Comparison between S-CDMA and TDMA for Cable Modem Upstream Channel

Ki Yun Kim*, Hyoung Geun Lee*, Pan Soo Kim*, Hyung Jin Choi*, and Byung Hak Cho**
* : Dept. of Electronics Engineering, Sung Kyun Kwan University
** : Multimedia Research Center, Korea Electronics Technology Institute
Tel: +82-331-296-9144, Fax: +82-331-296-9146
E-mail: hjchoi@ece.skku.ac.kr

Abstract: In this paper, we compare the major issues associated with TDMA and S-CDMA, which is planned to be adopted as a new cable modem technique for upstream channel. In particular, we mainly deal with the following 3 topics: MAC protocol, modem structure and BER performance comparison between TDMA and S-CDMA.

1. Introduction

Recently, interest in cable modem technology is growing to achieve two-way high speed data transmission. In this situation, S-CDMA (Synchronous - Code Division Multiple Access) is highlighted as a new upstream channel cable modem technology, which is scheduled to be adopted by MCNS as DOCSIS 1.2 cable modem standards, while TDMA employed in DOCSIS 1.0 and DOCSIS 1.1 has shown difficulties in reliable data transmission owing to the upstream channel noise such as impulse noise.

The two most serious problems in the upstream channel are the capacity constraints in the limited 5-42 MHz bandwidth, and the occurrence of large amount of noise and interference. These impairments represent not only degradation of transmission performance in the upstream channel but also problems for the downstream channel, since downstream data transmission is dependent on the upstream message data. S-CDMA can solve these problems by using QAM (Quadrature Amplitude Modulation) spread spectrum technique which enhances reliability and capacity as CDMA technology. S-CDMA can make the upstream transmission very immune to impulse noise and narrowband interference. S-CDMA also has other benefits which are inherent to S-CDMA including dynamic bandwidth allocation and privacy.

Since the S-CDMA is a state of art technique, which is initially developed and patented for the cable modem by Terayon corporation in USA, it is hard to find technical references which provides a theoretical and systematic analysis.

This paper presents a detailed comparison between S-CDMA and TDMA. In section 2, we present a brief comparison of MAC protocol and in section 3, we illustrate the modem structural differences between them. In section 4, we analyze BER performance of S-CDMA and TDMA using εmixture impulse noise model and compare the performance. Finally, in section 5, we finish the paper with concluding remarks.

2. Comparison of MAC protocol

MAC (Media Access Control) protocol controls such that multiple RU (Remote Unit) and headend can be made to communicate in cable modem upstream channel reliably. Today, TDMA MAC protocol of DOCSIS 1.1 specification is used in the cable modem upstream channel, but there are some complexities in MAC frame format. S-CDMA MAC protocol which is proposed by Terayon [1] will be used as an alternative to solve the complexity of TDMA MAC. Both S-CDMA and TDMA MAC protocols commonly achieve the process of gaining upstream channel, ranging, registration at RU, channel assignment and contention resolution at headend, but there is a difference between the two MAC protocols. In TDMA [2], while MAP structure as an upstream access request format has a complexity, S-CDMA MAC protocol is designed for solving complexity of MAC frame as shown in Fig. 1. And as is the case for an initial registration, S-CDMA MAC uses a random number composed of 12 bits to insure uniqueness which reduces the assigned chance of the same IDs to 1:4096 [3].

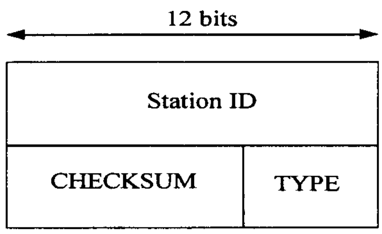
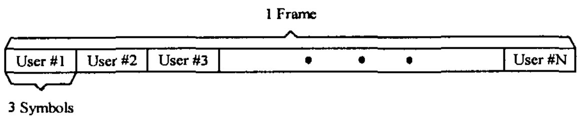


Fig. 1 Upstream Access Format

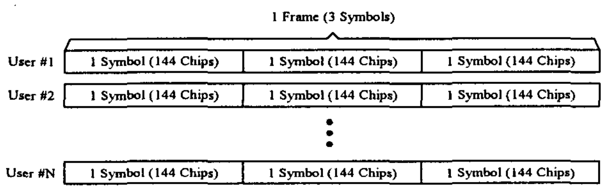
In general, MAC layer includes all the algorithms pertaining to access of the physical layer. These algorithms include registration, authentication and bandwidth requests. S-CDMA MAC type is similar to TDMA about initial registration process but authentication exhibits different aspects. S-CDMA authentication process is as follows. The headend identifies validity of the RU by having the RU send a unique 48 bit MAC ID assigned to manufacture of the RU by combination of 4 access channel and 12 SID bits and then checks the received MAC ID against a table containing all the authorized MAC IDs.

Besides these differences relating to upstream access, there is a difference in QoS (Quality of Service) between S-CDMA and TDMA MAC. S-CDMA is ATM cell-based MAC protocol that can ensure QoS better than TDMA MAC. Of course, TDMA also has scheme of ATM cell-based transmission protocol but generally uses a delivery scheme of variable length of IP packets [4]. S-CDMA MAC protocol of ATM cell-based is follows. First of all, ATM cell-based protocol is not compatible for cable modem structure with multipoint to point. So the method appears to be virtual point to point with the ability to reserve bandwidth to each RU. This virtual link structure is established by coding ID information in a two byte header containing the virtual link ID of the virtual link to which each ATM-cell belongs. This virtual header also makes possible broadcast and multicast of packets from the headend to all RU for upstream management and control purposes in resolving contentions on shared access channels, distributing code allocation decision and other management functions. And in order to minimize the MAC layer overhead contrary to complexity of TDMA MAC header, ATM cell boundary synchronization of S-CDMA is achieved using a 9th bit on each 8-bit byte in each ATM cell. i.e, each byte in each ATM cell has 8 bits of data and a 9th bit which is encoded with data to indicate where the ATM cell starts and includes CRC data for error detection and correction on the payload data in the cell. That is, S-CDMA MAC of ATM cell-based transmission protocol solves complexity of TDMA MAC frame and improves QoS by means of cell-based scheme.

3. Comparison of Modem



(a) The frame structure of TDMA



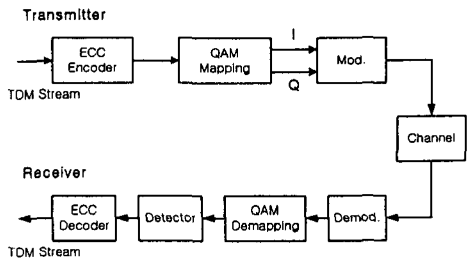
(b) The frame structure of S-CDMA

Fig. 2 The frame structure of TDMA and S-CDMA

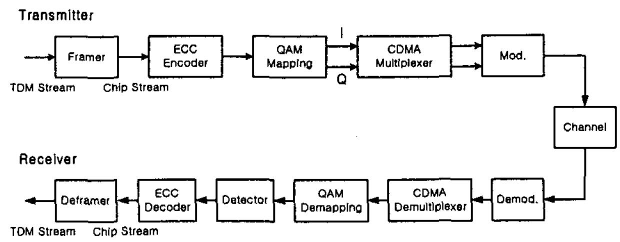
The most basic difference between TDMA and S-CDMA modem can be explained from a frame structure. Fig. 2 shows TDMA and S-CDMA frame structure based on Terayon patent [5]. In TDMA frame structure (Fig. 2 (a)), N users transmit the 1 timeslot data (3 symbols) at the given different timeslot during 1/N frame period respectively. In S-CDMA frame structure (Fig. 2 (b)), N users transmit simultaneously each 1 timeslot data (3 symbols) spreaded by orthogonal code during 1 frame period.

Fig. 3 shows the block diagram of S-CDMA and TDMA modem. As shown in Fig. 3 (a), TDMA modem is simpler than S-CDMA. The incoming TDM stream is transmitted at the different time without interferences through ECC (Error Correcting Code) encoder, QAM mapping, and modulator. And then the transmitted data are demodulated inversely in the receiver.

On the other hand, S-CDMA modem additionally needs framer, CDMA multiplexer, CDMA demultiplexer, deframer compared to TDMA modem for the spreading and despreading process as shown in Fig. 3 (b). S-CDMA modem works as follows. We assume that 1 frame



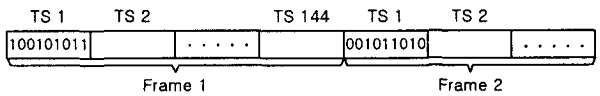
(a) TDMA modem



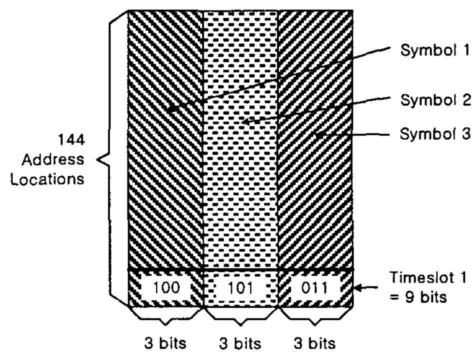
(b) S-CDMA modem

Fig. 3 S-CDMA and TDMA modem

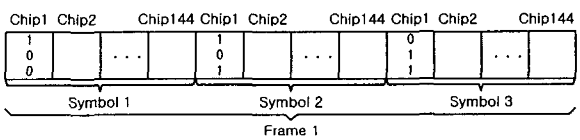
consists of 144 timeslot, 1 timeslot consists of 3 symbol (9 bit), the length of spreading code is 144, and modulation uses 16 QAM. The transmitting data of each device is converted to TDM stream, input to the transmitter modem which is assigned the spreading code, and output with chip stream to make room for spreading in advance. The TDM stream which is input to framer is shown in Fig. 4 (a). It is stored at framer memory as shown in Fig. 4 (b). 1 timeslot (9-bit) data is divided into 3 symbol, and output one after another. Each symbol is divided into 144-chip intervals as shown in Fig. 4 (c). Then 1 timeslot data is spreaded into 1 frame with 432 chips.



(a) The input of framer



(b) Framer memory



(b) The output of framer

Fig. 4 Operation of Framer

The output of framer passes through an ECC encoder to add redundancy by calculating a 4th bit from each 3-bit. The ECC encoder is used to provide greater accuracy and better noise immunity. The output of the ECC encoder is an array of 4-bit digital numbers for each of symbols 1, 2, 3. Each symbol is comprised of two linear arrays of 2-bit numbers: I (In-phase) and Q (Quadrature) channels. Each symbol maps 16 QAM with Gray encoding by conversion to their decimal equivalents (-3, -1, 1, 3).

The 16 QAM mapping symbols are input to the CDMA multiplexer with I and Q channels as shown in Fig. 5 (a). CDMA multiplexer spreads the mapping symbol over the spreading interval with an orthogonal code. The Gray encoding data of each symbol is multiplied to spreading code whose length is 144 as shown in Fig. 5 (b). The row of code matrix is the spreading code assigned to each user.

	Chip1	Chip2		Chip144	Chip1	Chip2		Chip144	Chip1	Chip2		Chip144
I	-3	0	. . .	0	-3	0	. . .	0	+1	0	. . .	0
Q	+1	0	. . .	0	-3	0	. . .	0	-3	0	. . .	0
	Symbol 1				Symbol 2				Symbol 3			

Frame 1

(a) The input of CDMA multiplexer

$$\begin{bmatrix} -3 & 0 & 0 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} -1 & -1 & -1 & \cdots & 1 \\ 1 & -1 & -1 & \cdots & 1 \\ 1 & 1 & -1 & \cdots & 1 \\ \vdots & \vdots & \vdots & & \vdots \\ -1 & -1 & -1 & \cdots & -1 \end{bmatrix} = \begin{bmatrix} +3 & +3 & +3 & \cdots & -3 \end{bmatrix}$$

(b) The matrix multiplication of CDMA multiplexer

	Chip1	Chip2		Chip144	Chip1	Chip2		Chip144	Chip1	Chip2		Chip144
I	+3	+3	. . .	-3	+3	+3	. . .	-3	-1	-1	. . .	+1
Q	-1	-1	. . .	+1	+3	+3	. . .	-3	+3	+3	. . .	-3
	Symbol 1				Symbol 2				Symbol 3			

Frame 1

(c) The output of CDMA multiplexer

Fig. 5 CDMA multiplexer

The components of these two channels are then output on separate I and Q channels to a modulator where they are used to amplitude modulate the amplitudes of two RF carriers that are 90 degrees out of phase. The resulting two AM carriers are summed and output on the shared transmission media. Because the spreaded signals are transmitted to the CU simultaneously over the shared transmission media using orthogonal code, no interference occurs among the data.

The composite data are passed through shared transmission media input to the receiver modem. In CDMA demultiplexer, the composite data is despreaded by multiplying with the transpose of the code matrix which was used to spread the timeslot to extract any timeslot information as shown in Fig. 6.

The despreaded data is compared to the closest points in the constellation of legitimate possible input data points that could have been transmitted. The ECC decoder used the 4-th ECC bit in each 4-bit component of each symbol to detect and correct errors, and output 3-bit stream. And deframer reconverts these chip streams to TDM bit streams.

$$\begin{bmatrix} +3 & +3 & +3 & \cdots & -3 \end{bmatrix} \times \frac{1}{144} \begin{bmatrix} -1 \\ -1 \\ -1 \\ \vdots \\ 1 \end{bmatrix} = \begin{bmatrix} -3 \end{bmatrix}$$

Fig. 6 The matrix multiplication of CDMA demultiplexer

As analyzed above, we can find that S-CDMA modem is more complex than TDMA modem in terms of adding the spreading and despreading process. But, by introducing spread spectrum techniques, S-CDMA modem can make data transmission highly immune to narrowband interference and impulse noise in the 5-42 MHz upstream path. The simulation results are shown in Section 4.

4. Comparison of BER Performance

To compare the BER performance between S-CDMA and TDMA scheme, it is needed for impulse channel modeling which is suitable for cable modem upstream channel.

Miller & Thomas proposed ε-mixture impulse noise model [6] using a first-order noise density which consists of a small variance Gaussian PDF (Probability Density Function) and a large variance impulsive PDF. This model describes statistical distribution of instantaneous amplitude and appropriately reflects impulse noise occurrence characteristic of cable modem upstream channel. So we adopt this model to design cable modem upstream channel by selecting suitable parameters. It is assumed that the total noise $n(t) = n_B(t) + n_I(t)$, which is the sum of a Gaussian background noise component $n_B(t)$ and impulsive component $n_I(t)$.

The first order PDF of this impulse noise model with occurrence rate probability(ε) is as follows [7], [8],

$$f_n(x) = (1-\varepsilon) f_B(x) + \varepsilon f_I(x), \qquad (1)$$

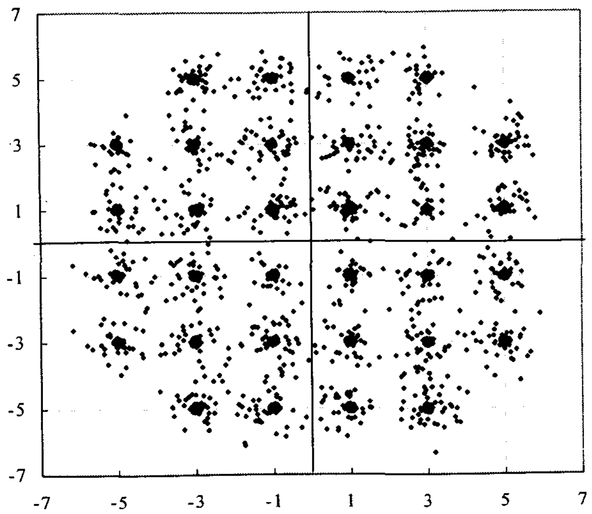
where f_B is the PDF of the background AWGN with a power spectral density $N_o/2$, f_I is the PDF of the impulsive component (0<ε<1) and the ratio of the variances of f_I and f_B, defined as

$$\gamma^2 = \sigma^2{}_I / \sigma^2{}_B \qquad (2)$$

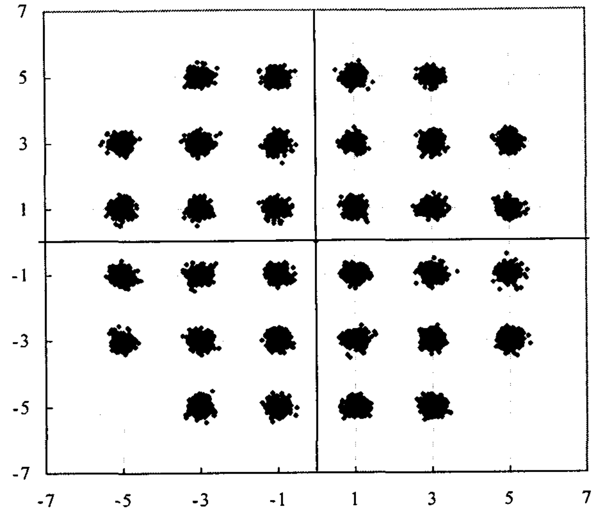
is usually taken to be a simulation parameter meaning the power ratio of impulse noise. Here, total noise variance σ^2 is given by

$$\sigma^2 = N_0[(1-\varepsilon) + \varepsilon\gamma^2]/2 \ . \qquad (3)$$

Fig. 7 shows the 32 QAM constellation of TDMA and S-CDMA scheme in the ε-mixture impulse noise model environment. In Fig. 7, we can find that S-CDMA scheme has less out-of-decision area symbols than TDMA scheme owing to the spreading effects.



(a) Constellation of TDMA



(b) Constellation of S-CDMA

Fig. 7 Comparison of constellation
(32 QAM, Eb/No=30 dB, $\gamma^2 = 100$, $\varepsilon = 0.1$)

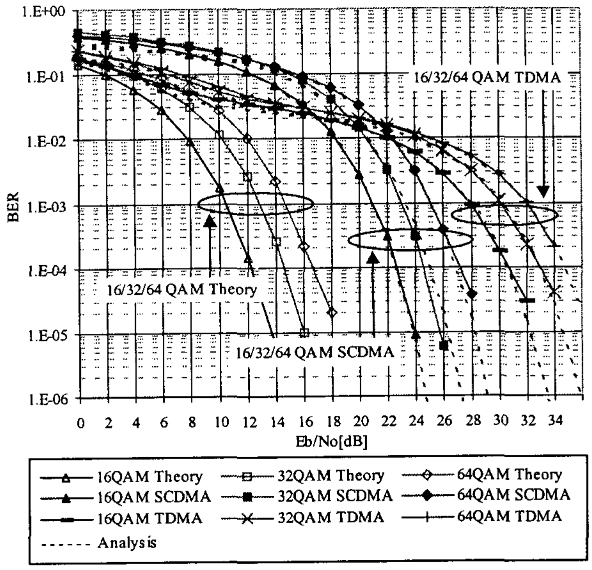
Based on the ε – mixture impulse noise model, we can analyze S-CDMA and TDMA BER performance relative to 16/32/64 QAM. From the QAM BER in AWGN [9] and the binomial expansion, the following TDMA BER equation for QAM in impulse noise channel can be obtained.

$$P_{B\,TDMA} = \varepsilon \frac{2(1-L^{-1})}{\log_2 L} Q\left(\sqrt{\frac{3\log_2 L}{L^2-1}\frac{2E_b}{N_0\gamma^2}}\right) + (1-\varepsilon)\frac{2(1-L^{-1})}{\log_2 L} Q\left(\sqrt{\frac{3\log_2 L}{L^2-1}\frac{2E_b}{N_0}}\right) \quad (4)$$

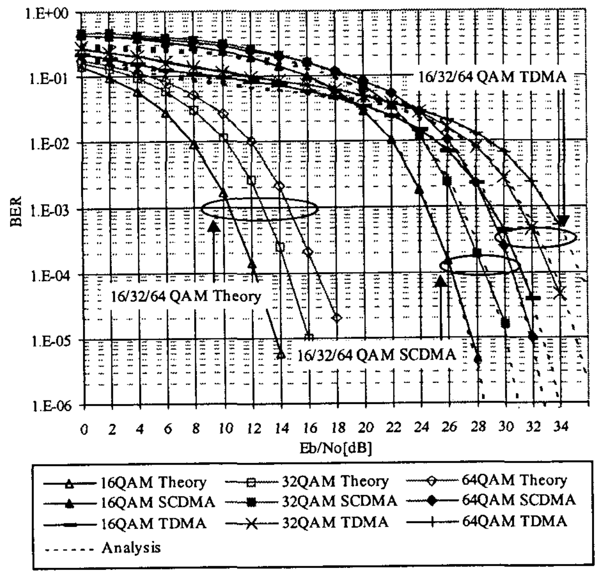
Where $Q(x)$ is Q function and L represents the number of amplitude levels in one dimension. This TDMA BER equation is composed of two terms. The first term is $\gamma^2 N_o/2$ noise power during ε fraction of normalized noise interval and the second term is $N_o/2$ AWGN noise power during $(1-\varepsilon)$. The S-CDMA BER can be obtained by a total average noise power, since the noise power σ^2 is uniformly spread in the spreading interval. Therefore S-CDMA BER can be expressed as

$$P_{B\,S\text{-}CDMA} = \frac{2(1-L^{-1})}{\log_2 L} Q\left(\sqrt{\frac{3\log_2 L}{L^2-1}\frac{2E_b}{N_0(\varepsilon\gamma^2+(1-\varepsilon))}}\right). \quad (5)$$

Based on the impulse noise modeling and the derived BER equations, we show S-CDMA and TDMA BER performance for 16/32/64 QAM scheme in Fig. 8.



(a) Occurrence of impulse noise in 13chips ($\varepsilon = 0.1$)



(b) Occurrence of impulse noise in 32chips ($\varepsilon = 0.25$)

Fig. 8 S-CDMA and TDMA BER performance for 16/32/64 QAM ($\gamma^2 = 100$)

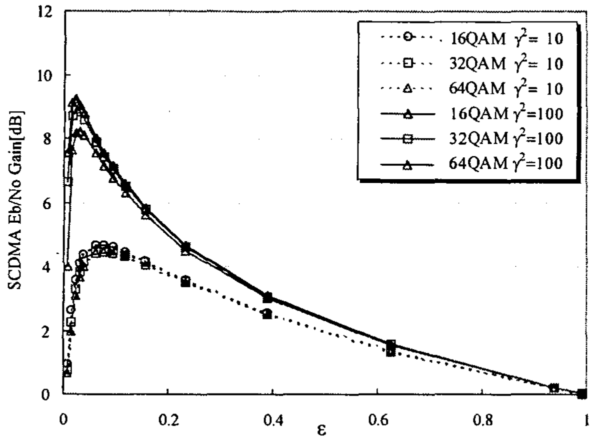


Fig. 9 Eb/No Gain of S-CDMA over TDMA (at $BER = 10^{-3}$)

Fig. 8 (a), (b) show 16/32/64 QAM BER performance for 13 chips and 32 chips duration respectively in impulse noise environment which is using 128 perfect orthogonal code sets (Walsh code sets) with γ^2= 100. The simulation results are close to the analysis results with Eq. (4), (5). Since we assume that one chip duration is about $313\,n\text{sec}$, the impulse noise interval of 13 chips ($\varepsilon = 0.1$) corresponds to $4\,\mu\text{sec}$ and 32 chips ($\varepsilon = 0.25$) corresponds to $10\,\mu\text{sec}$ within 128 chip code spreading duration. In Fig. 8, we can find that S-CDMA scheme has Eb/No gain over TDMA about 7.1 dB, 7.1 dB, 6.9 dB for each 16/32/64 QAM in the $\varepsilon = 0.1$ (Fig. 8(a)) and has Eb/No gain over TDMA about 4.7 dB, 4.6 dB, 4.5 dB for each 16/32/64 QAM in the $\varepsilon = 0.25$ (Fig. 8(b) at BER=10^{-3} respectively. This means each 16/32/64 QAM shows similar gain performance with one another regardless of the order of QAM. We can also know from the results that as the occurrence interval of impulse noise is varied, S-CDMA Eb/No gain also changes.

In Fig. 9, we show S-CDMA Eb/No gain over TDMA by varying ε (occurrence interval of impulse noise) at BER=10^{-3} based on Eq. (4), (5). Fig. 9 shows that as ε becomes larger, S-CDMA Eb/No gain sharply increases, and reaches maximum performance point at certain ε and finally shows the tendency to decrease slowly. And as γ^2 (the ratio of impulse noise power) becomes higher, maximum Eb/No gain point is smaller in ε axis. As γ^2 is increased, we find that S-CDMA scheme is superior to TDMA in terms of BER performance.

5. Conclusions

In this paper, we compared the major issues associated with S-CDMA and TDMA scheme. In MAC protocol, we could find that S-CDMA MAC protocol solves complexity of TDMA MAC and improves QoS by means of cell-based scheme. We also analyzed that S-CDMA modem is more complex than TDMA modem, but owing to spread spectrum techniques, S-CDMA modem can make data transmission highly immune to narrowband interferences and has superior BER performance in the impulse noise environment. We believe that these results will be helpful for someone who wants to achieve better design of S-CDMA modem.

References

[1] A. M. Fuhrmann, Apparatus and Method for Digital Data Transmission over a CATV System Using an ATM Transport Protocol and S-CDMA, US Patent, 5,745,837, Apr. 1998.

[2] Data-Over-Cable Service Interface Specifications, Radio Frequency Interface Specification, SP-RFIv1.1-I01-990311.

[3] S. S. Rakib, Apparatus and Method for Digital Data Transmission over Video Cable Using Orthogonal Cyclic Codes, US Patent 5,793,759, Aug. 1998.

[4] N. Golmie, F. Mouveaux, and D. Su, "A comparison of MAC protocols for HFC networks: IEEE 802.14 vs. MCNS," *IEEE International Conference on Communications - Volume 1*, V.1, pp. 266~272, June 1999.

[5] S. S. Rakib, Apparatus and Method for Digital Data Transmission over Video Cable Using Orthogonal Cyclic Codes, US Patent 5,793,759, Aug. 1998.

[6] J. H. Miller and J. B. Thomas, "The detection of signals in impulse noise modeled as a mixture process," *IEEE Trans. Comm.*, vol. COM-24, pp. 559~563, May 1976.

[7] S. Kapoor, V. P. Telang, J. D. Mills, and M. G. Makhija, "Mitigating impulse noise over HFC network for telephony-over-cable," *Proc. GLOBECOM'95*, vol. 2, pp. 967~971, 1995.

[8] B. Aazhang and H. V. Poor "Performance of DS/SSMA comunications in impulsive channels-part I: Linear correlation receivers," *IEEE Trans. Comm.*, vol. COM-35. no. 11, pp. 1179~1183, Nov. 1987.

[9] B. Sklar, *Digital Communications : Fundamentals and Applications,* NJ: PTR Prentice-Hall, pp. 546~549, 1988.