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CDMA Systems for Wireline Communications

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1 Introduction

There is ever-increasing demand for intrabuilding communications systems as computer networks. Because they are virtually universal in building coverage and easily accessed via a standard wall plug, intrabuilding electric power distribution circuits are potentially useful as telecommunication networks. Using electric power distribution circuits obviates the need for specialized wiring, which can be costly to install, unattractive to view, and restrictive in the location of equipment served by the network. Coupling a modem to a power line requires a small transformer and two capacitors, typically with a total cost of less than $10 [1,7].

Power lines were not designed for communications and suffer from high and unpredictable variations in impedance, signal attenuation, and noise [1,2]. Considerable recent effort has been devoted to determining the communication characteristics of intrabuilding power line channels, including their inpairments [3,4] and bit error probability performance. The effects of using block codes for forward error correction have also received preliminary attention.

2 Power lines as communication channels

Electric power lines within a building carry power from the customer (secondary) side of a distribution transformer to electrical loads (see Fig. 1). A circuit panel protects loads for excessive currents or voltages. Split single-phase power is provided to single-family homes or apartment units, and three-phase power is provided to industrial buildings. In large buildings, several distribution transformers may be used, with each providing power to a specific part of the building. The neutral power wire is common to all electrical loads. Indirect connection of loads between phases is provided by capacitive coupling across the distribution transformer secondary or across loads such as electrical water heaters, which connect across phases (see Fig. 1).

Communication signals above a few kilohertz do not pass through distribution transformers [5]. A transformer isolates that portion of an intrabuilding power line network which it serves from network served by other transformers. Interconnection of these networks, for communication purposes, would be by a separate backbone cable or radio network. In large buildings, separate distribution transformers supply each floor or group of floors, thereby partitioning a building into several separate networks such as LAN’s (Local Area Network).

Because electrical loading changes over time, communication signal attenuation between any pair of network points also varies over time; such variations can exceed 20 dB (power) over a 24 h period [3]. Attenuation between any two points is frequency-dependent and tends to increase with frequency. The attenuation between different pairs of points is different at any given moment by up to 40 dB. Finally, attenuation can exhibit short-time periodic variations at 120 Hz or even at 6 Hz.

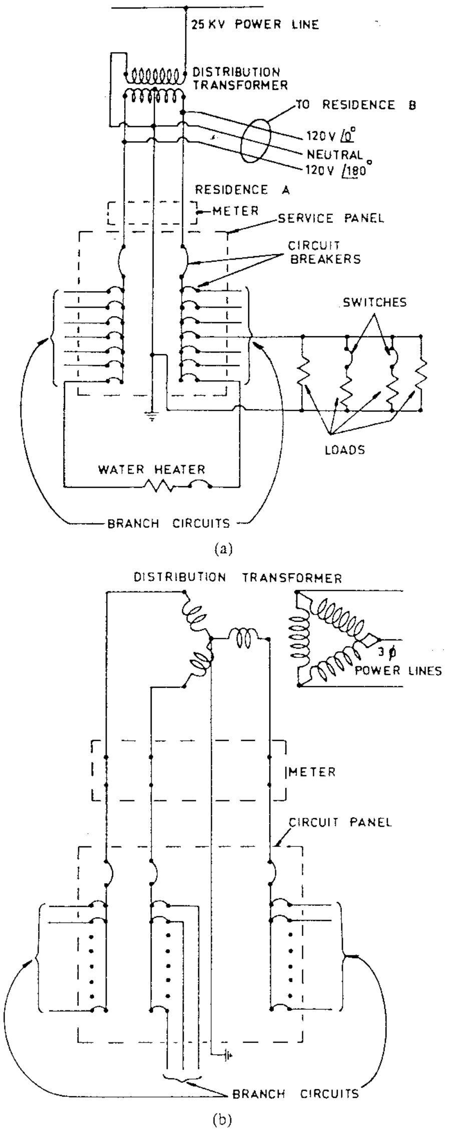

Fig. 1. Intrabuilding power line networks. (a) single-family home
(b) industrial building (Ref. [7]).

Power line noise includes both background and impulse components and is caused primarily by electrical loads [2]. Background and impulse noise levels vary over time and with point of observation. Noise power levels tend to decrease as the frequency increases at approximately 30 dB/decade [4]. This decrease in noise level occurs because noise as well as wanted signals suffer increased attenuation with frequency. The noise sources nearest to a receiver contribute most of the noise and are the primary cause of bit errors.

Fig. 2 shows a simple model of a power line communication channel. The filter frequency response H(f, t) varies over time as electrical loads change; t and f denote time and frequency, respectively. The fading, given by A(t), is often periodic at 120 kHz, but may include other periodic components (at 6 Hz, for example) and may also attenuate the noise. The fading level of the noise relative to that of the signal is determined by the factor B. The complexity as well as the unavailability of wiring schematics and lack of information regarding loads makes actual calculation of H(f, t), A(t) and B virtually impossible, even in single-family homes.

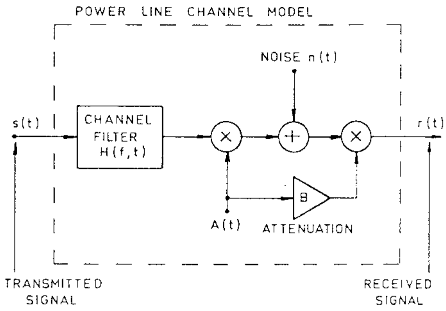

Fig. 2. Model for power line communications channel (Ref. [7]).

Similar results have been obtained at other direct sequence spread spectrum (SSMA) data rates and carrier frequencies and by a conventional FSK modem operating at 115 kHz carrier frequency at rates up to 19.2 kbit/s. SSMA is useful at data rates below 4.8 kbit/s to combat narrowband signal fades or peaks in the noise spectral density, to allow data rate versus error rate tradeoffs without changing the transmitted signal bandwidth, and to enable multiplexing [1]. Fast syncronization of SSMA codes is obtained by the use of 60 Hz zero crossings; however, harmful zero-crossing jitter and the associated BER increase with code rate, which would eventually increase with data rate [1]. At data rates above 4.8 kbits/s, the signal bandwidth of conventional PSK or FSK is normally high enough to overcome narrowband impairments.

In the Fig. 3 it is presented power line network node.

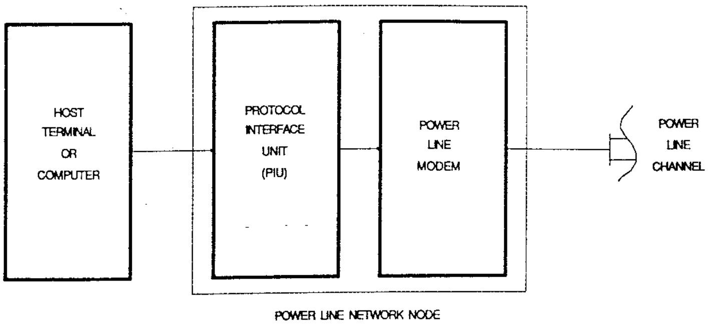

Fig. 3. Power line network node (Ref. [7]).

Higher data rates than 9.6 kbits/s are possible, depending on the bandwidth, noise, and interference. One possible fast data rate might be 1,5 Mbits/s in the future, but there are problems to solve. Advanced ADSL modem will be probably used.

ADSL (asymmetric digital subscriber line) provides 1.5 megabits per second access to networks. ADSL can take advantage of unused capacity by dividing a copper wire into hundreds of segments, each of which is large enough to carry one call channel. To provide this high-speed service, a pair of ADSL modems are connected to each end of a wireline or powerline. The ADSL modems convert a single twisted-pair line into three information channels: a high-speed (1.5 megabits per second), a medium-speed (64 kilobits per second) upstream channel and a standard (voice frequency) call channel [11].

It is known that the power line input impedance is typically 10 Ω, but varies with electrical loading, increases with frequency, and becomes increasingly inductive as the frequency increases.

The following realities bear on the choice of protocol for power line and wireline network.

1. Implementation costs for power line network should be low. The advantage of these networks is the availability of the communication lines at zero incremental cost. The inherent communication capabilities of power line links are available and limited, and high-cost modems, protocol hardware, and software are hard to justify.
2. In many applications, terminals would exhibit bursty and variable traffic profiles, which would change over time.
3. Frequent addition and removal of terminals would be common in many applications.
4. Because of the variability of communication signal attenuation and noise characteristics of the networks, all network stations may not be able to receive all other stations at all times. One solution to this problem is to install repeaters to facilitate communication between otherwise isolated stations.
5. To simplify modem hardware implementation, it is advantageous for data and acknowledgements to co-operatively share the same frequency spectrum.

One possibility to satisfy above demands is to use CDMA packet radio network protocols. It seems that the busy code broadcasting and sensing (BCBS) protocol is a suitable choice of MAC protocol for power line and wireline networks for many applications.

On power line networks, the wide variation in received signal and noise levels makes collision detection difficult and unreliable; it is easy for noise to be mistakenly regarded as the beginning of a transmission from another terminal.

On actual power line channels, errors tend to occur in bursts, unless special precautions are taken to randomize errors. Also, the bit error probability varies over a wide range, and the optimum packet length would have to be based on some appropriate weighting of the range of error probabilities encountered.

3 Busy code broadcasting and sensing protocol for CDMA network

It is developed recently a protocol for a collision-free CDMA packet radio networks. The name of the protocol is the busy code broadcasting and sensing (BCBS) protocol. The protocol lets each busy terminal broadcast the codes identifying either receivers or transmitters in a common CDMA channel, and an attempting transmitter can sense the target codes existing in the channel to avoid transmitting to the busy terminals which are only in successful communication pairs. Thus the collisions in the channel due to lack of information on busy terminals can be avoided. The analytical results show that the BCBS protocol can provide an evenly high throughput over a wide range of offered channel packet load and keep the network stable. In addition, the new protocol is easy to implement and is inherently suitable for different distributed CDMA packet networks. The sensing algorithm adopted in each terminal is rather simple and thus can be realised by a software which is integrated with the transmitter control program of each terminal. Thus no extra hardware is involved, which is particularly welcomed in reducing the terminal cost. A direct application of the proposed protocol is in various distributed communication networks, including both data and voice communications, such as the power line and wireline networks. As a matter of fact, the BCBS protocol is suitable also for other networks with different physical media, such as copper line networks, optical-fibre networks, packetised radio channel networks and so on, provided that they operate in the packet-switched CDMA fashion. Probably the most exciting potential application for the presented protocol will be the packet-switched personal communication networks (PCNs) which are expected to provide the ubiquitous services to users in the future mainly via radio channels, because the BCBS protocol can provide a higher packet transmission efficiency than any other CDMA spreading code protocol [8] .

4 Analytical model for BCBS

We wish to consider a distributed CDMA packet network, with N users, in which each user U_i (i = 1, ... , N) in the network is assigned two codes; one is the transmitter code t_i and the other is the receiver code r_i. It is assumed that U_i (as a transmitter) wants to send packets to U_j (as a receiver).

(i) At transmitter U_i side (transmitter algorithm)

When a transmitter U_i wants to send packets to a receiver U_j, U_i first senses both the transmitter code t_j and the receiver code r_j of U_j in the CDMA channel to see whether U_j is either transmitting or receiving. If neither t_j nor r_j is in use, then U_i can be sure that U_j must be in the idle state and it can initiate the transmission of the packets to U_j right away. Otherwise, after a random delay, U_i will sense the channel for t_j and r_j again until both t_j and r_j are free. The random delay introduced here can reduce the probability that two waiting transmitters will initiate packets to the same receiver as soon as that receiver quits a previous communication pair.

When it is confirmed that U_j is in the idle state, then U_i will use both the t_i code representing the transmitter U_i itself and the r_j code representing the receiver U_j to encode 'request packets' to U_j simultaneously. After sending 'request packets', U_i will continue to use the t_i code to despread the incoming signals to check whether the 'acknowledgment packets' from U_j appear in the channel or not. If no 'acknowledgment packets' from U_j have been received for a certain period of time, then U_i will go back to sense t_j and r_j again after a random delay and repeat the above algorithm. Otherwise, U_i can send 'data packets' to U_j by the use of the t_i code until the communication is over. The transmitter algorithm is shown in Fig. 4.

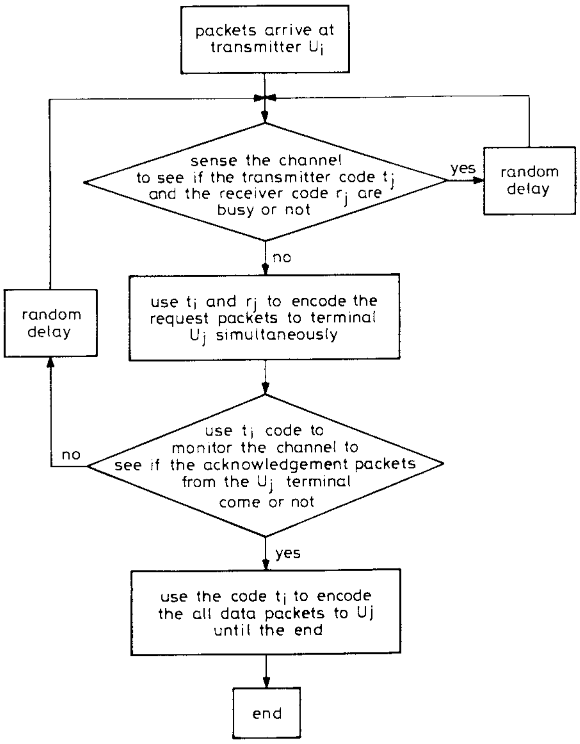

Fig. 4. Transmitter algorithm for BCBS protocol (Ref. [8]).

(ii) At receiver U_j side (receiver algorithm)

When U_j is in the idle state, it always uses the local r_j code to monitor the channel to see if the 'request packets' from any other terminals appear or not. If yes, U_j first processes the 'request packets' which contain the address of transmitter Ui sending the 'request packets' and then uses the t_i code to send the 'acknowledgment packets' Ui to confirm its ready status. Afterwards, U_j will use

t_i code to monitor the channel again until the 'data packets' from U_i is received. While receiving the 'data packets' from U_i, U_j will use the r_j code to broadcast its 'busy tone packets' simultaneously until the end of communication with U_i. The receiver algorithm is shown in Fig. 5.

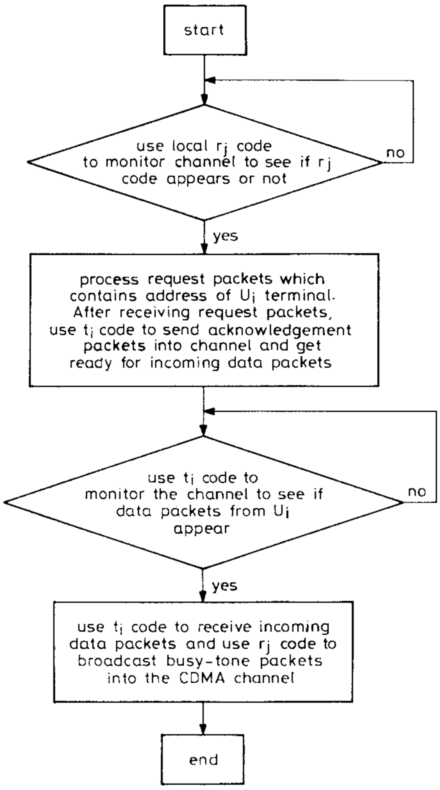

Fig. 5. Receiver algorithm for BCBS protocol (Ref. [8]).

In order to explain further the transmitter and receiver algorithms Fig. 6 is used to show the three stages of the pair-up of a successful communication pair between U_i and U_j. From the above description of the protocol, we can see that the handshaking scheme is employed in the protocol to ensure a successful communication pair-up.

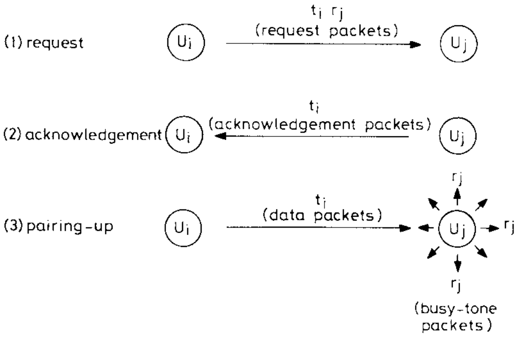

Fig. 6. Three stages of a successful pair-up (Ref. [8]).

Unlike the conventional spreading code protocols, the BCBS protocol gives clear knowledge of the status of all terminals in the network by their busy codes, so that blind packet initiations are avoided. Usually, the ‘request’ and ‘acknowledgment’ stages are very short compared with the time occupied for the ‘pairing-up’ stage, in which a successful communication pair always send out their busy information by themselves actively, i.e. it is not sent by others passively. Therefore the ‘hidden terminal problem’, which results from the busy information for a terminal being passively given by another terminal to whom other attempting terminals are out of line-of-sight, does not exist in the BCBS protocol.

4.1 Analytical model

In order to analyse the performance of a distributed CDMA packet network with the BCBS protocol, the following assumptions are made. A distributed CDMA packet network adopts the BCBS protocol as described above. The network consists of N independent users, each of which generates the packets with the same mean λ packets per unit time. The length of a ‘packet group’ (here the ‘packet group’ containing several successive packets actually means the time duration that a continuous transmission lasts) obeys an exponentially distributed random variable law with a mean of 1/u unit time/packets. The ratio $r = \lambda/u$ is referred to as the normalised offered channel packet load. The time required by both transmitters and receivers to sense the busy codes is negligibly short compared with the time required for the data packet transmission. The errors in packet receptions caused by random noise are not considered as a serious problem. Each user in the network at any given time will take one of the following three exclusive states:

(i) Quiet idle single state Q-I

The terminals are neither transmitting nor receiving and are not attempting to transmit or receive. There are qN terminals in this state at any given time. They are denoted by the name of ‘q-terminals’.

(ii) Waiting idle single state W-I

The terminals are quiet temporarily and waiting for the target terminals to quit previous communications. The number of W-I terminals is wN at any given time. They are denoted as ‘w-terminals’.

(iii) Successful pair state P

The terminals are in successful communications pairs. There are pN/2 such pairs of pN terminals at any given time. They are denoted as ‘p-terminals’.

Thus, the numbers of q, w and p represent the percentages of the terminals in the Q-I, W-I and P states and q + w + p = 1 is always true all the time. The interactions between these three states can be illustrated in Fig. 7. The states are connected by the state transition rates, at which a certain number of terminals are transferred from one state to another dynamically. Obviously, only the following four possible terminal transition paths exist:

Q-I → P:	the rate is denoted by A
Q-I → W-I:	the rate is denoted by B
W-I → P:	the rate is denoted by C
P → Q-I:	the rate is denoted by D

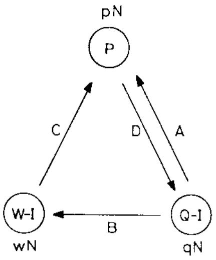

Fig. 7. State transition diagram for BCBS protocol (Ref. [8]).

5 Numerical analysis

5.1 Interactions among the states

From Fig. 7, we shall further calculate the transition rates among the different states: A, B, C and D. The q-terminals leave the state Q-I as transmitters at the rate qNλ per unit time. And only if the transmissions are addressed to other q-terminals or w-terminals {with the probability [(q + w)N - 1] / (N - 1) } then the transmitters join the state P. Thus, the terminals transfer from Q-I to P at the rate of qNλ[(q + w)N - 1] / (N - 1) pairs or 2qNλ[(q + w)N - 1] / (N - 1) terminals per unit time:

$$A = 2qN\lambda \frac{(q+w)N-1}{N-1} \qquad (1)$$

If a q-terminal is going to address packets to a busy terminal which belongs to the state P, the terminal must wait until the target becomes free and this q-terminal enters the state W-I. Thus, the transition rate from the Q-I state to the W-I state is qNλpN/ (N - 1) terminals per unit time, or

$$B = qN\lambda \frac{pN}{N-1} \qquad (2)$$

As assumed earlier, 1/u is the average length of the continuos packet transmissions. Therefore u is the rate at which a successful pair completes its transmission. The successful pairs leave the state P at the rate of (pN/2)u pairs or 2(pN/2)u terminals per unit time.

$$D = pNu \qquad (3)$$

If we define the number of awaited p-terminals NAPT as the number of the different p-terminals awaited by the w-terminals at a given steady state of the network, then the rate C will depend only on the NAPT. Apparently, the NAPT is a random variable, changing with the values of wN and pN, and is just a version of the classic occupancy problem, and its analytical results are readily available. Therefore

$NAPT = (1 - e^{-w/p})Np$ and (4)

$$C = (1 - e^{-w/p})Npu \qquad (5)$$

where N is the number of users of the network, p is the percentage of users that are in the successful pairs, w is the percentage of users that are in the waiting idle state, and 1/u is the average packet length. Thus Np just represents the number of terminals in the P state.

5.2 Throughput-delay evaluation

We can solve for q, w and p by equating the total terminal transition rate into a state to the total terminal transition rate out of the state:

$$(1 - e^{-w/p})pNu + 2qN\lambda \frac{(q+w)N-1}{N-1} = pNu \qquad (6)$$

$$2qN\lambda \frac{(q+w)N-1}{N-1} + qN\lambda \frac{pN}{N-1} = pNu \qquad (7)$$

$$pNu = (1 - e^{-w/p})Npu \qquad (8)$$

$$w + p + q = 1 \qquad (9)$$

Of eqns. 7-9, only two equations need to be combined with eqn. 10 to solve the three parameters q, w and p. The throughput for a terminal can be defined as the percentage of time that it is transmitting the packets which are successfully received. When the network is in the steady state, the percentage of time for the terminals to transmit is equal to the percentage of the terminals which are in the state P. Thus, we can solve p in above equations for the throughput per pair S(N, r) = (2/N)pN/2 = p. The backlog

K(N, r) is defined as the average number of terminals that intend to transmit packets to others but cannot. Thus, the backlog is K(N, r) = wN. Similarly, we can obtain the delay from D(N, r) = K(N, r)/S(N, r). Therefore, after solving eqns., we can obtain

$$r = \frac{p(N-1)}{(2N - pN - 2)(1 - p - w)} \qquad (10)$$

$$w = p \ln \frac{2N - pN - 2}{2N - 2pN - 2} \qquad (11)$$

Therefore p can be found from the following equation:

$$r = \frac{p(n-1)}{(2N - pN - 2)(1 - p - p \ln \frac{2N - pN - 2}{2N - 2pN - 2})} \qquad (12)$$

The throughput S(N, r) is plotted in Fig: 8, respectively, against the offered channel load for the BCBS protocol.

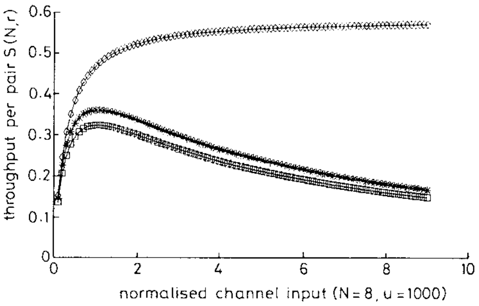

Fig. 8. Throughputs against channel load (Ref. [8]).

*	R-T	code
❑	R	code
◊	BCBS	code

Under the very heavy traffic circumstance of the network, in essence, there are no quiet idle users in the network. Every user is either in the W-I state or in the P state. Table 1 shows how the terminal distribution changes when r becomes very large.

r	1.0	10	100	1000
p	0.4680	0.5737	0.5858	0.5871
w	0.2126	0.3837	0.4098	0.4125
q	0.3194	0.0426	0.0044	0.0004
p/w	2.2013	1.4952	1.4295	1.4233

Table 1: Terminal distribution when r becomes very large (N = 8)

5.3 Throughput-delay upper bounds and ECU analysis

In the BCBS protocol, the throughput monotonously increases as the channel load increases and, eventually, it will approach an upper bound. Therefore, a CDMA network with the BCBS protocol is actually stable.

On using the exponential series approximation $e^x \cong 1 + x$, it can be easily shown that

$$\lim_{r \to \infty} S(N,r) = \lim_{r \to \infty} p(N,r) \approx \frac{2(N-1)}{3N-2} \qquad (13)$$

When N = 8, eqn. 13 turns out to be 7/11 ≈ 0.636, which is much greater than any achievable throughput value for the other conventional protocols. This means that, as the channel load increases, unlike other protocols in which the packet collisions exist, the throughput for the BCBS protocol constantly increases until it approaches a certain upper bound. Furthermore, in eqn. 13, on letting N be infinite too, we can obtain

$$\lim_{\substack{r \to \infty \\ N \to \infty}} S(N,r) = \lim_{\substack{r \to \infty \\ N \to \infty}} p(N,r) = \frac{2}{3} \cong 0.667 \qquad (14)$$

The fact that eqns. 13 and 14 are very close again proves that the throughput performance obtained from solving the network with N = 8 can closely approximate that for any larger-sized network. Similarly, we can also obtain the upper bound of the backlog K(N, r) and the delay D(N, r) for the BCBS protocol:

$$\lim_{r \to \infty} K(N,r) = \lim_{r \to \infty} w(N,r)N = \frac{2N(N-1)}{3N-2} \ln \frac{2(N-1)}{N-2} \qquad (15)$$

$$\lim_{r \to \infty} D(N,r) = \lim_{r \to \infty} \frac{w(N,r)N}{p(N,r)} = N \ln \frac{2(N-1)}{N-2} \qquad (16)$$

When N = 8, the eqns. 15 and 16 give the finite constants 4.314 and 6.778, respectively. On the contrary, as the channel load becomes infinite, the backlogs and delays in the ordinary protocols, such as the R code and R-T code protocols, will be infinite too. The performance bounds of different CDMA protocols are listed in Table 2. Therefore, the BCBS protocol is particularly suitable for the distributed CDMA packet networks with heavily packet traffic.

	R code	R-T code	BCBS
S(N, 1.0)	0.323	0.360	0.468
K(N, 1.0)	2.061	1.840	1.700
D(N, 1.0)	6.375	5.114	3.634
NCIU(N, 1.0)	3.354	3.280	3.744
ECU(N, 1.0)	0.096	0.110	0.125
S(N, ∞)	0	0	0.636
K(N, ∞)	∞	∞	4.314
D(N, ∞)	∞	∞	6.778
NCIU(N, ∞)	8.0	8.0	5.088
ECU(N, ∞)	0	0	0.125
Stable range	r = (0, 1)	r = (0, 1)	r = (0, ∞)

Table 2: Performance bounds for different protocols (N = 8)

Although the BCBS protocol needs two CDMA codes to set up one successful communication pair, it still offers a big advantage in effective code utilisation (ECU) over the other CDMA protocols.

In the BCBS protocol, each successful communication pair broadcasts two codes into the channel simultaneously. Provided that there are pN/2 successful pairs in the network, the total number of CDMA codes in use is 2(pN/2), which is just twice the number of the codes used by the successful pairs in any conventional CDMA protocols. Will it increase the crosstalk noise in the network? We may speculate that the answer is most probably not, because the BCBS protocol dispels all the useless ‘blind’ transmissions which exist abundantly in conventionally CDMA channels, especially when the traffic is high. The number of codes being used in the network with the BCBS protocol may be even lower than those in the networks with the other protocols. We can prove our above conjectures by the following analysis. We denote the number of codes in use as NCIU(N, r), which is a function of the number of users N and the normalised channel load r. For the BCBS protocol, NCIU(N, r) will be simply equal to double the average number of successful transmission pairs. Thus, for this protocol, we have

$$NCIU(N,r) = \frac{2p(N,r)N}{2} \qquad (17)$$

But, for the other protocols, we must consider the codes used by both the successful packet transmissions and the collided packet transmissions. The number of codes used by the collided packet transmissions in the channel can be obtained by calculating the average number of terminals transmitting but failing. Thus, for the conventional protocol, we have

$$NCIU(N,r) = \frac{p(N,r)N}{2} + K(N,r) \qquad (18)$$

To characterise the different protocols more reasonably, we introduce the effective code utilisation (ECU), which integrates both the throughput and the NCIU and is defined as

$$ECU(N,r) = \frac{throughput\ per\ pair}{NCIU(N,r)} \qquad (19)$$

What makes the ECU performance meaningful is that, when the network size becomes large, the ECU can be an important parameter for a CDMA protocol because the demand for the CDMA codes might be extremely great. Thus, every CDMA code should be used as efficiently as possible in the sense of ensuring a high throughput. An obviously high ECU makes the BCBS protocol suitable for large-sized CDMA packet-switched networks.

6 Conclusions

This report dealt with CDMA systems for wireline communications. Three CDMA protocols for wireline networks were considered: the BCBS protocol, R code and R-T code protocols. Comparisons between these three protocols have been made. The results show that a dramatic advantage of the throughput-delay performance over the R code and R-T code protocols can be achieved by using BCBS protocol.

The BCBS protocol is a collision-free CDMA packet protocol, which is easy to implement. The performance of the BCBS protocol has been analysed in detail in this paper, showing that the throughput performance can be about 0.47 when the offered normalised channel load is 1. When the channel packet input increases, the throughput also monotonously increases, displaying the favourably stable characteristic of the protocol. The BCBS protocol can offer not only an evenly high throughput and a small packet delay, but also an ideal ECU, which makes it a very promising alternative to the CDMA wireline networks with large size and heavy traffic.

As a matter of fact, the BCBS protocol is suitable for networks with different physical media, such as copper line networks, power line networks, optical-fibre networks, radio networks and so on, provided that they operate in the packet-switched CDMA fashion.

Intrabuilding power lines provide a readily available and easily accessed network for communications within buildings.

The communication characteristics of intrabuilding power line channels are summarised and found to suffer from highly variable, ever-changing, and unpredictable signal-to-noise ratios and bit error rates.

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