved with DWMT over the conventional single-carrier and DMT systems within the same conditions. The conditions covered in the tests are those experienced in subscriber line such as additive noise and cross talks (both near and far ends).

الخلاصة

*ان التضمين متعدد النغمات الناقلة (**Multi-Carrier Modulation**) أو (**MCM**) هو من التقنيات المميزة و المستخدمة في شبكات الأتصالات ذات الأداء الكفوء المطبقة في تكنلوجيا التوصيلات النحاسية (مثل خط المشتركين الرقمي ذو السرع العالية والخط غير المتناظر). ان التطبيق الرقمي لتقنية (**MCM**) يعتمد على دمج عملية توليد نغمة الناقل الثانوي(**sub-carrier**) مع تضمين البيانات بواسطة استخدام التحويلات المتعامدة لصفوف البيانات والمسماة*

*(**Discrete Multi-Tone modulation**) أو (**DMT**) حيث ان هذه التقنية اثبتت كفائة عالية فيما يتعلق بالأستخدام الأمثل لوسع النطاق الترددي ودرجة تعقيد معدات التراسل.*

*تتناول هذه المقالة أستخدام نوع مغاير لمنظومة الـ(**MCM**) الرقمية أي الـ(**DMT**) وهوأرسال (**Discrete Wavelet Multi-Tone modulation**) أو (**DWMT**). أن المضمنات(**modems**) القياسية في حالة خط المشترك الرقمي غير المتناظر تستعمل ترميز نوع(**DMT**) وهي قادرة على ايصال بيانات بسرع عالية ولغاية(**8Mbps**). يوضح هذا البحث ومن خلال نتائج اختبارات المحاكات بالحاسوب،أفضلية الأداء لتقنية(**DWMT**) بالمقارنة مع المنظومات ذات التردد الناقل المنفرد التقليدي وكذلك مع تلك التي تستخدم (**DMT**) ضمن شروط الفحص نفسها. الشروط التي تم أعتمادها هنا في الأختبارات غطت تلك المجربة في خط المشترك مثل الضوضاء المضاف وكذلك التداخل(**crosstalk**) بنوعيه القريب وذو النهايات البعيدة.*

1. Introduction

With the development of Internet and multimedia applications, a demand has created for high-speed communication that links the end-user to the backbone network. The difficulty is to provide a high-speed data-transmission-channel for the last few kilometers to the home.The problem being the huge number of subscribers who need to be connected [1, 2].

Hybrid fiber-coaxial is a shared access medium was designed for analog and digital broadcasting, therefore, it is not able to carry voice telephony, interactive video, and high-speed data transmission at the same time [3]. Fiber to the home is still expensive in a market place soon to be driven by competition rather than cost.

An attractive alternative, is a combination of fiber cables feeding Optical Network Unit (ONU) and last leg premises connections by existing copper loops. This topology is called Fiber To The curb, neighborhood, cabinet, home, or exchange (FTTx) depending on the location of the ONU from the customer premises, as shown in **Fig.(1)** [2] .

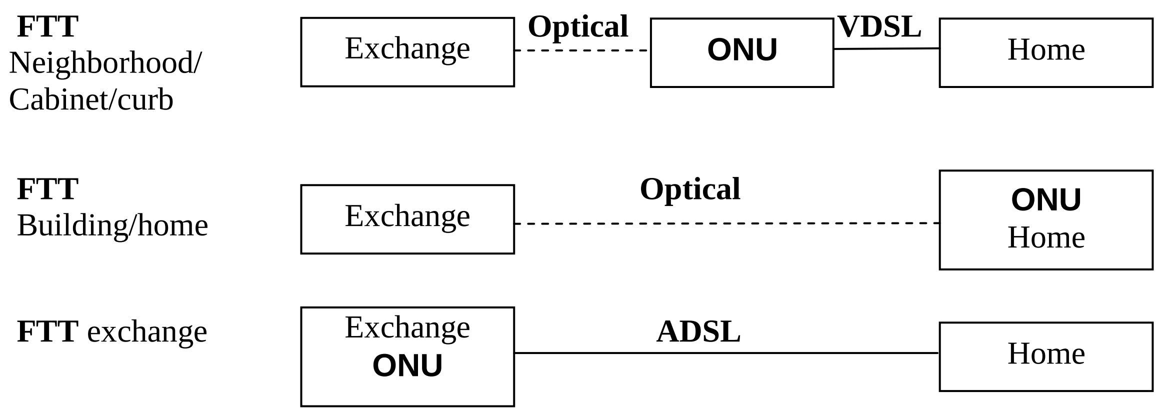


Figure (1) FTTx Topoligies

2. Technology Overview

The enabling technologies for FTTx are Digital Subscriber Lines (xDSL), where "x" denotes one of its versions such as ISDN DSL (IDSL), High-rate DSL (HDSL), Asymmetric DSL (ADSL), and Very high-rate DSL (VDSL). In simple terms xDSL transmits high-speed data over short reaches of twisted-pair (TP) copper telephone lines with a range of speeds depending upon actual line length [2,4,5] . The copper telephone channel is (up to now) the widely communication tool throughout the world that connects the remote subscriber to the central office. It was designed primarily to transport voice signals in the region 0.3-3.4 kHz. Therefore, it has the limitations of narrow bandwidth and moderate SNR figure [2,5] . These limitations can be mitigated by using the principle of transmitting data by dividing it into several interleaved bit streams, and using these to modulate several carriers, then we can adapt these carriers to the channel response. This technique called Multi-Carrier Modulation (MCM) [6] .

MCM that use FFT bases as carriers is called Discrete Multi-Tone (DMT) modulation. DMT has many advantages over single-carrier modulation [6] and has been adopted as an ANSI standard for Asymmetric Digital Subscriber Line (ADSL) [5] . In recent years, there has been a lot of interest in the application of wavelets and filter bank to communication [7-9]. One such application is called Discrete Wavelet Multi-Tone (DWMT) transmission, which uses overlapped orthogonal wavelet bases as carriers. Wavelet bases, when used in modulation, provide more flexible signal shaping design that leads to many preferred transmission-signal characteristics such as high stop-band attenuation and more power containment in the main lobe. Therefore DWMT can provide a high level of immunity against narrow band interference and subchannels crosstalk.

3. Asymmetric Digital Subscriber Line

An ADSL circuit connects an ADSL modem on each end of a TP telephone line, creating three information channels-a high-speed downstream channel, a medium-speed duplex channel, and a basic telephone service channel. The high-speed channel ranges from 1.5 to 6.1 Mbps, and duplex rates range from 16 to 640 kbps [4]. Each channel can be sub-multiplexed to form multiple lower-rate channels. ADSL modems provide data rates consistent with North American T1 1.544 Mbps and European E1 2.048 Mbps digital hierarchies and can be purchased with various speed ranges and capabilities. Downstream data rates depend on a number of factors, including the length of the copper line, its wire gauge, presence of bridged taps, and cross-coupled interference. Line attenuation increases with line length and frequency and decreases as wire diameter increases. Ignoring bridged taps ADSL performs as shown in **Table (1)** [4,10].

Table (1) Claimed ADSL Physical-Media Performance

Data rate (Mbps)	Wire gauge (AWG)	Distance (feet)	Wire size (mm)
1.5 or 2	24	18000	0.5
1.5 or 2	26	15000	0.4
6.1	24	12000	0.5
6.1	26	9000	0.4

3-1 ADSL System Reference Model

Figure (2) shows an overview of a copper access network employing **ADSL** modem. The pair of modems that constitute the ADSL link are the ADSL transmission unit-C (ATU-C) at the local exchange and the ATU-R at the subscriber premises (remote site). Terminal equipment, such as TV set-top box or a PC is connected to the premises distribution network in the subscriber's premises. At the local exchange the access node can be connected via a Digital Subscriber Line ADSL analog signals are superimposed on the subscriber line in the upstream direction. In the downstream direction, splitters with low- and high-pass filters are used to separate the POTS signal from the ADSL signal. At the DSLAM, the ADSL and POTS signals are separated in the upstream direction, and coupled in the downstream direction by means of two filters. Low pass filter, transparent to POTS and attenuating ADSL signal and high pass filter, inhibiting any disturbance to the ADSL path by typical POTS signals [11, 12].

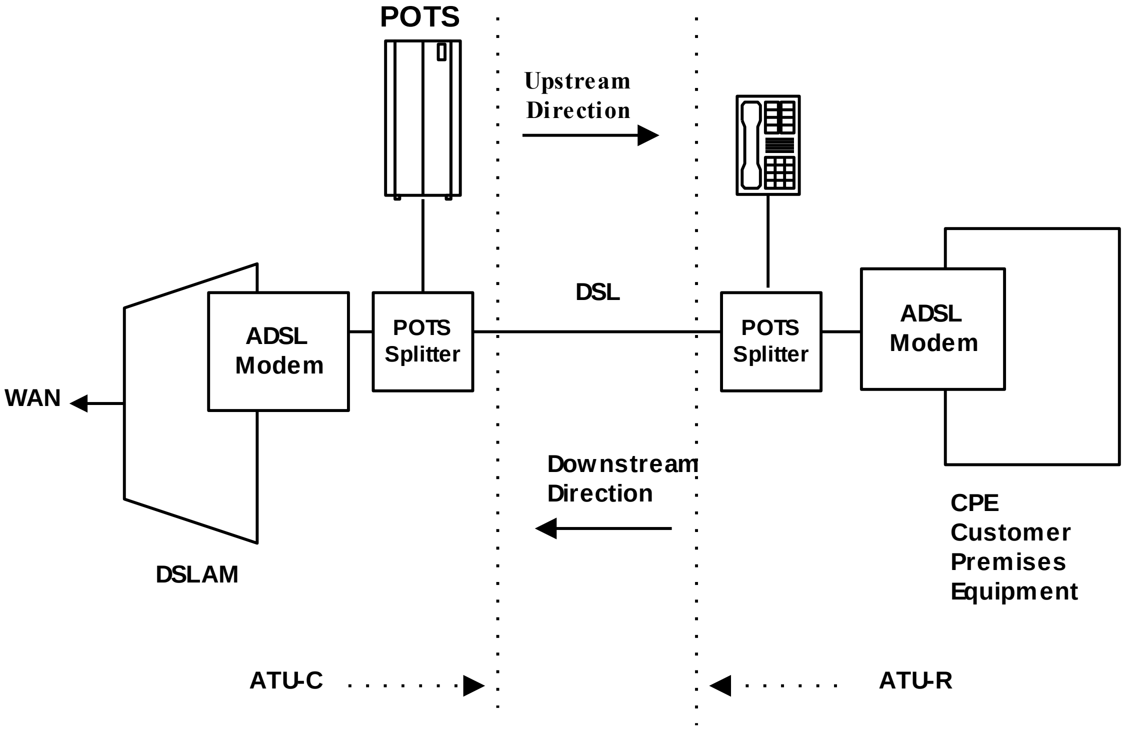


Figure (2) A typical Copper Access Network Employing ADSL Modem

3-2 Impairments of DSL Systems

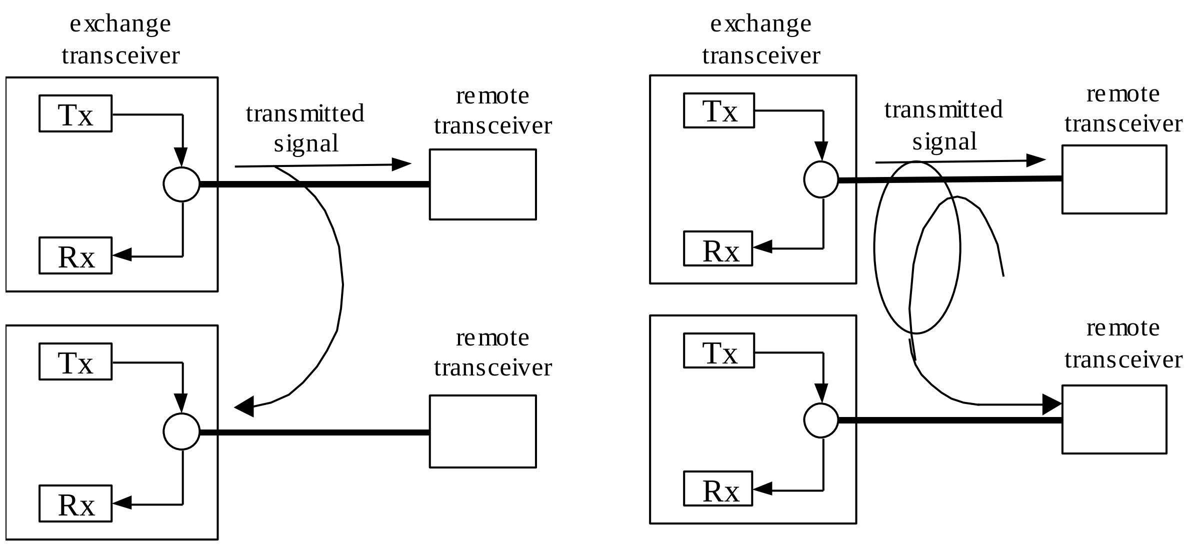
The major channel impairments that affect system performance in the local loop and must be considered for the assessment of systems are the near-end and far-end-crosstalks.

3-2-1 Near-End Crosstalk (NEXT)

NEXT [**Fig.(3a)**] arises due to signals from transmitters on other pairs operating in the same multi-pair cable. These are signals that interfere with the input of a transceiver at the same end. Therefore, NEXT is usually the dominant noise source for symmetrical digital transmission systems like VDSL [13].

3-2-2 Far-End Crosstalk (FEXT)

FEXT occurs when signals from transmitters on other pairs in the same cable leak into the input of the wrong transceiver at the other end. This is shown in **Fig.(3b)**. FEXT is usually the most significant noise source which limits the reach of high-rate asymmetrical transmission systems like ADSL, where the same directions of transmission occupy the same frequency band [13].



(a) NEXT noise coupling **(b) FEXT** noise coupling

Figure (3) Crosstalk-Noise Occurrence in the Local Loop

4. Transmission Techniques

4-1 Quadrature Amplitude Modulation (QAM)

QAM is a well-established and documented modulation technique used extensively in voice band modems. The source data is split onto two half-rate streams which are then modulated into a pair of orthogonal carriers for transmission. The orthogonality is provided by a sine and cosine mixing function which can be implemented digitally. At the receiver, the orthogonality allows the two-bit streams to be separated by demodulation for subsequent detection of data. Detection involves identifying the received 2-D symbol and then mapping this back into binary [14]. Gray mapping provides better Bit-Error-Rate (BER) [14], therefore, it was used in this work.

4-2 Discrete Multitone (DMT) Modulation

DMT is a form of MCM. DMT divides time into regular 'symbol periods', each of which will carry a fixed number of bits. The bits are assigned in groups to signaling the tones (carriers) of different frequencies. Hence, in the frequency domain the DMT divides the channel into a large number of subchannels (tones) [15]. The tone capacity depends on the transmitted signal power over that tone according to Shannon capacity theorem [16]. The tone's SNR varies with frequency, thus, the bits assigned for each tone will be varied. The bits for each tone are converted into a complex number that will set the tones amplitude and phase from the symbol period. Hence, conceptually, DMT can be thought of as a bank of contiguous QAM systems operating simultaneously in parallel, each with a carrier frequency corresponding to a DMT tone frequency [17].

MCM requires orthogonality between the various tones this can be implemented in an efficient all digital realization by exploiting FFT methods [18]. Each narrow subchannel has the advantage that the cable characteristic is approximately linear across the entire subchannel, and thus pulse dispersion within each tone is minimum. The energy from an impulsive noise event will modify a received symbol but the FFT spreads the effect over the large number of tones within the FFT window [15,18]. The DMT system block diagram is shown in **Fig.(4)**.

4-3 Discrete Wavelet Multitone Modulation

DWMT is a form of MCM that uses the wavelet transform instead of the FFT [19]. The wavelet transform, specifically, the wavelet packet decomposition is convenient technique by which waveforms providing self and mutual orthogonalities can be obtained. This technique is called Wavelet Packet Modulation (WPM) [20]. WPM, specifically, the Hierarchical Lapped Transform (HLT) [21] has attractive properties that make it more preferable to be used for DWMT [22]. HLT is very simple to design, where the problem of designing large wavelet system (more tones in the DWMT) is reduced to the problem of the design of two-band wavelet filters [21]. Also the design of HLT is relatively flexible, the required filter characteristics are imposed to the wavelet two-band system design procedure, such that lower stop-band attenuation (below –45dB or more) subchannel concentration were obtained. The block diagram of the DWMT system is shown in **Fig.(5)** [8]. This is shown to be similar to that of **Fig.(4)**, except the orthogonal transformation part that uses the wavelet transform.

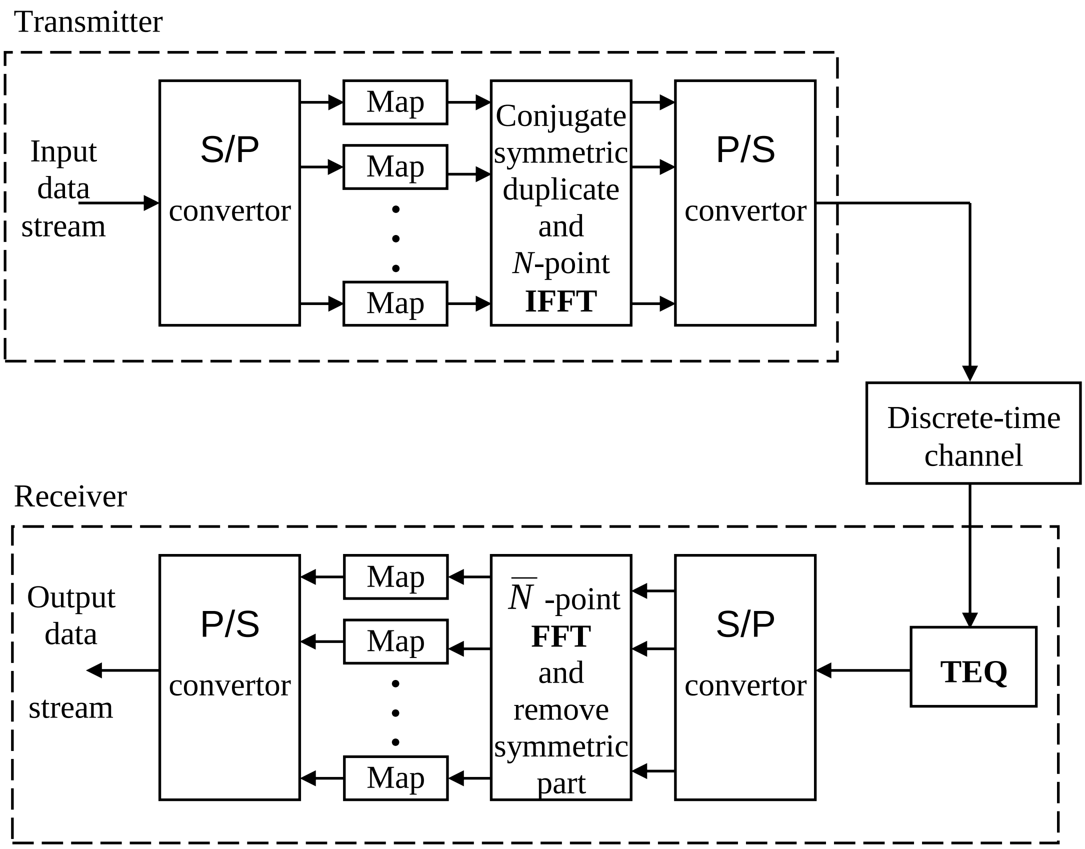


Figure (4) Block Diagram of the DMT System

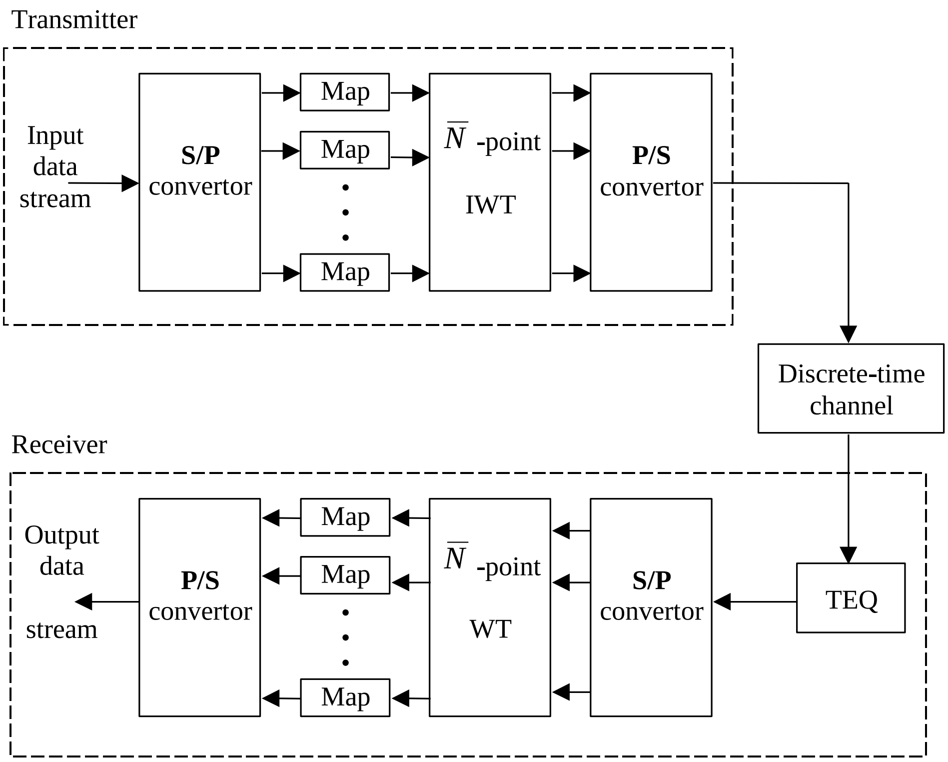


Figure (5) Block Diagram of the DWMT System

5. Simulation Results

System parameters were chosen to agree with the standard DMT based ADSL modem (ANSI T1.413 or ITU G992.1) [23,24], with simplifications. The system is simulated with additive white Gaussian noise and FEXT or/and NEXT effects, which are common in an ADSL environment. DMT and DWMT simulation parameters are shown in **Table (2)**.

The system common parameters are:

- A 24-AWG TP channel of length 360 m with a relative maximum usable frequency of 1.1 MHz is assumed.
- Tone spacing 4 kHz which is equal to the symbol rate.
- Average number of bits $\bar{b}$ =6 or $\bar{b}$ =8 corresponding to 64-level or 256-level QAM signal constellations respectively.
- Number of tones is 256 and the actual occupied bandwidth is 1.024 MHz.
- Total transmission rate is 6.144 Mbps for $\bar{b}$ =6.
- No pilot carriers are used since no synchronization problem is considered (i.e. all systems are tested with perfect synchronization).
- Equalizer: Linear Time domain EQualizer TEQ (using feedback transversal filter) or nonlinear Frequency domain EQualizer (FEQ).
- For DWMT, the length of the scaling and wavelet filters is taken to be twenty-six (D26), since it has desired spectral properties, such as lower spectral overlap.
- Chow's loading procedure [25] was simulated to mitigate the effect of the channel distortion.

To combat the physical channel distortions, D26 was used as the wavelet basis functions. Also the loading algorithm was applied to match the spectra of the multitone signal according to channel frequency characteristics. The bit assignment by the loading algorithm and the channel capacity for the TP channel is shown in **Fig.(6)**.

Table (2) Simulation Parameters of DMT and DWMT

DMT	DWMT
FFT size: 512	**WT** size: 256
FFT time is 256 μs	**WT** time is 128 μs
Symbol duration 256μs (When no cyclic prefix used)	Symbol duration 128μs (When no cyclic prefix used)
Symbol rate 3.906 k symbol/s (When no cyclic prefix used)	Symbol rate 7.8125 k symbol/s (When no cyclic prefix used)

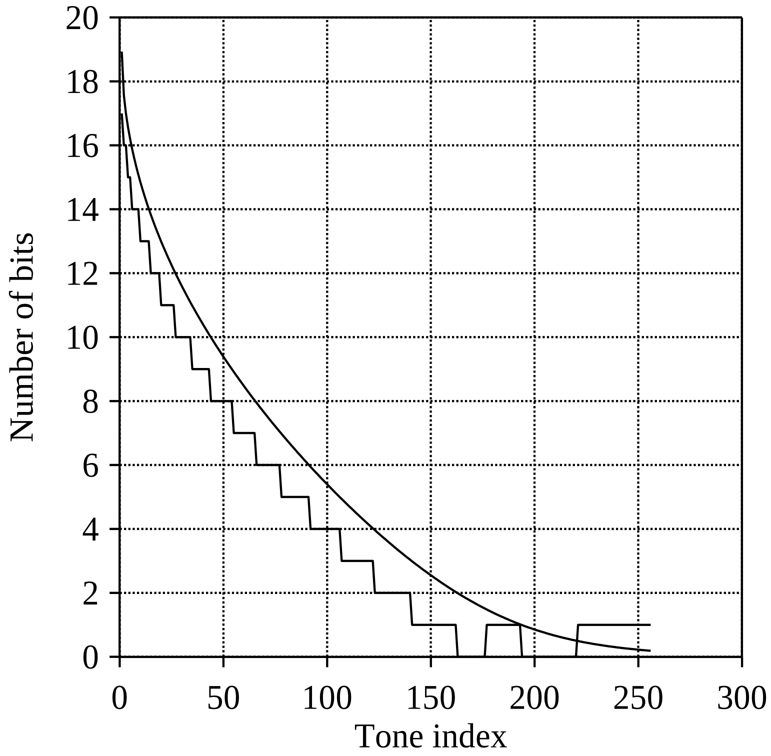
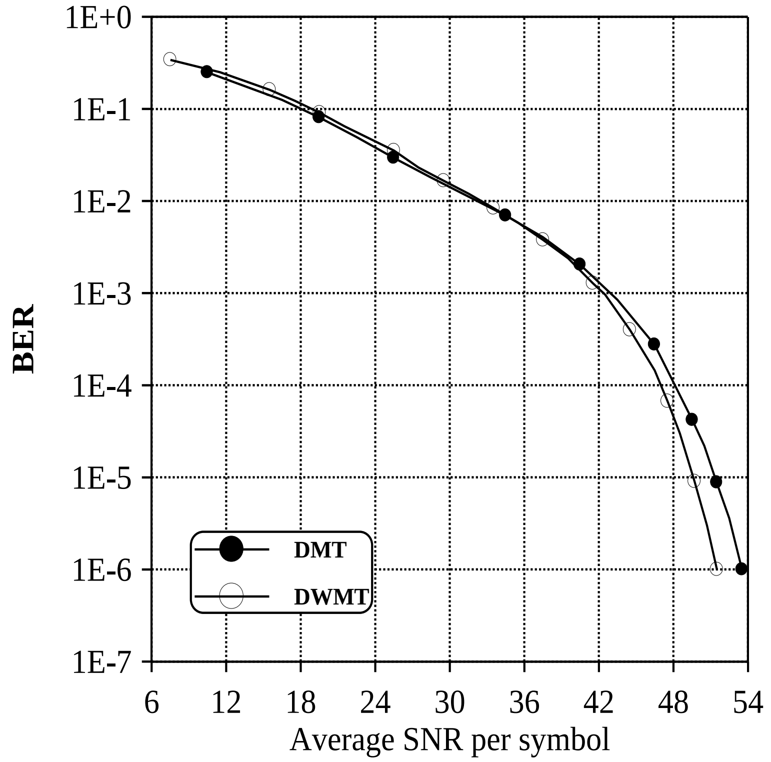


Figure (6) The Bit Loading Assignment and the Capacity of a 24 Gauge TP Channel

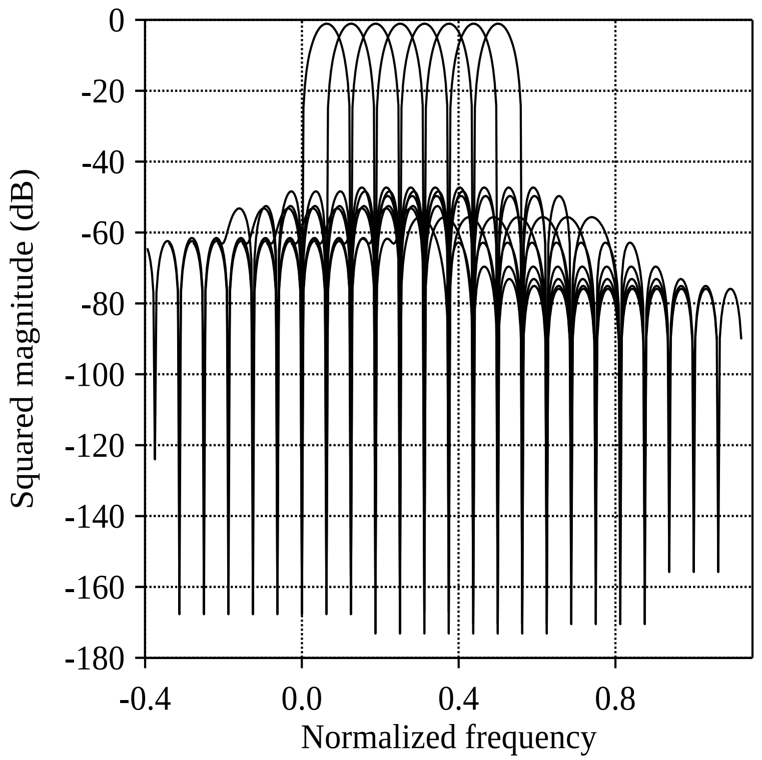
5-1 Twisted-Pair Channel

The performance of the DMT and DWMT subjected to TP channel is shown in **Fig.(7)**. As shown in the figure, the potential advantages of DWMT over the DMT being at low BER. At 10^{-4} BER, the difference in SNR is 1.5 dB advantage gained by DWMT and this value increases as the BER decreases. Practically speaking, 1.5 dB saving power for given requirements, is very attractive. This is due to the improved frequency characteristics of the DWMT signal. More specifically;

- The Daubechies basis has better frequency localization than the Fourier basis. This effectively reduces the Inter-Channel Interference (ICI).
- The D26 basis has lower stop-band attenuation approximately 47 dB as shown in **Fig.(7b)** for eight tones only. While for the rectangular Fourier basis is only 13 dB. This has the effect of reducing the crosstalk between the subchannels. Also, the out-of-band attenuation is significantly increased to mitigate the Inter-Block Interference (IBI).



(a) Performance of the DMT and DWMT



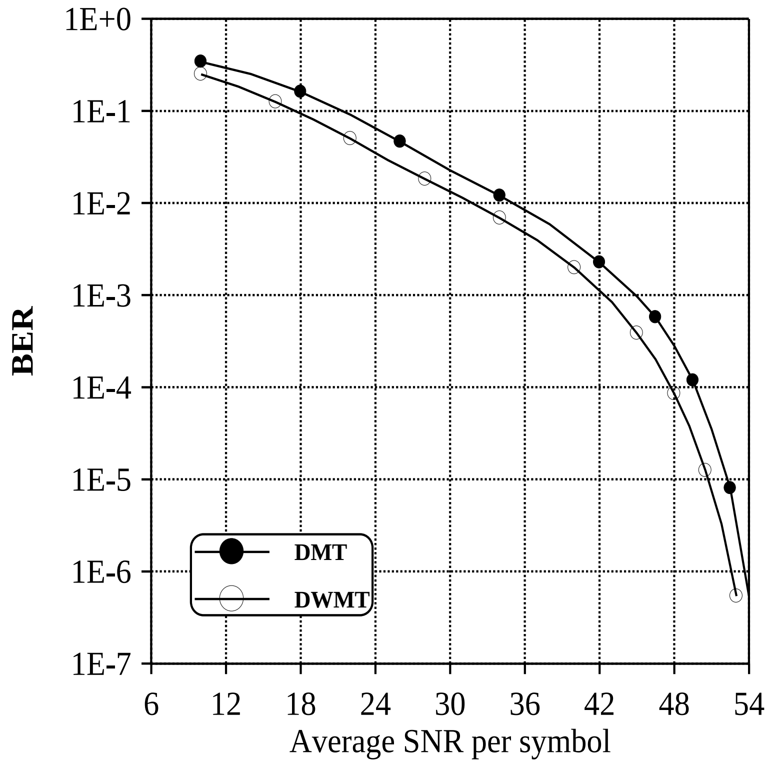
(b) The transmitted DWMT signal

Figure (7) The Multitone System Over the TP Channel

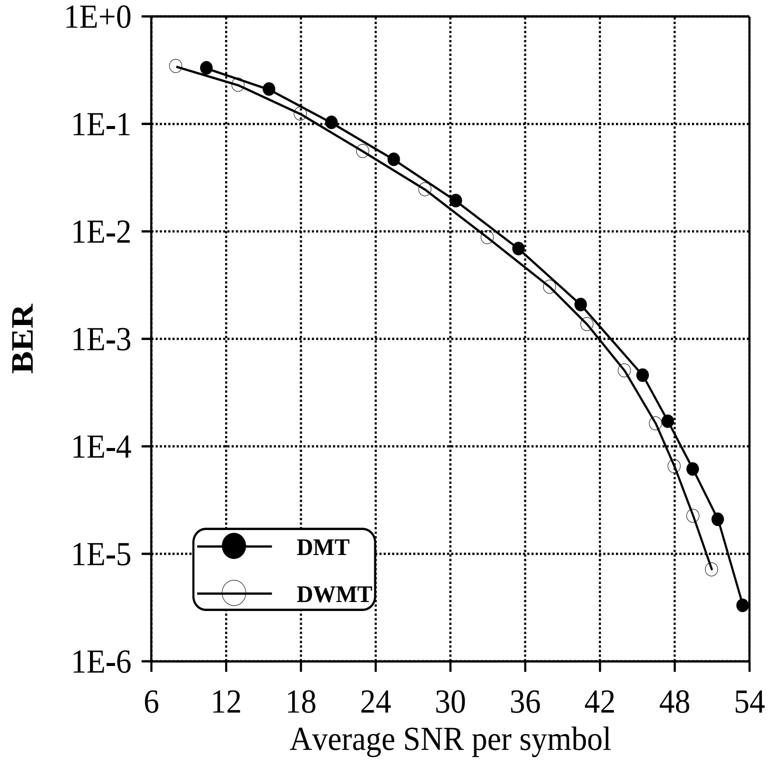
5-2 Twisted-Pair Channel Perturbed by External Crosstalk

Since ADSL modem transmits data in one direction that occupy a specified frequency band, the dominant noise is the FEXT [13]. The performances of the DMT and DWMT are shown in **Fig.(8a)**. The SNR advantage of DWMT is 2.1 dB. This states that even an external crosstalk disturbs the transmitted multitone signal that occupies the same frequency band, the DWMT signal still more robust than the DMT signal.

The system performance subjected to NEXT effect is shown in **Fig.(8b)**. The performance gain is 1.7 dB in SNR for DWMT over that of DMT. A summery of the above results is shown in **Table (3)**.



(a) Perturbed by FEXT



(b) Perturbed by NEXT

Figure (8) The Performance of the DMT and DWMT Perturbed by External Crosstalk

Table (3) The SNR (in dB) Required to Achieve 10^{-4} BER in TP Channel

	TP	FEXT	NEXT
DMT	48.1	49.8	48.7
DWMT	46.6	47.7	47

5-3 The Performance in a Pessimistic Condition

In this test both FEXT and NEXT effects perturbed the TP channel. The performance of the competitive modulation schemes DMT and DWMT and the single carrier system employing QAM (denoted by SC) were measured. These are shown in **Fig.(9)** and **Table (4)**.

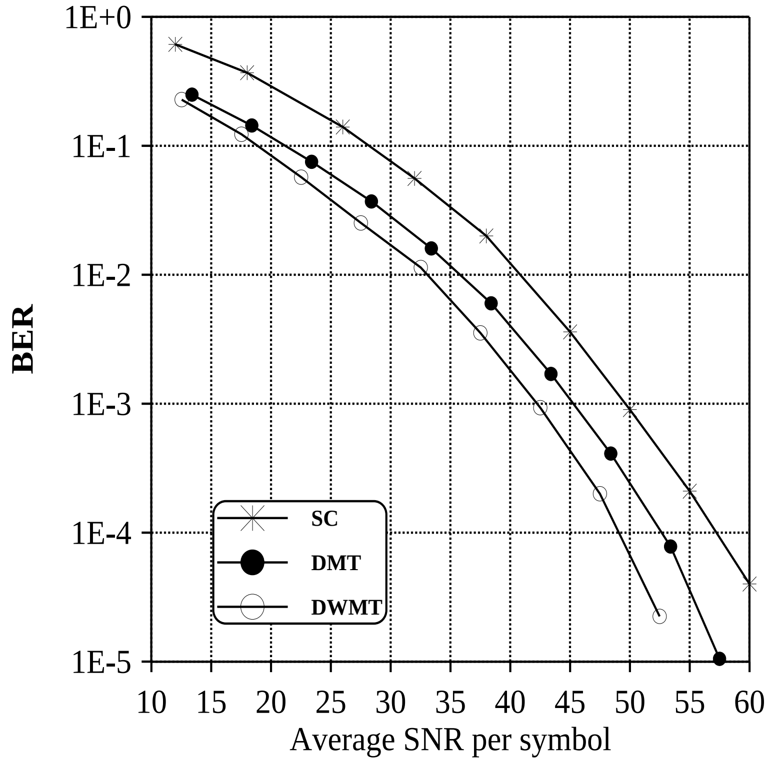


Figure (9) The Performance of the SC, DMT and DWMT under Pessimistic Condition

Table (4) The SNR (in dB) Required to Achieve 10^{-4} BER in the Pessimistic Condition

	SC	DMT	DWMT
BER	57.2	53.7	49

From **Table (4)**, it is obvious that MCM (i.e. both DMT and DWMT) outperforms the SC modulation over the TP channel that suffers from high spectral attenuation.

6. Conclusion

The DWMT modulation introduced here provide an alternative MCM scheme to DMT systems that use FFT as its basis functions. The presented simulation results show that a considerable SNR gain can be achieved by applying DWMT under different channel effects. When considering DSL environments the advantage gained in SNR by DWMT is about 5dB over the underlying DMT at low error rates (less than 10^{-4}). This is obtained with the same bandwidth efficiency (i.e. the ratio of the average bit rate to the occupied bandwidth).

The main advantages of DWMT can be summarized by:

a) It provides better channel isolation due to the more concentration of main lobe of the power spectral than DMT.

b) DWMT is less sensitive to channel environments such as NEXT and FEXT.

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Notations

ADSL	= Asymmetric Digital Subscriber Line
ANSI	= American National Standard Institute
ATM	= Asycronous Transfer Mode
ATU-C	= ADSL Terminal Unit-Central office
ATU-R	= ADSL Terminal Unit-Remote
AWG	= American Wire Gauge
DMT	= Discrete Multi-Tone
DSLAM	= Digital Subscriber Line Access Multiplexer
DWMT	= Discrete Wavelet Multi-Tone
FEQ	= Frequency domain EQualizer
FEXT	= Far End crossTalk
FTTx	= Fiber To The “x”
HDSL	= High-rate Digital Subscriber Line
HLT	= Hierarchical Lapped Transform
IDSL	= ISDN Digital Subscriber Line
IFFT	= Inverse Fast Fourier Transform
ISDN	= Integrated Service Digital Network
ITU	= International Telecommunications Union
IWT	= Inverse Wavelet Transform
MCM	= Multi-Carrier Modulation
NEXT	= Near End crossTalk
ONU	= Optical Network Unit
POTS	= Plain Old Telephone Service
QAM	= Quadrature Amplitude Modulation
SC	= Single Carrier
TEQ	= Time domain EQualizer
TP	= Twisted-Pair
VDSL	= Very-high-rate Digital Subscriber Line
WPM	= Wavelet Packet Modulation
WT	= Wavelet Transform
xDSL	= Any Digital Subscriber Line