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TRANSMISSION CAPABILITY OF DISCRETE MULTITONE MODULATION FOR TAIWAN'S SUBSCRIBER LOOPS

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SUMMARY

The transmission of 1.5 Mb/s and beyond data rate in the conventional twisted-pair local loops, called asymmetrical digital subscriber line (ADSL) technology, will be possible to create a new transport access capability to provide economic wideband voice/data/video integrated services directly to residential customers. The term 'asymmetric' in ADSL refers to the much higher data rate in the direction from central office (CO) to the customer and the lower rate of return (control) data from the customer to the CO. Discrete multitone (DMT) modulation has been selected as the modulation scheme in ADSL. Because the crosstalk of local loops in Taiwan is 10–15 dB worse than that in the US, the service capability of DMT ADSL for Taiwan's local loops may be different from that in other countries, and thus needs to be evaluated. On the basis of the characteristics of Taiwan's local loops, transmission capability is estimated to be 1.544 Mb/s and 6 Mb/s in Taiwan. Simulation results also show what percentage of users in Taiwan may have 1.544 Mb/s or 6 Mb/s of ADSL services. Far-end crosstalk (FEXT) and additive white Gaussian noise (AWGN) are considered to be the dominant noise sources in the work.

KEY WORDS: residential communications; asymmetrical digital subscriber line (ADSL); discrete multitone (DMT); transmission capacity

1. INTRODUCTION

Visual communications and video services over existing public switching telephone networks (PSTN) have become possible with the advent of the fast development of digital signal processing (DSP), very large scale integrated (VLSI) circuits, and new digital subscriber line (DSL) technologies.[1] The recently proposed asymmetric digital subscriber lines (ADSL) technology may provide data service of 1.544 Mb/s and beyond via the existing twisted-pair telephone lines, unidirectional, from the central-office (CO) to the customer premises with the intended application of compressed video distribution. ADSL is distinguished from the related high-speed digital subscriber line (HDSL) services because HDSL transmits the same data rate bi-directionally. HDSL is intended for conventional T1 or DS1 data services for constrained loops in the set known as the carrier serving area (CSA). Whereas ADSL is a consumer service with the intended application being the transmission of compressed VCR-quality video, and with an intended distribution over almost all the loop plant, ADSL is also superimposed on the same single twisted pair that delivers the plain old telephone service (POTS) or basic-rate ISDN service.[2]

Initially, three modulation schemes, the discrete multitone (DMT), the quadrature amplitude modulation (QAM), and the carrierless AM/PM (CAP), are presented as candidates for ADSL. QAM is an efficient modulation scheme, which enables two double-sideband amplitude modulation (DSB-AM) signals that occupy the same frequency band to be able to separate at the receiver because their carriers are orthogonal to each other. The CAP scheme avoids the carrier modulation and demodulation required in QAM. Therefore, the task of carrier offset recovery may be neglected in CAP. Both the QAM and the CAP schemes require a complex equalizer for achieving error-free transmission over severely distorted channels. DMT can be regarded as a hardware implementation of multicarrier modulation (MCM), which has been confirmed as one of the optimum modulation techniques for severely distorted channels for many years.[3] Since the 1980s, the digital implementation of MCM using the discrete Fourier transform (DFT) or fast Fourier transform (FFT) techniques has been developed, and is known as the DMT modulation.[4–7] Since 1995, DMT modulation has been selected as a standard modulation scheme for ADSL in the US.[8]

From 1986 to 1988, a loop survey was performed in Taiwan by the Directorate General of Telecommunications (DGT), Taiwan, ROC. Various kinds of physical compositions and transmission characteristics were investigated and measured. It was found that if 100-pair unit star quad cable is used, the

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crosstalk power of local loops in Taiwan is approximately 10–15 dB worse than that in the US.[9,10] The average working length of local loops in Taiwan is 4.2 km (with 0.4 mm wire gauge). The insertion loss of 4.2 km 0.4 mm wire gauge cable in Taiwan is equivalent to about 18 kft 24 American wire gauge (AWG) cable in the US. The loop characteristics of Taiwan's local loops are covered in detail in References 9 and 10. Because the transmission characteristics of local loops in Taiwan are worse than that in the US, it is necessary to re-estimate the service capability of DMT ADSL in Taiwan. According to the measured data, a simulation program used to represent Taiwan's loop characteristics has been developed.[11] The program may be used to simulate the crosstalk and channel response of Taiwan's subscriber lines. On the basis of the simulation program, the ADSL service distance in Taiwan may be estimated by simulation. In this study, the possible service rate for Taiwan's subscriber loops using the DMT modulation technique is evaluated. The ADSL service distance is also estimated in terms of the transmission capacity of the DMT modulation system. The rest of this paper is organized as follows: the characteristics of Taiwan's loop plant are summarized in Section 2; in Section 3, the transmission capacity of the DMT modulation system for ADSL is derived; the achievable data rate for Taiwan's subscriber lines is simulated and analysed in Section 4; according to the simulation results, the percentage of users in Taiwan who may have ADSL1 (1.544 Mb/s) or ADSL3 (6 Mb/s) services can be estimated.

2. CHARACTERISTICS OF TAIWAN'S LOCAL LOOPS

By far the most common transmission medium for both voice and data communications in Taiwan is twisted-pair copper wires. It is the backbone of the telephone system as well as the workhorse for intra-building communication. In the telephone system, individual telephone sets are connected to the CO by a twisted-pair. It is referred to here as a *subscriber line*. A subscriber line consists of two insulated copper wires arranged in a regular spiral pattern. A wire pair acts as a single duplex communication link. A number of these pairs are typically bundled together into a cable by wrapping them in a tough protective sheath; the polyethylene-insulated cable (PIC), the paper-insulated cable (PULP), and the new foam-skin (FS) PIC cable are the most common examples. The cable may contain hundreds of pairs over longer distances. The twisting of individual pairs minimizes electromagnetic interference between them. In Taiwan both the PULP and the FS PIC cable have three different wire gauges, 0.4, 0.5 and 0.65 mm, which correspond to 26, 24 and 22 AWG, respectively. The following are possible loop conditions to develop digital subscriber lines in Taiwan, on the basis of the loop survey in 1988.[9,12]

1. Non-loaded cable only;
2. 0.4 mm (26-gauge) cable shorter than 4.2 km (including bridged taps);
3. 0.9 mm, 0.65 mm, 0.5 mm (19-, 22-, 24-gauge) cable shorter than 5.7 km;
4. Total length of bridged tap shorter than 1.5 km, single bridged taps shorter than 1 km, no condition for the number of bridged taps;
5. Length of multi-gauge cable (including 0.4 mm), length shorter than 5.7-[(3 × L26)/8.4–LBTAP] km in which L26 = total length of 0.4 mm cable, LBTAP = total length of bridged taps.

Fifteen test loops presenting the worst characteristics of Taiwan's local loops have been proposed.[9] These test loops are re-drawn in the Appendix. Crosstalk and white noise are the major sources of noise in local loops. Crosstalk can be classified as near-end crosstalk (NEXT) and far-end crosstalk (FEXT).[13] The power of the NEXT from one ADSL service pair to another becomes substantially less than that of the FEXT because the much greater transmission rate of ADSL is in one direction. This feature enhances the data transport capacity of twisted pairs. However, a significant amount of spill-over NEXT from bi-directional baseband services can be attained in the same wire bundle as a result of non-ideal filtering.[14] It was found that if 100-pair unit star quad cable is used, the crosstalk power of local loops in Taiwan is about 10–15 dB worse than that in the US.[10] The power spectral density (PSD) of self-NEXT can be modelled as

$$P_{\mathrm{NEXT}}(f) = P_s(f)K_{\mathrm{NEXT}}f^{3/2} \tag{1}$$

in which $P_s(f)$ is the PSD of the transmitted signal for neighbouring lines, f is frequency in Hz and K_{NEXT} is determined through empirical measurement. For Taiwan's existing local loops, K_{NEXT} is about 8.8×10^{-13} corresponding to the scenario of a 99-crosstalker. The PSD of self-FEXT can be modelled as

$$P_{\mathrm{FEXT}}(f) = P_s(f)|H(f)|^2K_{\mathrm{FEXT}}f^2 \tag{2}$$

in which $|H(f)|^2$ is the amplitude spectrum of the subscriber line and $K_{\mathrm{FEXT}} = 1.0 \times 10^{-15}$ is used for Taiwan's subscriber loops. The effect of varying the level of K_{FEXT} at one saturation power level is investigated in Section 4. In addition to crosstalk noise, an additive white Gaussian noise (AWGN) term is included in this work, which is fixed at −140 dBm/Hz. As a result, self-FEXT and AWGN are assumed here to be the dominant sources in Taiwan's ADSL environment.

3. TRANSMISSION CAPACITY OF DMT MODULATION FOR ADSL

The concept of MCM entails dividing the transmitted data into several interleaved bit or symbol-streams. Next, each stream is modulated onto a corresponding carrier. Each bit stream may be encoded to become a two-dimensional QAM signal with or without half symbol time offset, where each carrier is referred to as a subchannel. Furthermore, all the subchannels will form the wide-band transmitted spectrum, as shown in Figure 1. Analogue implementation of MCM is impractical because of a large number of subchannels. The partitioning into parallel subchannels can be achieved by using DFT.[6] When the space of each carrier is equal, the modulation process may be implemented by using an inverse fast Fourier transform (IFFT) as a modulator and a FFT as a demodulator.[6,15,16] For efficient use of the available spectrum, the orthogonality relationship may be used to eliminate the inter-channel interference between adjacent channels.[3,16] If both the in-phase and quadrature channels of a subchannel is delayed half-symbol time with its adjacent channels, then the subchannel will be orthogonal to its adjacent channels. All the QAM signals thus obtained are staggered QAM signals. It is referred to as orthogonally multiplexed staggered QAM (O-QAM). O-QAM may also be implemented digitally by using the DFT.[17] To reduce the circuit complexity, DMT modulation does not employ the subchannel orthogonality used in O-QAM. Instead, DMT introduces a time window function in order to reduce the interchannel interference.[6,7,17] This is called the *cyclic extension*. A general structure of the DMT modulation system is illustrated in Figure 2. The input bit stream at a rate of R bits/s is buffered into a block of $B_{\mathrm{DMT}} = RT_{\mathrm{DMT}}$ bits, where T_{DMT} is the symbol period of DMT modulation. Bits of each block are distributed into N subchannels according to the bit allocation strategy, which follows an optimization criterion based on the achievable signal-to-noise ratio (SNR) level in each subchannel. Next, the blocks of partitioned bits in each subchannel are encoded into QAM signals. The data rate of each subchannel is determined by the performance of the subchannel. Suppose the input data rate R is partitioned into N sets with a rate R_i, $i = 1, 2, \ldots, n$, in the ith subchannel; consequently, the transmission capacity of DMT, R, can be determined if the transmission capacity of each subchannel is known, that is

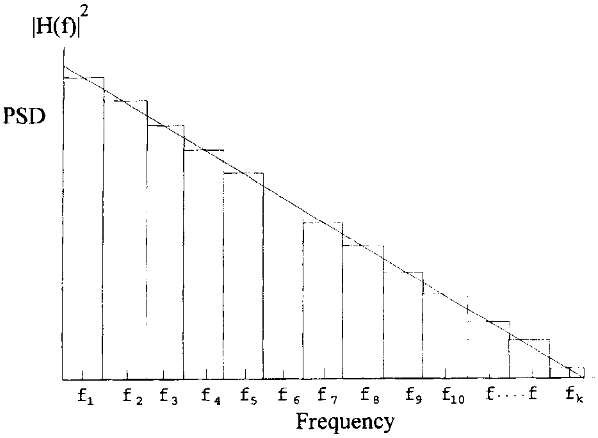


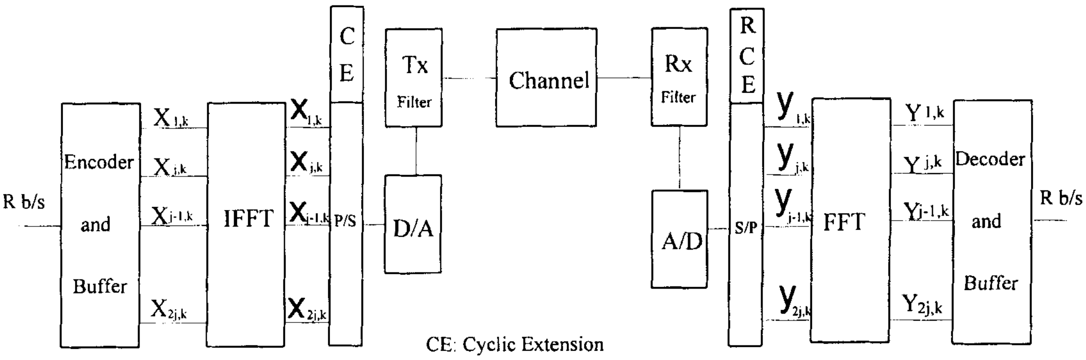
Figure 2. Channel spectrum decomposition to sub-spectral

$$C_{\mathrm{ADSL}} = R = \sum_{i=1}^{N} R_i \tag{3}$$

Consider an arbitrary distortion channel $H(f)$, when N is sufficiently large. The channel amplitude transfer function can be approximated by

$$|H(f)|^2 = \sum_{k=1}^{N} |H_k|^2\, \Pi\left(\frac{f-kf_0}{1/T_{\mathrm{DMT}}}\right) \tag{4}$$

in which $|H_k|^2 = |H(kf_0)|^2$, termed as channel gain, are the sampled values of the channel spectrum at $f_0 = 1/T_{\mathrm{DMT}} = \Delta F$, where $1/T_{\mathrm{DMT}}$ is the Nyquist bandwidth of each subchannel, and $|H_k|$ remains nearly constant if N is sufficiently large, for example as shown in Figure 1. The rectangular function $\Pi(\bullet)$ is defined here as



CE: Cyclic Extension

RCE: Remove Cyclic Extension

Figure 1. DMT transceiver block diagram

$$\Pi\left(\frac{f}{f_0}\right)=\begin{cases}1, & |f|\leq\frac{f_0}{2}\\ 0, & \text{otherwise.}\end{cases} \tag{5}$$

Therefore, each subchannel can now be regarded as a distortionless channel,[18] even for a severe distortion wideband channel. The major noise source may not be essentially a white noise, e.g., FEXT, however, its power spectrum can also be partitioned and be presented as

$$P_{\text{FEXT}}(f)=\sum_{k=1}^{N}P_{\text{FEXT},k}\Pi\left(\frac{f-kf_0}{1/T_{\text{DMT}}}\right) \tag{6}$$

in which $P_{\text{FEXT},k}=P_{\text{FEXT}}(kf_0)$ are the sampled values of the crosstalk spectrum. As a result, the FEXT within each subchannel can now be viewed as a white noise. This feature is true for any kind of noise power distribution.

Single-carrier QAM analysis can be used as a basis for analysing DMT systems because DMT modulation is a multiplexed QAM. For a square QAM constellation, the distance between points in the constellation is denoted by d, and all points are assumed to be equally likely. The constellation is centred at the origin and has zero mean value. The energy of such a constellation is as shown in Reference 19

$$E=\frac{M-1}{6}d^2 \tag{7}$$

for a two-dimensional symbol, where $M = 2^b$ represents the number of points in the constellation, and b is the number of bits that can be carried by a QAM symbol. Suppose the QAM signal is expressed as follows

$$m(t)=m_I(t)\cos\omega_c t+m_Q(t)\sin\omega_c t \tag{8}$$

where, the PAM signal $m_I(t) = m_I h_I(t-kT)$ modulated by $\cos\omega_c t$ is called in-phase channel (I-channel) whereas the other PAM signal $m_Q(t) = m_Q h_Q(t-kT)$ modulated by $\sin\omega_c t$ is called the quadrature channel (Q-channel). $h_I(t)$ and $h_Q(t)$ are shaping functions of I and Q-channels, respectively. The rectangular non-return-to-zero (NRZ) shaping function is one of the most employed shaping functions and is employed in DMT modulation. The NRZ shaping function is given as

$$h_I(t)=h_Q(t)=\begin{cases}1, & 0\leq t\leq T_{\text{DMT}}\\ 0, & \text{elsewhere}\end{cases} \tag{9}$$

Obviously, complex number m_I+jm_Q may be an arbitrary point of the QAM constellation. The average power of a QAM signal $m(t)$ can be easily calculated as

$$S=\overline{m(t)^2}=\frac{E}{2} \tag{10}$$

in which $\overline{(\bullet)}$ means taking the time average, and E is the average symbol energy as mentioned in equation (7). The probability of above two-dimension symbol error in QAM is closely approximated by

$$P_e=4Q\left(\frac{d_{\min}}{2\sigma}\right) \tag{11}$$

where σ^2 is the noise variance, and $d_{\min}$ is the minimum distance in the QAM constellation that is received at the output of the distortion or distortionless channel and is given by

$$d_{\min}^2=d^2|H|^2 \tag{12}$$

in which $|H|^2$ is the channel gain as mentioned earlier. The well-known Q function in equation (11) is defined by

$$Q(x)=\int_x^\infty\frac{1}{\sqrt{2\pi}}e^{-y^2/2}dy \tag{13}$$

The probability of bit error rate (BER) P_e should be 10^{-7} for ADSL applications. Obtaining such an uncoded bit error probability requires that[19]

$$\left(\frac{d_{\min}}{2\sigma}\right)^2\cong 14.5\text{ dB} \tag{14}$$

The number of bits within each subchannel can be found by rewriting equation (7) in the form

$$M=1+\frac{6E|H|^2}{d_{\min}^2} \tag{15}$$

Consequently, the number of bits that can be carried by a QAM signal at the required bit error rate (BER) is

$$b=\log_2(M)=\log_2\left(1+\frac{6E|H|^2}{d_{\min}^2}\right) \tag{16}$$

and is termed the *loading-bit* number. The channel's output SNR can be defined by

$$\text{SNR}=\frac{E|H|^2}{2\sigma^2} \tag{17}$$

From equations (16) and (17), the loading-bit number can be re-expressed as shown in Reference 7

$$b=\log_2\left(1+\frac{\text{SNR}}{\Gamma}\right) \tag{18}$$

by means of defining a convenient quantity Γ, called the normalized SNR as

$$3\Gamma = \frac{d_{\min}^2}{4\sigma^2} \tag{19}$$

The system performance can be guaranteed by using a design margin, DM, in a range of 6–12 dB in the system feasibility study. Thus, equations (14) and (19) yield

$$3\Gamma \cong (14.5 + \mathrm{DM})\ \mathrm{dB} \tag{20}$$

$$\Gamma = (9.8 + \mathrm{DM})\ \mathrm{dB} \tag{21}$$

Applying equations (10) and (15) to a large number of subchannels, the number of loading bits for the kth subchannel is then given by

$$\begin{aligned} b_k &= \log_2\left(1 + \frac{\mathrm{SNR}_k}{\Gamma}\right) \\ &= \log_2\left(1 + \frac{E_k|H_k|^2 10^{-(9.8+\mathrm{DM})/10}}{2\sigma_k^2}\right) \\ &= \log_2\left(1 + \frac{S_k|H_k|^2\ 10^{-(9.8+\mathrm{DM})/10}}{P_{n,k}}\right) \end{aligned} \tag{22}$$

in which SNR_k is the SNR of the kth subchannel. S_k and $P_{n,k} = \sigma_k^2$ are the transmitted power and the equivalent noise spectrum within the kth subchannel, respectively. Figure 3 shows the signal power density levels of NEXT, FEXT, AWGN and the channel amplitude $|H(f)|$ for 12 kft of 24 AWG and 26 AWG loops. The $P_{\mathrm{FEXT},k}$ is assumed here to be the power spectrum of FEXT in the kth subchannel, and N_{AWGN} is the AWGN power spectrum within the kth subchannel. Consequently, the transmission capacity of the kth subchannel for a Nyquist bandwidth of $1/T_{\mathrm{DMT}}$, as perturbed by FEXT and AWGN, is given by

$$R_k = \frac{1}{T_{\mathrm{DMT}}} \log_2\left(1 + \frac{S_k|H_k|^2\ 10^{-(9.8+\mathrm{DM})/10}}{P_{\mathrm{FEXT},k} + N_{\mathrm{AWGN}}}\right) \tag{23}$$

Therefore the transmission capacity of a DMT system with N subchannels under self-FEXT and AWGN is given by

$$C_{\mathrm{ADSL}} = \sum_{k=1}^{N} \frac{1}{T_{\mathrm{DMT}}} \log_2\left(1 + \frac{S_k|H_k|^2\ 10^{-(9.8+\mathrm{DM})/10}}{P_{\mathrm{FEXT},k} + N_{\mathrm{AWGN}}}\right) \tag{24}$$

in which $P_{\mathrm{FEXT},k}$ can be expressed in detail as

$$\begin{aligned} P_{\mathrm{FEXT},k} &= P_{\mathrm{FEXT}}(kf_0) \\ &= \frac{1}{T_{\mathrm{DMT}}} P_s(kf_0)|H(kf_0)|^2 K_{\mathrm{FEXT}}(kf_0)^2 \\ &= S_k|H(kf_0)|^2 K_{\mathrm{FEXT}}(kf_0)^2 \end{aligned} \tag{25}$$

4. ADSL SERVICES IN TAIWAN

An illustrative example of optimal bit allocation (i.e., loading-bit distribution) is shown in Figure 4 which could be achieved if the number of subchannels is sufficiently large (i.e., the Nyquist bandwidth of each subchannel is sufficiently small) and non-integer-bit mapping by the QAM encoder is possible. The transmission capacity can be obtained by inte-

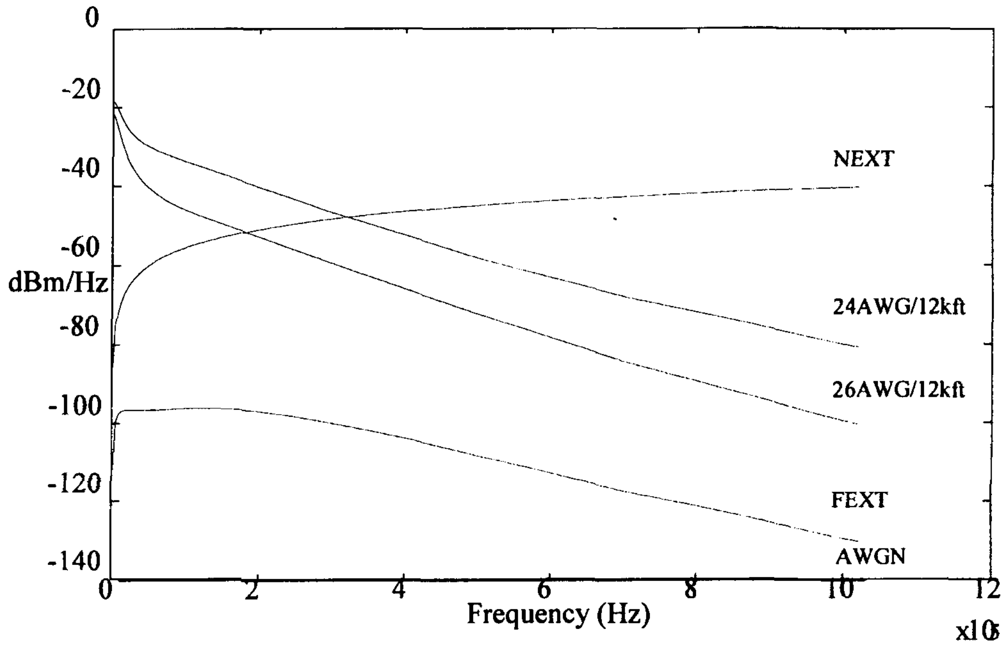


Figure 3. Signal power density levels

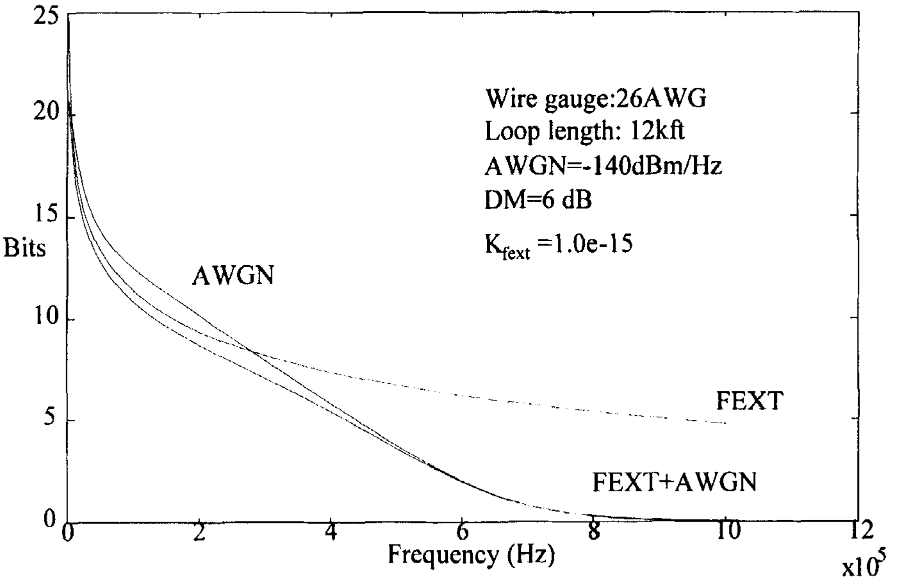


Figure 4. Bit spectral efficiency with 100 mW of transmit power

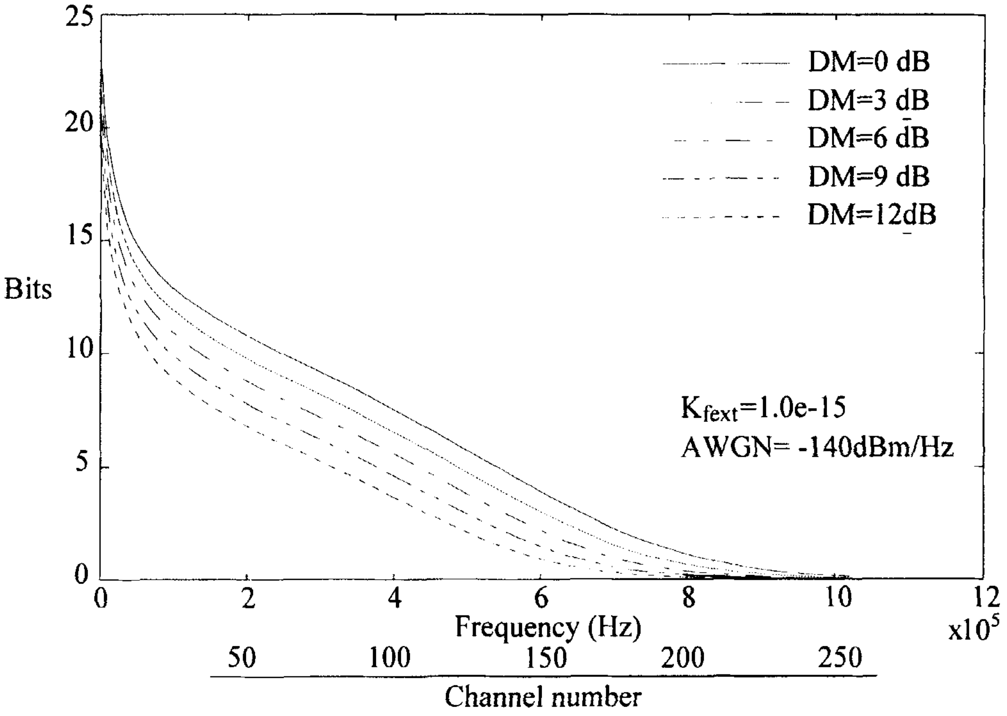


Figure 5. Bit efficiency for 26 AWG/12 Kft with 20 mW transmit power

grating the curve shown in Figure 4. For a reasonable value of N, say 256, and interger bit content of QAM signals, the loading bit number of each subchannel will be truncated to an integer number. In this case, the transmission capacity will be degraded slightly. As confirmed by simulation, the loss of transmission capacity is around 400 Kb/s for varied subscriber lines.[20] However, this degradation may be diminished if a variable transmitted PSD is allowed in the transmitter*.[20] Hence, the transmission capacity derived in equation (24) is used here in the analytical work. Simulation results in Figure 4 indicate that having one loading bit higher than 1 MHz for a longer loop is difficult. Therefore, if a fixed subchannel bandwidth $\Delta f = f_0 = 4$ kHz is assumed, a total of 256 subchannels is sufficiently large for ADSL applications.

Figure 5 shows the number of loading bits within each subchannel for various design margins. The transmission power used here is 20 dBm.[21] There is approximately a one bit difference in the same subchannel for each 3 dB design margin gap, that is, approximately $N \times \Delta f \times 1 = 256 \times 4000 \cong 1$ Mb/s loss for each step of 3 dB design margin. This

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* As confirmed by simulation, the variation is only within the 4 dBm range.[20]

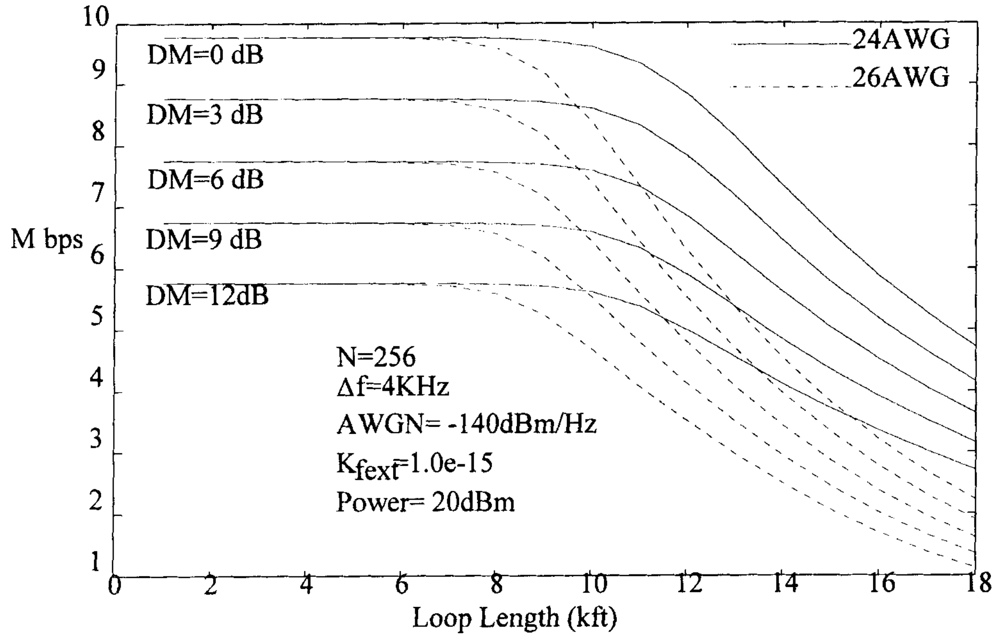

Figure 6. Transmission capacity as a function of loop length

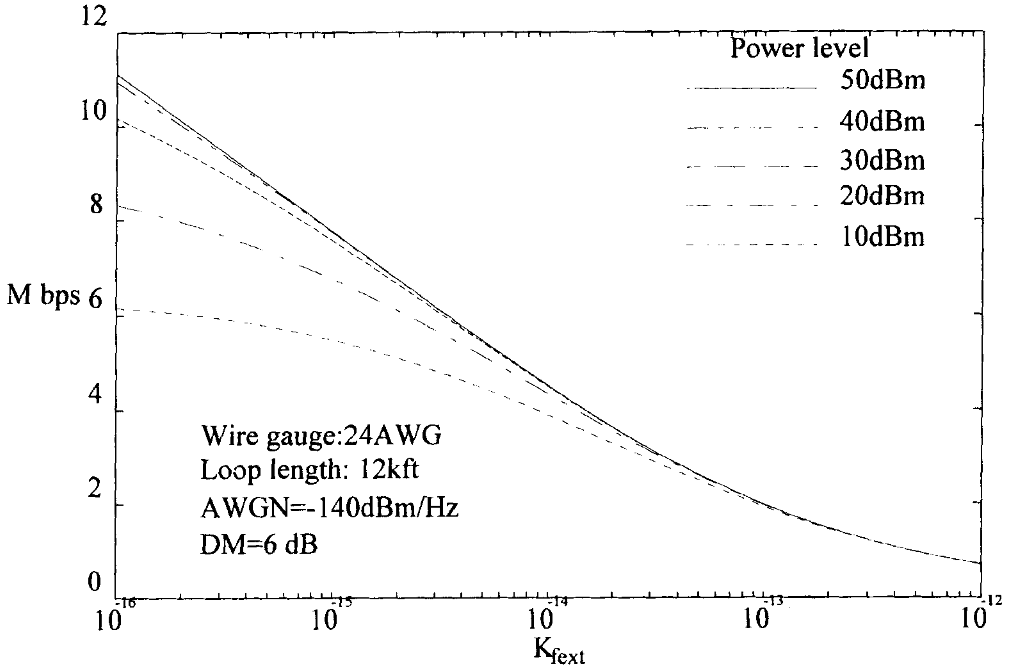

Figure 7. Transmission capacity as a function of K_{FEXT}

phenomenon is also shown in Figure 6. Figure 6 also sketches the transmission capacity for different wire gauges and loop lengths. The service distance for 6 Mb/s service rate (ADSL3) is found to be about 10 kft for 0.5 mm wire gauge at 20 dBm transmission power. This result implies that roughly 85 per cent of users in a metropolitan area and 65 per cent in other areas can have ADSL3 services*.[9] This figure reveals that the transmission capacity varies slightly when the loop length is less than 8 kft. This is because, as seen in equation (24), if the loop length is less than 8 kft, then the channel loss factor $|H_k|$ varies slowly within the 1 MHz range, and FEXT thus becomes the dominant noise source. In this case the transmission capacity C_{ADSL} depends primarily on the design margin factor DM. As the DM remains fixed, C_{ADSL} will approach the value of $1/T_{\mathrm{DMT}} \log_2 (10^{-9.8+\mathrm{DM})/10}/K_{\mathrm{FEXT}}(kf_0)^2)$. Conversely, when the loop length exceeds 10 kft, the transmission capacity C_{ADSL} decreases because of the effects of channel loss, $|H_k|$ and AWGN.

The transmission capacity is illustrated in Figure 7 as a function of K_{FEXT} for 24-gauge wire (of

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* Please refer to Figure 1 of Reference 10.

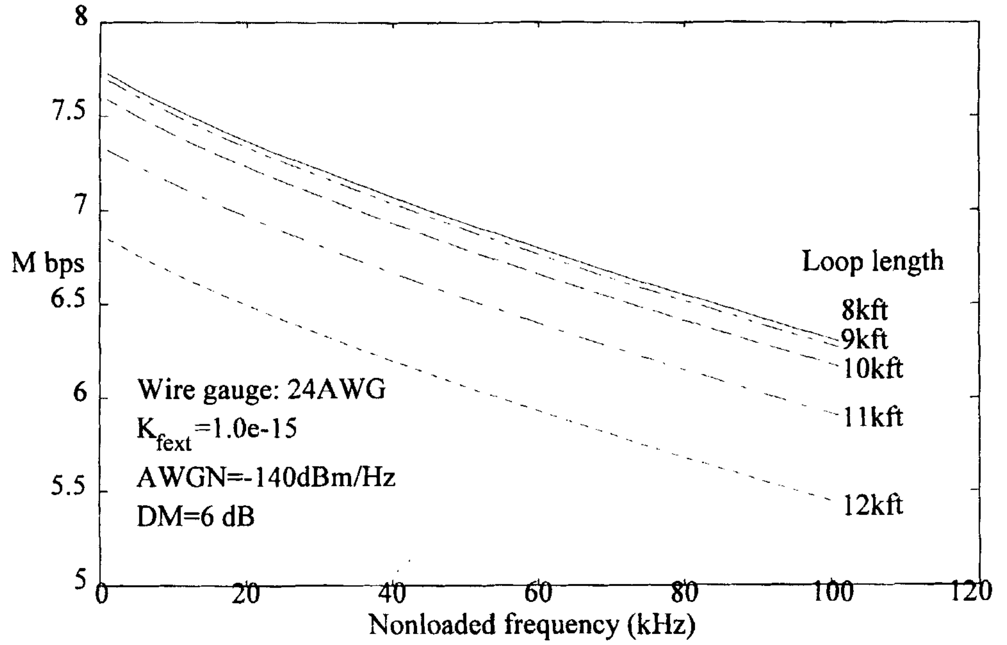

Figure 8. Transmission capacity as a function of non-loaded frequency

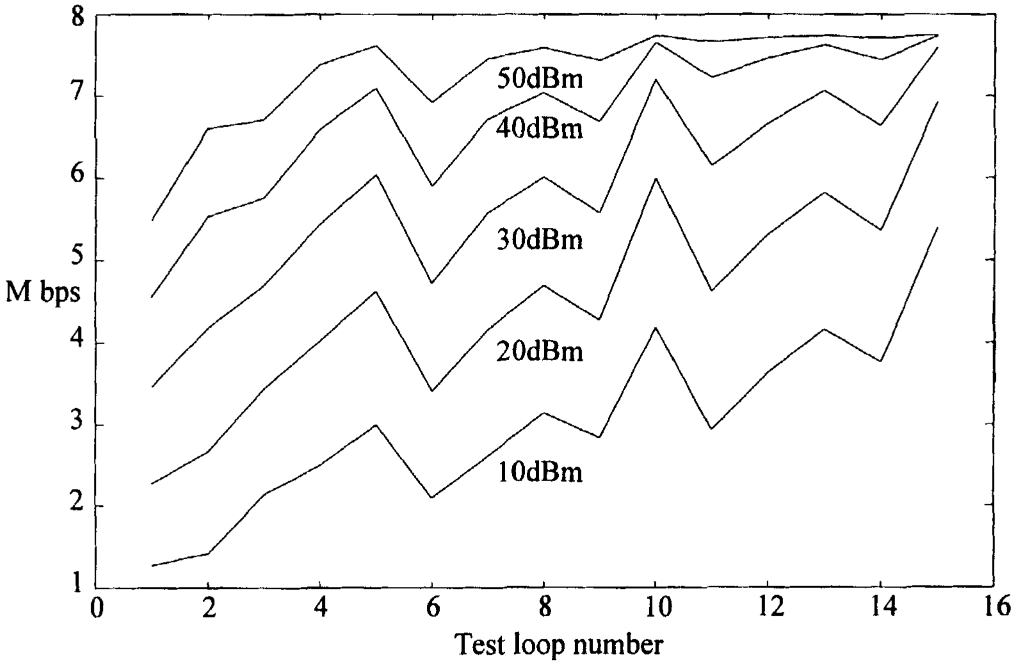

Figure 9. Transmission capacity of Taiwan's test loops nos. 1–15 for different power levels

diameter 0.5 mm) at various power levels. When the power level of the transmitted signal is increased to 50 dBm, the transmission capacity will be saturated. As S_k is increased sufficiently, the transmission capacity depends only on a fixed value $1/T_{\mathrm{DMT}} \log_2 (10^{-(9.8+\mathrm{DM})/10}/K_{\mathrm{FEXT}}(kf_0)^2)$ in each subchannel. As a result, the transmission capacity C_{ADSL} converges to a saturation level and no longer increases without placing a limit on increasing S_k. Besides this, the crosstalk coupling for the different types of cable used in Taiwan is slightly different. For example, the crosstalk of PULP cable is about 5 dB worse than that of old FS PIC cable. The loss of transmission capacity for each of the different types of cable can also be estimated by using Figure 7.

Two possible transmission methods are available for upstream and downstream data co-existing on the same subscriber line, i.e., the frequency-division multiplex (FDM) method and the echo canceller method (ECM). In the latter case, upstream and downstream spectra are allowed to have some spectrum overlap with each other during two-way transmission; in addition, these spectra can be separated

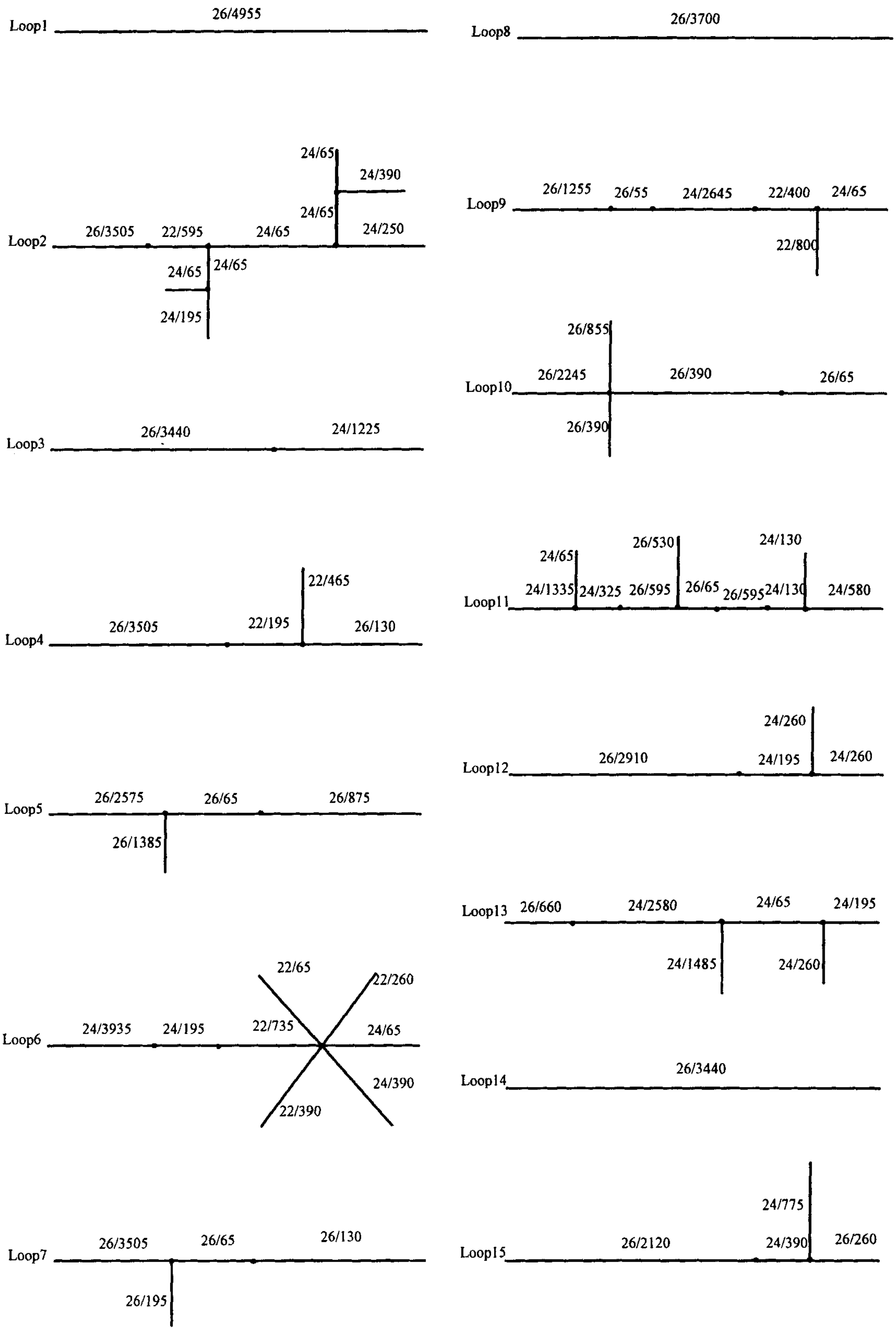

Figure 10. Loops under study in Taiwan (wire gauge/length in meters)

by a hybrid circuit combined with an echo canceller. In the FDM method the upstream and downstream spectra are separated into two parts within the transmission spectrum. The spectral allocations of these existing public switching network spectra and ADSL-upstream and -downstream spectra need to be defined. Because the bandwidth of POTS and upstream data is markedly less than that of downstream data, the low frequency part is vacated for a small data rate spectrum for implementation simplicity. To observe how much bit rate loss occurs in the FDM method, a non-loaded cut-off frequency is defined here for downstream data transmission in which no loading bit is assigned below that frequency. Figure 8 shows the relationship between the transmission capacity and the non-loaded cut-off frequency at various loop lengths. Accordingly, the transmission capacity of about 0.25 Mb/s is lost for each 10 kHz increase of no-bit-loaded frequency. This result can be used as a reference for the design of the spectral allocation of an ADSL transmission. From this simulation, it should be noted that although the FDM transmission method may avoid the use of an echo canceller, the FDM method for ADSL services produces a transmission capacity loss of about 1 Mb/s.

The transmission capacity of discrete multitone modulation for Taiwan's 15 test loops nos. 1–15 is also evaluated. The design margin is set to be 6 dB in this simulation, and transmitted power is varied from 10 dBm to 50 dBm. Figure 9 shows the simulation results. From the results at 20 dBm transmission power, most loops in Taiwan may be used to support the ADSL1 (1.544 Mb/s) services. Because the 15 test loops represent worst 15 per cent of cases of loop plant in Taiwan, the insertion losses of these test loops are all larger than those of a typical 12 kft loop (CSA in the US). Therefore, the 15 test loops cannot satisfy the requirement of the ADSL3 bit rate. However, the service distance and service area of ADSL3 services in Taiwan have been estimated according to the previous simulation result of Figure 6.

5. CONCLUSIONS

An evaluation has been undertaken of the performance of the DMT modulation system for ADSL services on channels of Taiwan's subscriber lines. A direct coupling FEXT loss of $K_{\mathrm{FEXT}} = 1.0 \times 10^{-15}$ is used in the work because the crosstalk power of old FS PIC cable in Taiwan is about 10 dB worse than that of PIC cable used in the US. As confirmed by the simulation, shown in Figure 7, the capacity loss resulting from the FEXT being 10 dB worse is about 1.5 Mb/s with 12 kft PIC cable. Besides, the crosstalk coupling loss for different types of cables is slightly different in Taiwan. Generally speaking, the crosstalk of PULP cable is about 5 dB worse than that of old FS PIC cable. In that case, the loss of transmission capacity will be greater. Simulation results indicated that the service distance for ADSL 3 6 Mb/s service is about 10 kft/24 AWG, which is about 85 per cent of users in a metropolitan area or 65 per cent of users in other areas. Furthermore, ADSL1 1.544 Mb/s data transmission could be achieved on most of Taiwan's loop plants. There is approximately one bit difference in the same subchannel for each 3 dB design margin gap. This implies that there is about 1 Mb/s capacity loss for each step of 3 dB design margin. An increased operational margin and decreased transmission power would be expected from using coding in the DMT transceiver. Simulation results further indicate that, although the FDM transmission method may avoid the use of an echo canceller, the FDM method for ADSL services produces a transmission capacity loss of about 1 Mb/s.

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APPENDIX A

The 15 test loops for representing Taiwan's loop environment

Figure 10 shows the 15 test loops that are used to present the worst 15 per cent of cases of Taiwan's loops. To obtain the characteristics of local loops in all of Taiwan, Telecommunication Labs. (TL) of the Directorate General of Telecommunications (DGT) first established a loop survey model in Chung-Li, a local city in Taiwan, in 1986. Then, the model was applied to the whole Taiwan area from 1986 to 1988 by DGT's three distinct operating organizations. About 2800 lines out of a total of 8,500,000 lines in all Taiwan areas were sampled and characterized. Various kinds of physical compositions and transmission characteristics were investigated and measured. A database with about 8 million records of source data from these 2805 lines was built. From these data statistics, it was found that if 100-pair unit star quad cable was used, the crosstalk power of local loops in Taiwan would be approximately 10–15 dB worse than that in the US.[8] Furthermore, according to the value of insertion loss, the 15 worst samples of the 2800 sample lines are obtained. Then, one test loop of each percentage of the worst 15 per cent of samples is selected. The number of BTs and physical composition are taken into consideration during the selection of test loops. Finally, 15 test loops were selected to present the worst 15 per cent of cases of Taiwan's local loops.[9]

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