Multi-carrier CDMA (MC-CDMA) with Space time codes

1. *Introduction:*

- Most of the codes provide high reliability but have a low data rate. Hence, it is clear that the codes with high rate and reliability are the design target in minds of most researchers.

- To provide high transmission bandwidth efficiency in mobile communications, multiplexing schemes are introduced such as direct-sequence code division multiple access (DS-CDMA), orthogonal frequency division multiplexing (OFDM).

- These techniques are mostly considered in the time and frequency domain. In addition, we can consider the space domain to improve the performance, i.e. space-time coded modulation (STCM), array techniques. Thus, the combination of coding and multiplexing may provide better performance if they are considered in space domain as well.

- Multi-carrier code division multiple access (MC-CDMA) takes the advantages from the combinations of both DS-CDMA and OFDM considering mobile communication in multi-path fading channels.

- STCM can guarantee that the diversity occurs at transmitting side and maximizes both coding gain and diversity gain. Consequently, this modulation scheme has a capability of combating the multipath fading in wireless communications (**Naguib et al**, 1998, 1997).

Objectives:

- Performance of space-time coded MC-CDMA is evaluated over slow frequency-selective fading channel

- Performance of MC-CDMA with STCM employing multiple transmit antennas and TCM with single antenna are compared with respect to the complexity and spectral efficiency of the codes

Assumptions:

- Number of users is limited to sixteen users in the fading channel.
- Urban or suburban area is the environment of interest.
- Ideal channel estimation is assumed.
- Frequency offset and peak-to-average power ratio are not considered in this thesis.
- The data rate of every user is assumed to be equal.
- Time and frequency synchronization is assumed in downlink communications.
- Delay between each tap in the channel model is assumed to equals to sampling period.

2. MC-CDMA Overview

- The multi-carrier CDMA schemes are mainly categorized into two groups.
- One spreads the original data stream using a given spreading code, and then modulate a different subcarriers with each chip (in a sense, the spreading operation in the frequency domain) (**Yee et al.**, **Fazel and Papke**, **Chouly et al.**, 1993),
- and another spreads the serial-to-parallel converted data streams using a given spreading code, and then modulates different subcarriers with each data stream (the spreading operation in time domain) (**DaSilva and Sousa**, **Vandedrope**, 1993), similar to a normal DS-CDMA scheme.

- *Here MC-CDMA transmitter which spreads the original data stream over different subcarriers using a given spreading code in the frequency domain is considered.*

- In a (synchronous) down link mobile radio communication channel, we can use the Walsh-Hadamard codes as an optimum orthogonal set, because we do not pay attention to the auto-correlation characteristic of the spreading code. The Figure 2.1 and 2.3 show the MC-CDMA transmitter for coherent binary phase shift keying (CBPSK) scheme and the power spectrum of the transmitted signal respectively.

The transmitted signal of the j^{th} user is written as

$$s_{MC}^{j}(t) = \sum_{i=-\infty}^{\infty} \sum_{m=1}^{G_{MC}} a^{j}(i) g_{m}^{j} \cdot p_{s}(t - iT_{s}) \cos\{2p(f_{0} + m\Delta f)t\} \tag{2.1}$$

where Δf (= $1/T_S$) is the subcarrier separation, c_m^j is the spreading code at m^{th} subcarrier, $a^j(i)$ is the original data stream at time i, $p_s(t)$ is the pulse wave form defined as:

$$p_s(t) = \begin{cases} 1 & \text{for} \quad 0 \le t \le T_S \\ 0 & \text{otherwise} \end{cases} \tag{2.2}$$

- The main advantage of MC-CDMA scheme over other schemes (DS-CDMA, MC-DS-CDMA or MT-CDMA) is that the MC-CDMA receiver can always use the all received signal energy scattered in the frequency domain to detect the desired signal. However, through a frequency-selective fading channel, the subcarriers may have different amplitude level and phase shifts (although they have high correlation among subcarriers), and it results in the distortion of orthogonality among users.

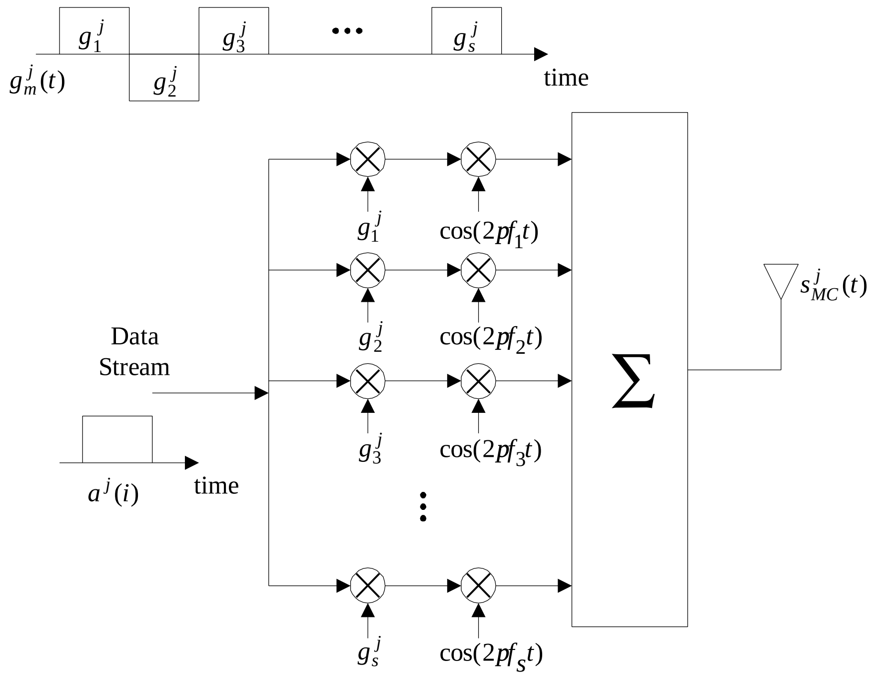

Figure 2.1 MC-CDMA Transmitter Block Diagram (**Prasad and Hara**, 1996)

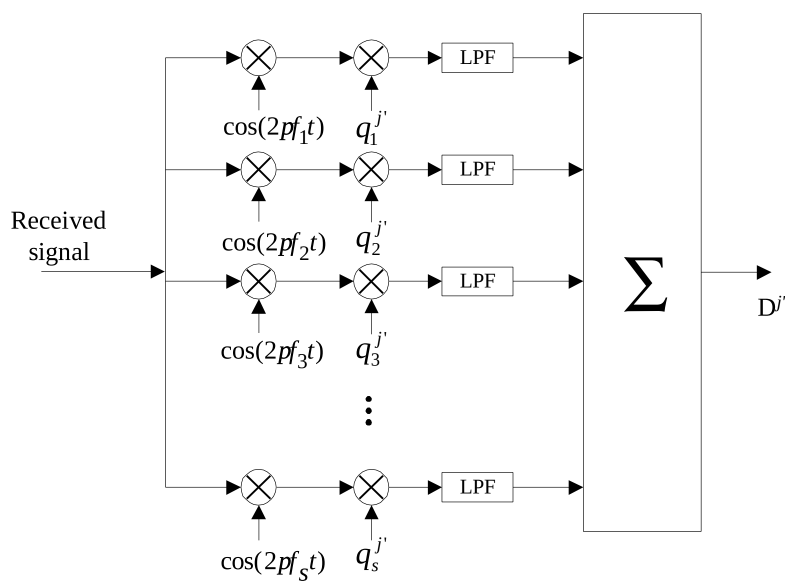

Figure 2.2 MC-CDMA Receiver Block Diagram (**Prasad and Hara**, 1996)

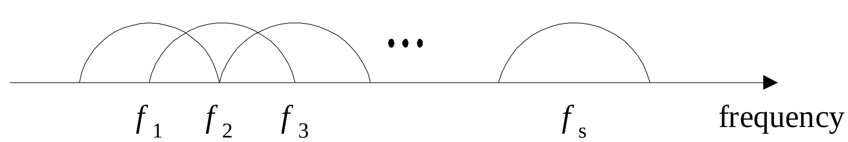

Figure 2.3 Power Spectrum of the Transmitted Signal (**Prasad and Hara**, 1996)

- Figure 2.2 shows the MC-CDMA receiver of the j'^{th} user, the m^{th} subcarrier is multiplied by the gain $q_m^{j'}$, which is the combination of the spreading code of the subcarrier f_m with the corresponding subchannel gain. The decision variable is given by (ignoring the subscription *i* without loss of generality)

$$
\begin{aligned}
D^{j'} &= \sum_{m=1}^{G_{MC}} q_m^{j'} y_m \\
y_m &= \sum_{j=1}^{J} z_m^j a^j c_m^j + n_m
\end{aligned} \tag{2.3}
$$

- where y_m and n_m are the complex baseband component of the received signal, which there are the properties of subcarrier frequency synchronization and the complex additive Gaussian noise after down conversion at the m^{th} subcarrier, respectively, z_m^j is the complex envelop of the m^{th} subcarrier for the j^{th} user. We can assume $z_m^j = z_m$ for $j = 1, 2, \cdots, J$ in a down-link channel.

- It is crucial for multicarrier transmission to have frequency flat fading over each subcarrier.
- Then, if the original symbol rate is high enough to experience with frequency selective fading, the signal needs to be first serial-to-parallel converted before spreading over the frequency domain. Additionally, the proper choice of the number of subcarriers and the guard interval is important to increase the robustness against frequency selective fading.
- However, the problems of frequency offset and peak-to-average power ratio should also carefully be considered when choosing the number of subcarriers and the subcarrier bandwidth.

General MC-CDMA System Implementation

- Figure 2.4 illustrates the typical MC-CDMA system. The incoming serial data is first copied from serial to form *N* parallel data streams and grouped into *b* bits. Each of *b* bits is spread over frequency domain and formed to be a complex number. The complex numbers are modulated in a baseband fashion by the IFFT and converted back to serial data for transmission. A guard interval consisting of a partial repetition of the output of the IDFT process (d_k) is inserted between symbols to avoid intersymbol interference (ISI) caused by multipath distortion. The discrete symbols are converted to analog by lowpass filtering and then feed to RF up-converter.

- The receiver performs the inverse process of the transmitter. After demapping, the received signals in subcarriers have to be combined to form a recovered received signal in series.

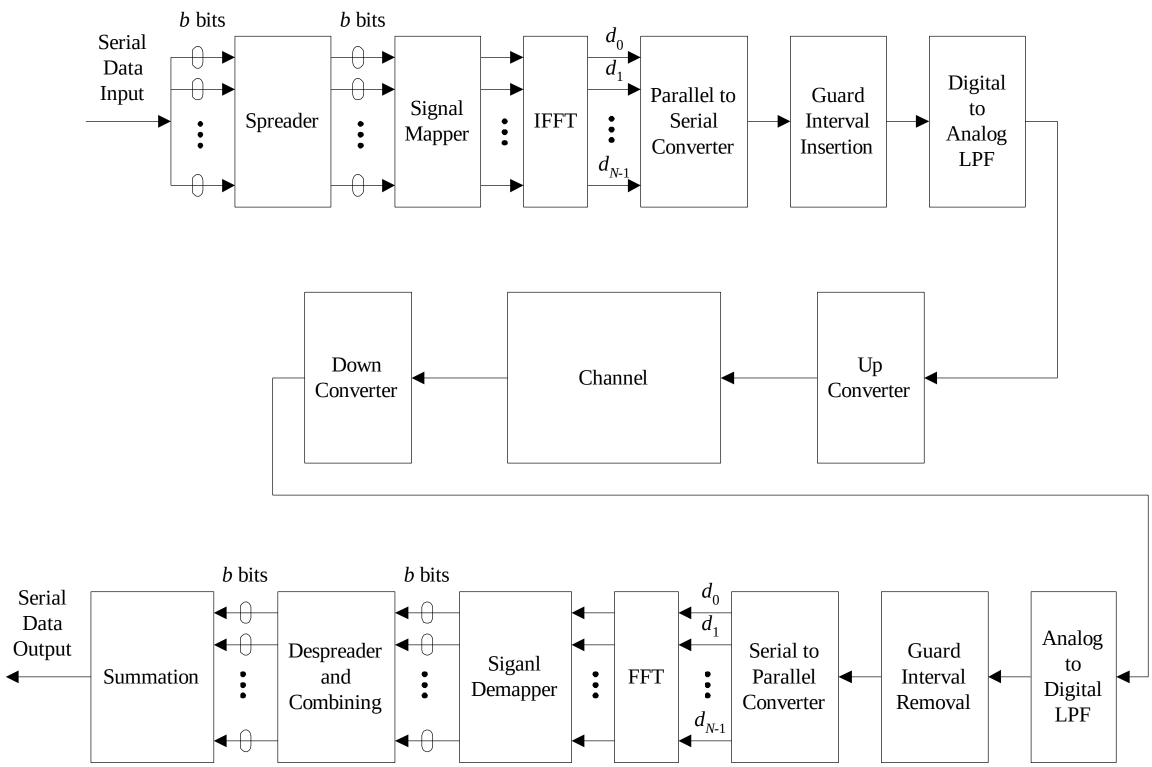

Figure 2.4 General MC-CDMA System Adapted from (**Zou and Wu**, 1995)

Signal Representation of MC-CDMA Using IDFT/DFT

- This part is adapted from (**Zou and Wu**, 1995). Let us consider an input symbols $(D_0, D_1, ..., D_{N-1})$, which are the output of digital modulator after spreading with N processing gain. Each D_n is a complex number, $D_n = A_n + jB_n$.

- The sequence is mapped into N subcarriers corresponding to N symbols. The modulated symbol at n^{th} subcarrier is transformed into time domain by N-point inverse discrete Fourier transform (IDFT). If we take the IDFT of this symbol sequence, the result is

$$d_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} D_n \exp\left(j \frac{2pnk}{N}\right) \quad \text{where } k=0, 1, ..., N\text{-}1 \text{ and } n=0, 1, ..., N\text{-}1 \qquad (2.4)$$

The MC-CDMA signal in continuous time domain is given by

$$Y(t) = \sum_{n=0}^{N-1} D_n \exp(jw_n t), \qquad \text{where } w_n = 2pf_n \tag{2.5}$$

The sampled signal of $Y(t)$ at sampling rate $1/T$ is

$$Y(kT) = \sum_{n=0}^{N-1} D_n \exp(jw_n kT) \tag{2.6}$$

- If we restrict the time over which we analyze the signal to N samples with sampling rate $1/T$, then the total MC-CDMA symbol period T_s equal to NT, and $f_n = \Delta f \times n$. Where Δf is the frequency spacing between sub-carriers. If we take $\Delta f = 1/NT = 1/T_s$ then

$$\begin{aligned}
Y(kT) &= \sum_{n=0}^{N-1} D_n \exp(jw_n kT) \\
&= \sum_{n=0}^{N-1} D_n \exp(j2pn\Delta fkT) \\
&= \sum_{n=0}^{N-1} D_n \exp(j\frac{2pnkT}{NT}) \\
&= \sum_{n=0}^{N-1} D_n \exp(j\frac{2pnk}{N}) \\
&= \sqrt{N} \times IDFT\{D_n\} \\
&= \sqrt{N} \times d_k
\end{aligned} \tag{2.7}$$

- It is therefore clear, from Equation (2.4), that IDFT can be used to modulate the MC-CDMA signal. Finally, the samples d_k are transmitted using ordinary T-spaced pulse amplitude modulation.

Walsh-Hadamard Codes for Orthogonal Design

- In MC-CDMA scheme, Walsh-Hadamard codes are used for the frequency spread coding to achieve the orthogonality among users.
- This code is simply obtained by selecting as codewords, the rows of Hadamard matrix. +1 and –1 denote the elements of the Hadamard matrix. The Hadamard matrix $\mathbf{H}_n$ is an $n \times n$ matrix such that n is an even integer with the property that any row differs from any other rows in exactly $n/2$ positions. Usually, the first row of the matrix contains all +1s. The other rows contain +1s of $n/2$ and -1s of $n/2$. The rows of the Hadamard matrix are then mutually orthogonal. To generate the code, the fundamental unit of Hadamard matrix is given as

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{2.8}$$

- The following recursive matrix operation is employed to produce the Walsh-Hadamard codes of length $2n$.

$$\mathbf{H}_{2n} = \begin{bmatrix} \mathbf{H}_n & \mathbf{H}_n \\ \mathbf{H}_n & -\mathbf{H}_n \end{bmatrix} \tag{2.9}$$

- where the matrix, $\mathbf{H}_{2n}$, of the size $2n \times 2n$ is formed by using the matrix, $\mathbf{H}_n$, of size $n \times n$ with $\mathbf{H}_2$ given above. These codes fulfill completely the orthogonality between each other when synchronization is regularly held.

3. Simulation Configuration

- The downlink of MC-CDMA system is considered. The block diagram of lowpass equivalent representation of the overall simulation model is shown in Figure 3.1.

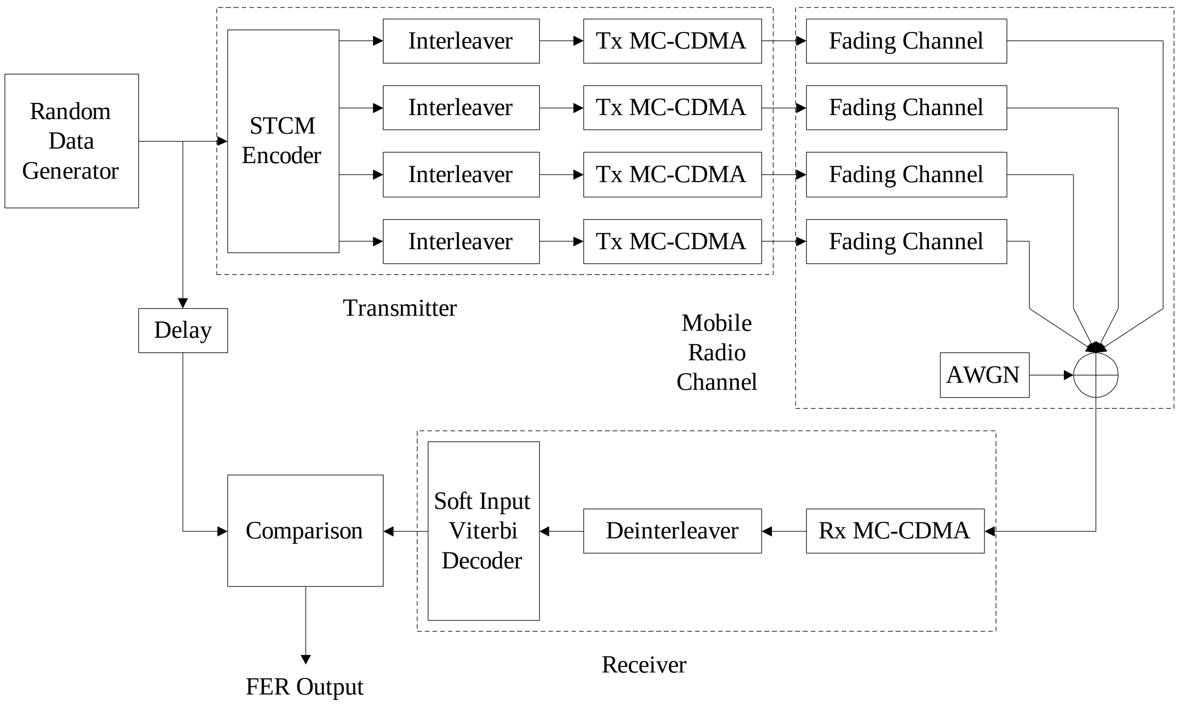

Figure 3.1 **Block Diagram of Lowpass Equivalent System Model Followed for Monte Carlo Simulation Implementation**

- In the simulation, FER is used for comparison. One frame in this simulation is equal to 256 bits or 128 symbols. The comparison is made on the error of bit in each frame. If there is any bit error in a frame, that frame will be taken to be a frame error.

Transmitter Section

- At the transmitter, the proposed system employs STCM encoder considering four transmitting and one receiving antennas. Each branch at the output of the encoder has an interleaver with block size corresponding to one-frame symbols. After that the MC-CDMA scheme, is used to both multiplexing and modulating the interleaved coded symbol.

Encoder

- STCM code can be viewed as delay diversity code with four transmit antennas and QPSK modulation. The number of states in a trellis diagram is at least 64 states and the constraint length, the minimum number of bits on a single output stream that can be affected by any input bit, of the encoder is three.

- Therefore, the total number of memory, the number of shift register elements, for encoder is equal to six. As the number of memory increases, the number of possible states of the encoder increases, making a higher complexity in the Viterbi decoder at the receiver. Figure 3.2 shows an implementation of STCM encoder.

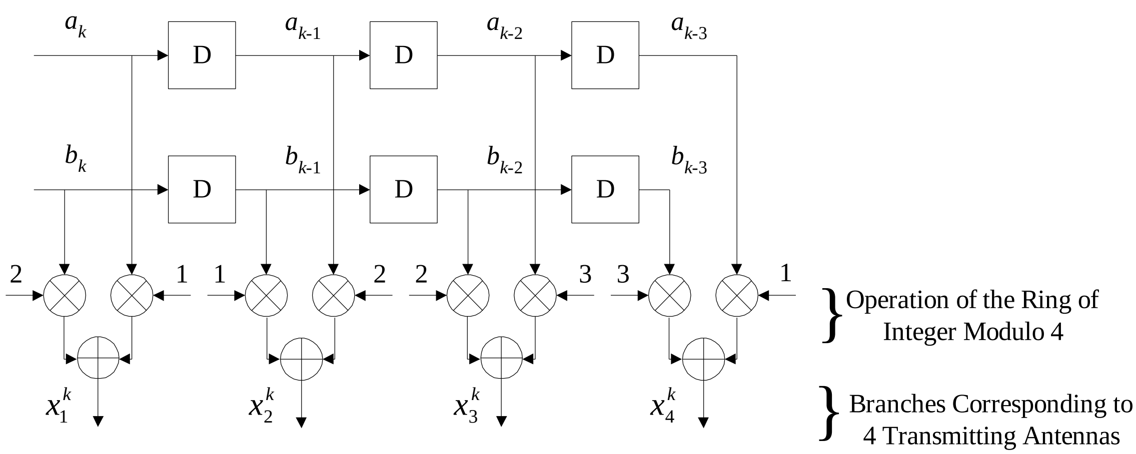

Figure 3.2 STCM Encoder Block Diagram

- It can be shown that this code guarantees a diversity advantage of 4 and coding advantage of 16 from the trellis diagram of the code.

- For comparison, trellis coded modulation (TCM) (**Schlegel and Costello**, 1989) is applied. instead of Ungerboeck's codes, which are designed to have the maximum Euclidean distance.

- Ihis TCM scheme is designed for fading channel, which maximize the minimum symbol distance or Hamming distance (d_H) and the minimum product distance (d_p^2) and minimize the path multiplicity (**Schlegel and Costello**, 1989). The roles of these designing parameters also vary depending on the level of SNR (**Ha and Rajatheva**, 1998). Given the same decoding complexity, a 64 states with code rate 2/3 8-PSK is utilized. The specification of the code is given in Table 3.1.

Table 3.1 Specification of Rate 2/3 8-PSK TCM Code Used for Comparison

Code Identification	$h^{(0)}$	$h^{(1)}$	$h^{(2)}$	Mapping	d_H	d_p^2
64 States	103	036	154	Natural	4	8

- In Table 3.1, the encoder polynomials $h^{(0)}$, $h^{(1)}$ and $h^{(2)}$ are in octal form. The mapping to 8-PSK signal constellation is natural mapping. The TCM encoder block diagram is given in Figure 3.3.

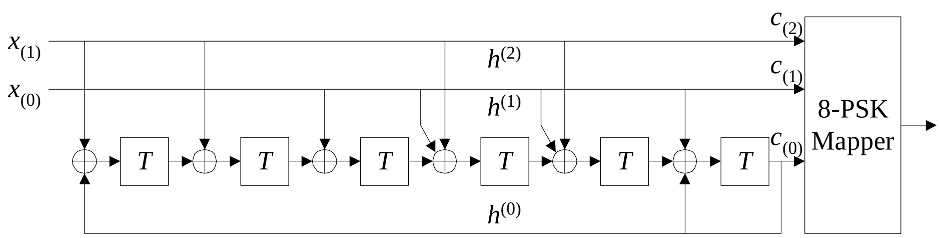

Figure 3.3 Feed Back Realization of 8-PSK, 64 States Trellis Code

Interleaver

- A rectangular-array symbol interleaver consisting of 8 rows and 16 columns is utilized. A128 symbols interleaver is shown in Figure 3.4.

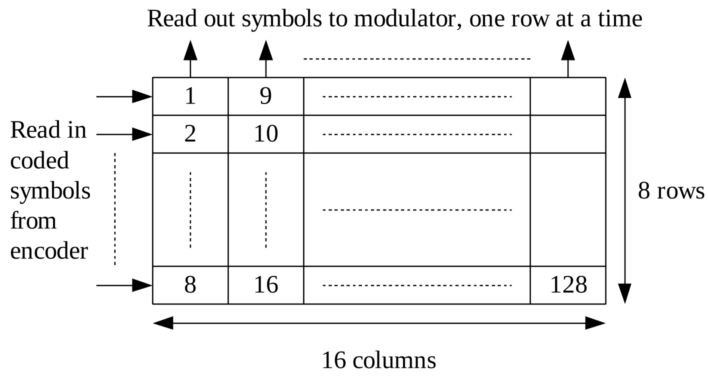

Figure 3.4 128 Arrays Symbol Interleaver

Tx MC-CDMA

- It is crucial for multicarrier CDMA to have frequency-flat fading in each subchannel. If the data rate is high enough to have frequency-selective fading, the system needs to use serial-to-parallel conversion before spreading. The number of subcarriers is equal to 128 to satisfy the data rate and required bandwidth. To determine the maximum number of user to 32, the processing gain for spreading codes is 32. Figure 3.5 shows the considered Tx MC-CDMA.

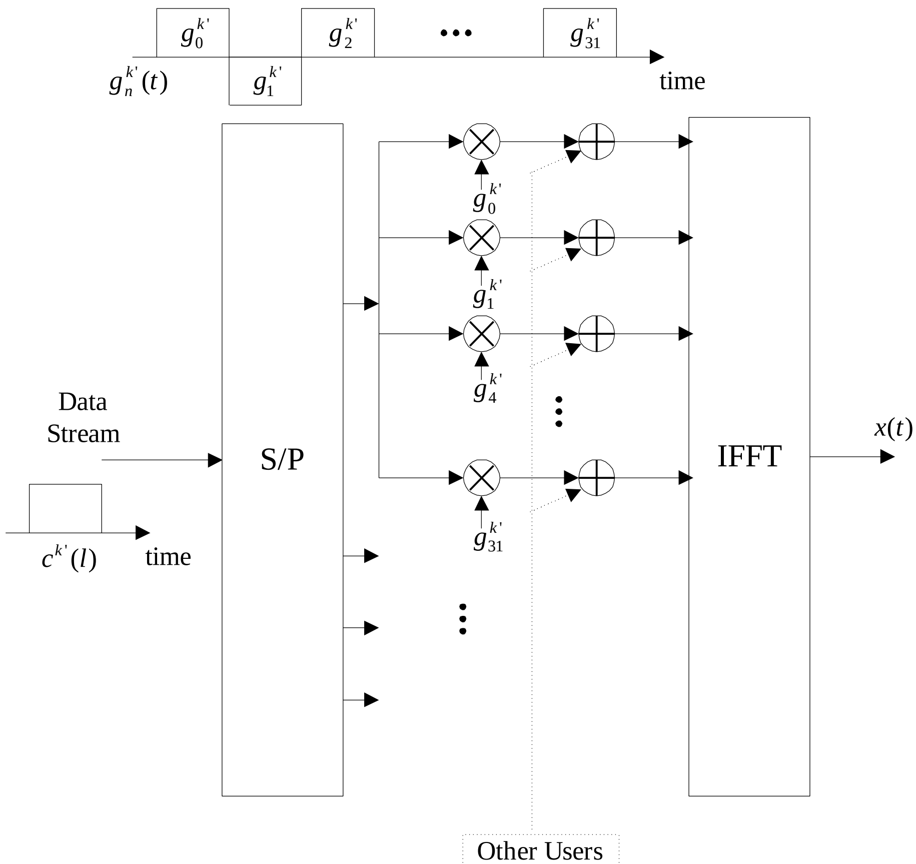

Figure 3.5 Tx MC-CDMA in the Simulation

Receiver Section

- At the receiver, the Rx MC-CDMA is employed to recover the information of the desired user by using FFT and multiply the receive signal with the specific spreading code. The deinterleaver is needed to rearrange the symbols into an appropriate way, which is the inverse version of the interleaver. The soft input Viterbi decoder is employed to reconstruct the transmitted signal from the noisy faded received signal.

Maximum Likelihood Decoder

- When the perfect channel estimation is assumed and only one receive antenna is used, the channel parameters H_n^i for i = 0, 2,..., 3 and n = 0, 2,..., 127 is available at the receiver. Then we can derive the maximum likelihood decoding rule for space-time code (**Naguib et al.**, 1998) as follows.

- Supposing that a code vector sequence given as

$$\boldsymbol{c}_t = c_t^1 c_t^2 \cdots c_t^N \quad , \boldsymbol{C} = \boldsymbol{c}_1 \boldsymbol{c}_2 \cdots \boldsymbol{c}_l \tag{3.1}$$

has been transmitted and a received vector sequence given as

$$\boldsymbol{r}_t = r_t \quad , \boldsymbol{r} = \boldsymbol{r}_1 \boldsymbol{r}_2 \cdots \boldsymbol{r}_l \tag{3.2}$$

has been received, where r_t is given in Equation (2.10). It is easily to see that $\boldsymbol{r}_t = \sqrt{E_s} \cdot H_t \cdot \boldsymbol{c}_t + \boldsymbol{n}_t$. At the receiver, the optimum decoding has designed to choose a decoded vector sequence

$$\boldsymbol{e}_t = e_t^1 e_t^2 \cdots e_t^N \quad , \boldsymbol{e} = \boldsymbol{e}_1 \boldsymbol{e}_2 \cdots \boldsymbol{e}_l \tag{3.3}$$

for which a posteriori probability is maximized. Assuming that all code words are equiprobable and noise vector is a multivariate additive white Gaussian noise, then the decoded vector can be written as

$$\boldsymbol{e} = \min \sum_{t=0}^{127} \left\| \boldsymbol{r}_t - \frac{1}{G_{MC}} \left[\sum_{i=0}^{3} e_t^i \left[\sum_{n=0}^{31} H_{n,t}^i \right] \right] \right\|^2 \tag{3.4}$$

- where $\|\cdot\|$ denotes the Euclidean norm. It is obvious that the optimum decoding rule in (3.4) can be implemented by using Viterbi algorithm, which is used to compute the path with the lowest metric, when the space-time code has a trellis representation.

- In the practical case, the receiver has to estimate the channel state information (CSI). The above equation will be changed due to CSI estimation error. Thereby the performance of STCM will be limited by property of CSI estimation.
- However (**Naguib et al.**, 1998), for the case of constant envelope signals such PSK, the decoding rule is still optimum even in the presence of channel estimation error. For QAM signals, the rule is still valid only if the system is assumed to use ideal CSI, or when the channel estimation error is negligible compared to the channel noise.

Multiuser Receiver

- The block diagram of multiuser receiver is shown in Figure 3.6. The first stage of the receiver is parallel interference canceller, which generates interference free statistics to estimate the transmitted bits for paticular user. The final stage is the conventional detector. Each of them is used for one user.

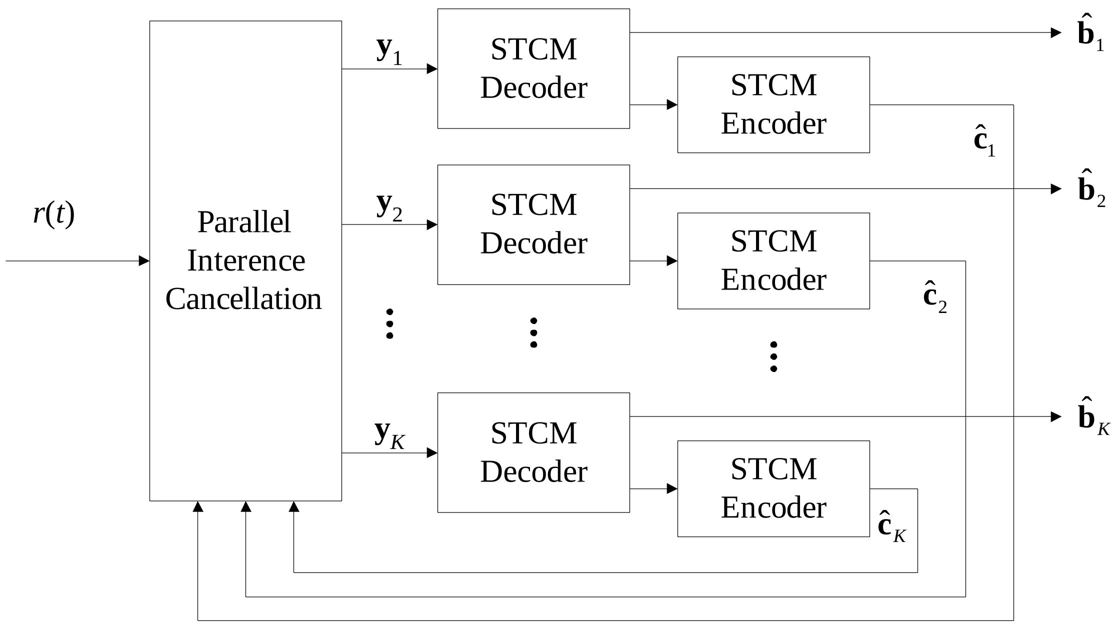

Figure 3.6 Block Diagram of PIC Multiuser Receiver

- Parallel processing of multiuser interference canceller removes the interference, being produced by the remaining users accessing the channel, from each user to estimate the interference free statistics of the transmitted bits for all users (**Nghia**, 1999). In the simulations, we focus on the last user without loss of generality. For multistage PIC taking channel fading into account, the MAI estimated at j^{th} stage can be expressed as

$$\hat{I}_1^{(j)} = \sum_{k=1}^{K-1} \sum_{i=1}^{L} H_k(l) g_k(t - lT_s) \sum_{i=0}^{3} \hat{c}_{i,k}^{(j-1)}(l) \tag{3.5}$$

where $\hat{c}_{i,k}^{(j)}(l)$ is the estimated of $c_{i,k}(l)$ of user k at l symbol interval at stage j.

- At the j stage, the estimated MAI is completely removed from the received signal. This process can be written as

$$r_{c1}^{(j)} = r(t) - \hat{I}_1^{(j)} \tag{3.6}$$

Channel Model

- The equivalent discrete-time channel model representing the overall transmission model in this thesis study is shown in Figure 3.7.

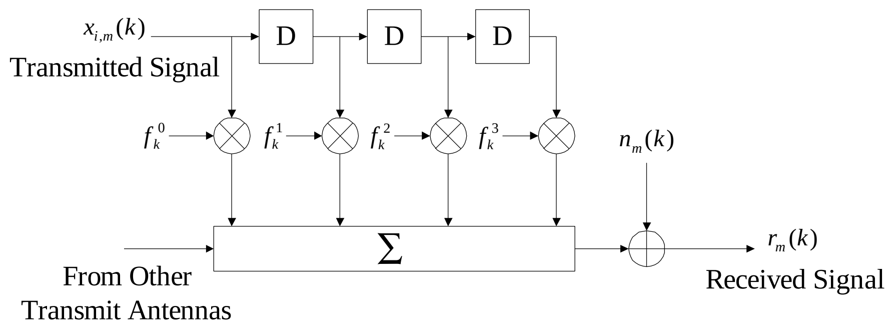

Figure 3.7 Tapped-Delay Line Channel Model under Consideration

To apply it in MC-CDMA system, the tap gain f_k^l of the channel from a transmit to a receive antenna can be expressed as

$$f_k^l = \lim_{N \to \infty} \frac{1}{\sqrt{N}} \sum_{n=1}^{N} \exp j\left(\theta_n + 2\pi f_{D_n} k T_s\right) \cdot \delta(l T_{samp} - \tau_n) \qquad (3.7)$$

- where the delays between taps are equal to sampling period (T_{samp}) with uniformly multipath intensity profile and T_s denotes the symbol period. From the central limit theorem, the magnitude and phase of the tap gain are Rayleigh and uniform distributed but the power spectrum density follows the classical Doppler spectrum.

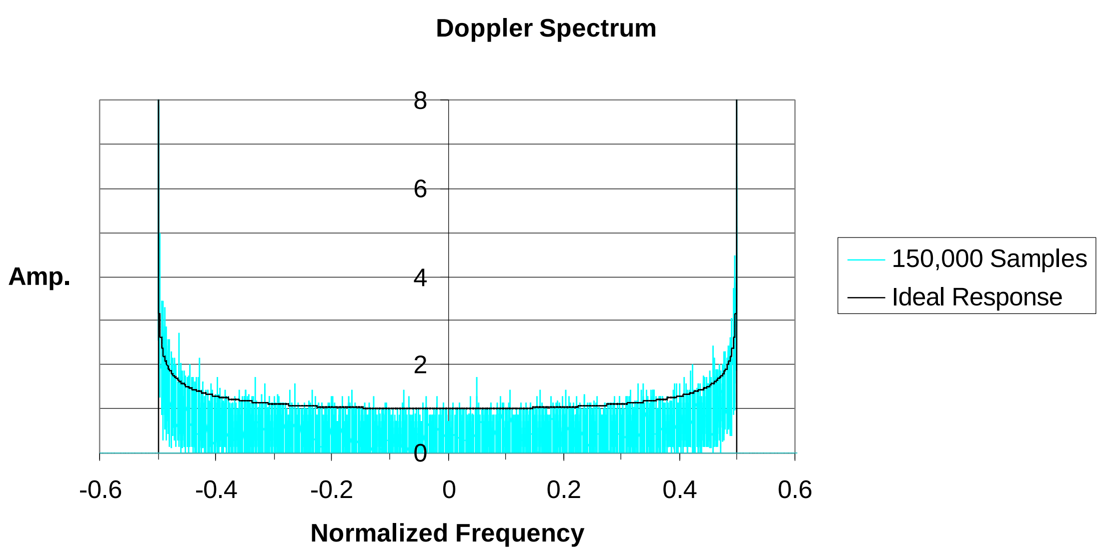

Figure 3.8 Frequency Response of the Tap Gain

- In this study, the multipath intensity profile is assumed to be uniform. The total average power of the channel is normalized to unity.

$$\sum_{n=0}^{L-1} 2s_n^2 = 1 \qquad (3.8)$$

where s_n is the standard deviation for both real and imaginary parts in each tap.

4. Simulation Results:

- This section presents the simulation results of the proposed system over slowly frequency-selective fading channel. By assuming a multipath channel model with a symbol spaced tapped-delay line for typical suburban environment, we can model the channel with 4 taps. Parameters and system configurations for the proposed system used in this thesis study are summarized below. In this thesis, the parameters are selected to be matched to the third generation standard.

Source Data Rate	72.56 kbit/s for STCM 74.3 kbit/s for Uncoded and TCM Case
Information Block Size	256 bits
Carrier Frequency	2 GHz
Required Bandwidth	1.258 MHz
Channel Coding Scheme	4-STCM and TCM Both 64 States
Modulation Scheme	QPSK for STCM and Uncoded 8 PSK for TCM
Number of Subcarriers	128
Spreading Codes	Walsh Hadamard Codes
Spreading Gain	32
MC-CDMA Symbol Duration	107.7 μs
Guard Interval	5.13 μs
Multipath Delay Spread	3 μs
Number of Paths	4
Power Delay Profile	Uniform Intensity Profile
Maximum Doppler Frequency (Corresponding Coherence Time)	2.6 Hz (20 Frames or 1.4 km./hr.) and 83.1 Hz (20 Symbols or 44.87 km./hr.)
Link Structure	Synchronous Downlink
Channel Model	Multipath Slow Fading
Decoding Scheme	Soft Input Viterbi
FER Simulation	Monte Carlo Method

- The simulation results are shown for FER comparison. The number of subcarriers is chosen to be 128 subcarriers to satisfy the required data rate and combat the multipath delay spread.

- In MC-CDMA system, the combining technique used in frequency domain for uncoded case and TCM is equal gain combining. Most of the results are simulated upto an FER of 0.01 giving satisfactory quality of service (QoS) in data transmission.

Figure 4.1 shows the FER performance of MC-CDMA over AWGN channel for 32 users.

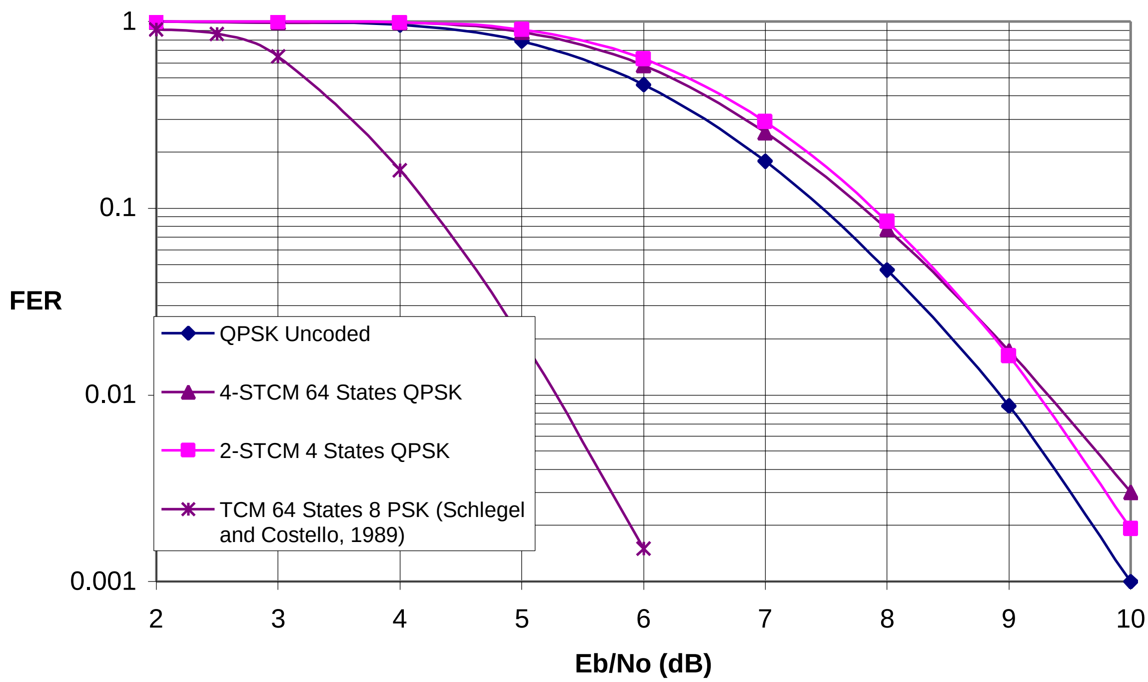

Figure 4.1 FER Comparison of Coded and Uncoded MC-CDMA 32 Users over AWGN Channel

- Both STCM coding schemes cannot achieve a gain over uncoded one and TCM (**Schlegel and Costello**, 1989) designed for fading channel achieves the best performance.(over AWGN channel) TCM can obtain a gain of around 3.5 dB SNR at FER of 0.01 beyond uncoded case and around 4 dB SNR at the same FER beyond both STCM codes. After 9 dB SNR, the performance of 2-STCM (2 antennas) is better than 4-STCM (4 antennas).

- Figure 4.2 shows the FER performance of coded and uncoded single user system perturbed by frequency-flat fading with the transmission rate is lower than coherence bandwidth of the channel.

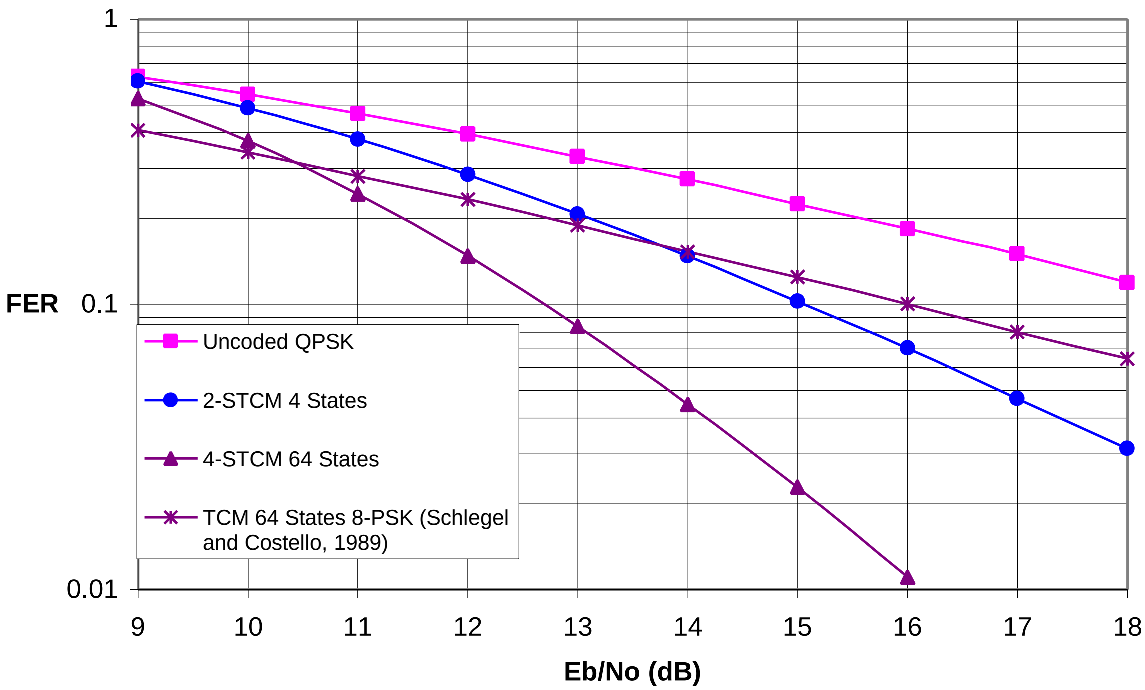

Figure 4.2 FER Comparison of Coded and Uncoded Single User over Slow Flat Fading with coherence time of 20 Frames

- Both STCM coding schemes achieve a gain over uncoded scheme and TCM code (**Schlegel and Costello**, 1989). With the same decoding complexity (**APPENDIX D**), 4-STCM can gain about 4 dB in SNR at FER of 0.07 compared to TCM. Moreover, 2-STCM (4 states) also has gain about 1.5 dB in SNR at 0.07 FER over TCM 64 states. When compare to the uncoded case, There is more than 2 dB gain in SNR at 0.1 FER for 2-STCM 4 states and 5 dB gain in SNR at 0.1 FER for 4-STCM (64 states). Therefore, if the application of interest is satisfied at 0.01 FER, we can expect more gain in STCM system over flat fading channel.

- Consequently, the performance of STCM code when no multiple access scheme is considered outperforms TCM code.

- Figure 4.3 shows the performance of MC-CDMA using 4-STCM (64 states) compared to uncoded case for different numbers of users over multipath channel with 20 frames coherence time.

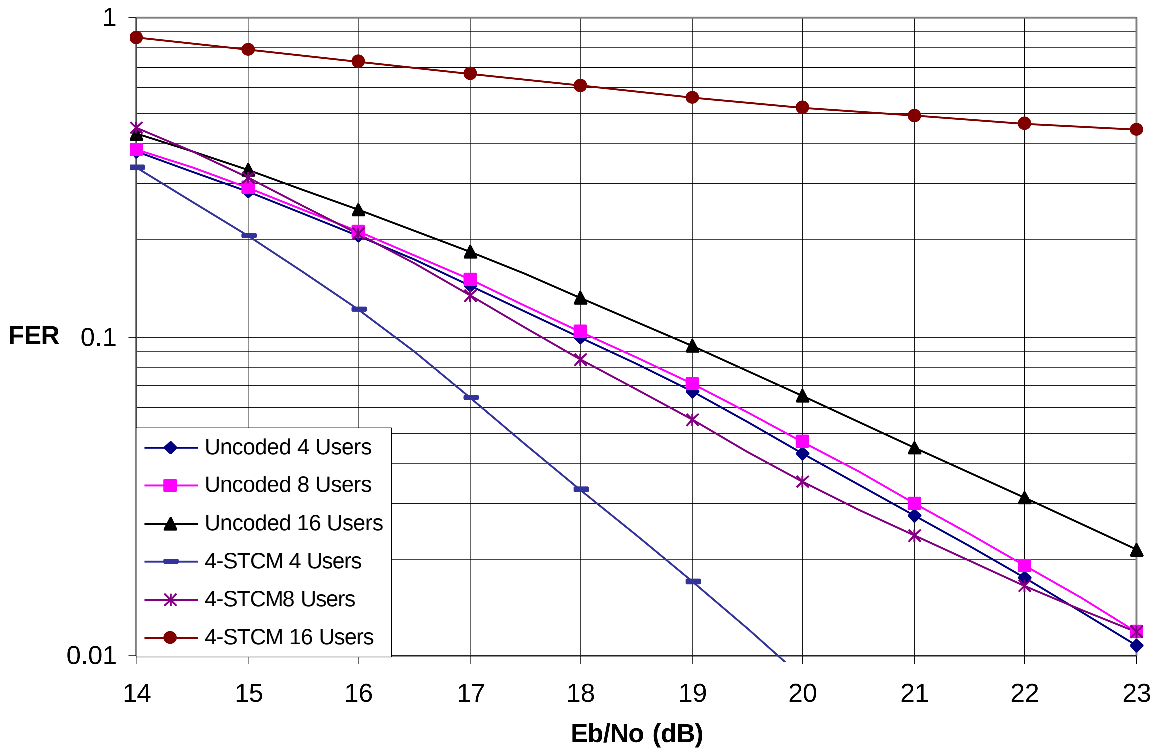

Figure 4.3 FER Comparison of 4-STCM and Uncoded MC-CDMA over Slowly Varying Frequency-Selective Fading channel with coherence time of 20 Frames

- There is about 3-dB gain for 4 users case but no gain in the case of 8 users or more. When the number of user is more than 8, it can be seen from the Figure 4.3 that the performance of STCM-MC-CDMA is much worse than the uncoded case with the corresponding number of users.

- MAI is a main problem in multiplexing system especially CDMA. We can say that due to the lack of combining techniques in the proposed system, MAI can destroy the proposed system performance.

- Figure 4.4 shows the performance of MC-CDMA using 4-STCM (64 states) compared to uncoded case for different numbers of users over multipath channel with 20 symbols coherence time.

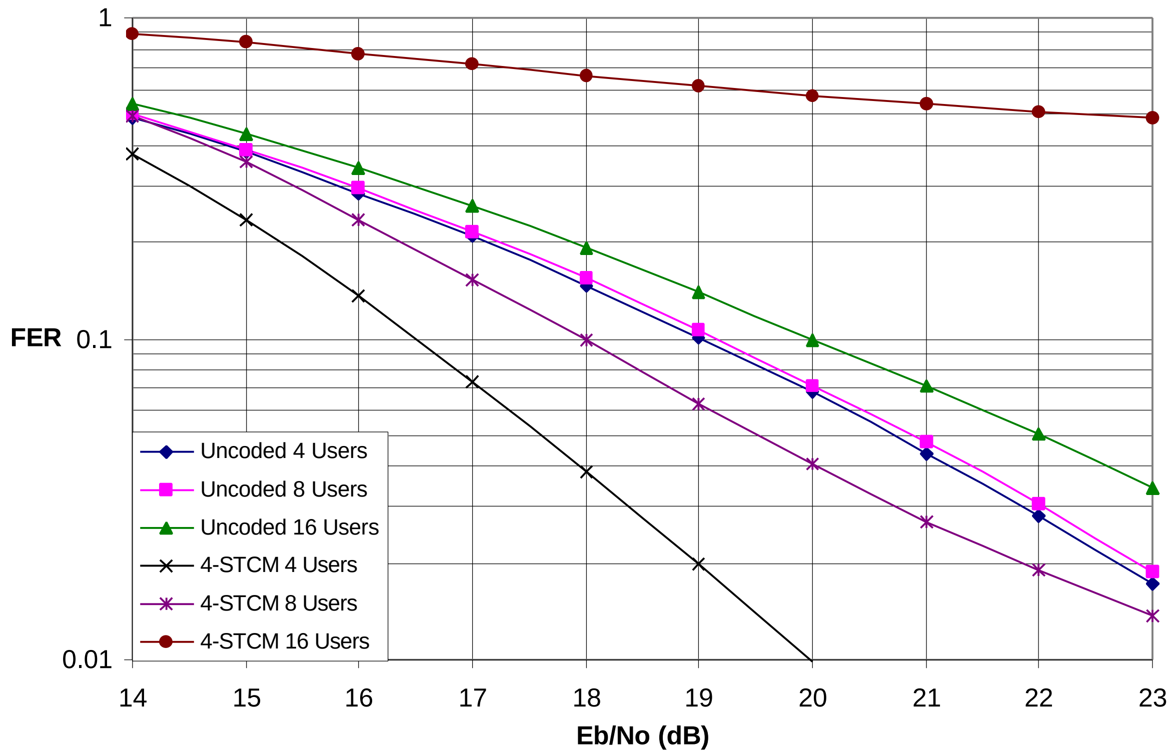

Figure 4.4 FER Comparison of 4-STCM and Uncoded MC-CDMA over Slowly Varying Frequency-Selective Fading channel with coherence time of 20 Symbols

- When considering a larger Doppler shift of 83.1 Hz, Figure 4.4 shows that STCM-MC-CDMA system is less sensitive than the uncoded case for all number of users. The performance still confirms the trends in Figure 4.3. For 0.01 FER, there is more than 3 dB gian in SNR of 4-STCM for 4 users.

- At the same SNR level, the performance of 8 users will be worse than uncoded case due to the floor as shown in Figures 4.3 and 4.4. It is clear that the performance of STCM-MC-CDMA with the lack of using combining techniques can be severely destroyed due to MAI. However, in some applications the weight, power and delay are negligible, the performance can be improved by using multiuser detection.

- As the channel fading becomes faster, the performances of STCM-MC-with different number of users give less degradation than the performance of the uncoded cases.

- Figure 4.5 shows the performance of MC-CDMA using multiuser detection called parallel interference cancellation (PIC) for 16 users compared to single user QPSK.

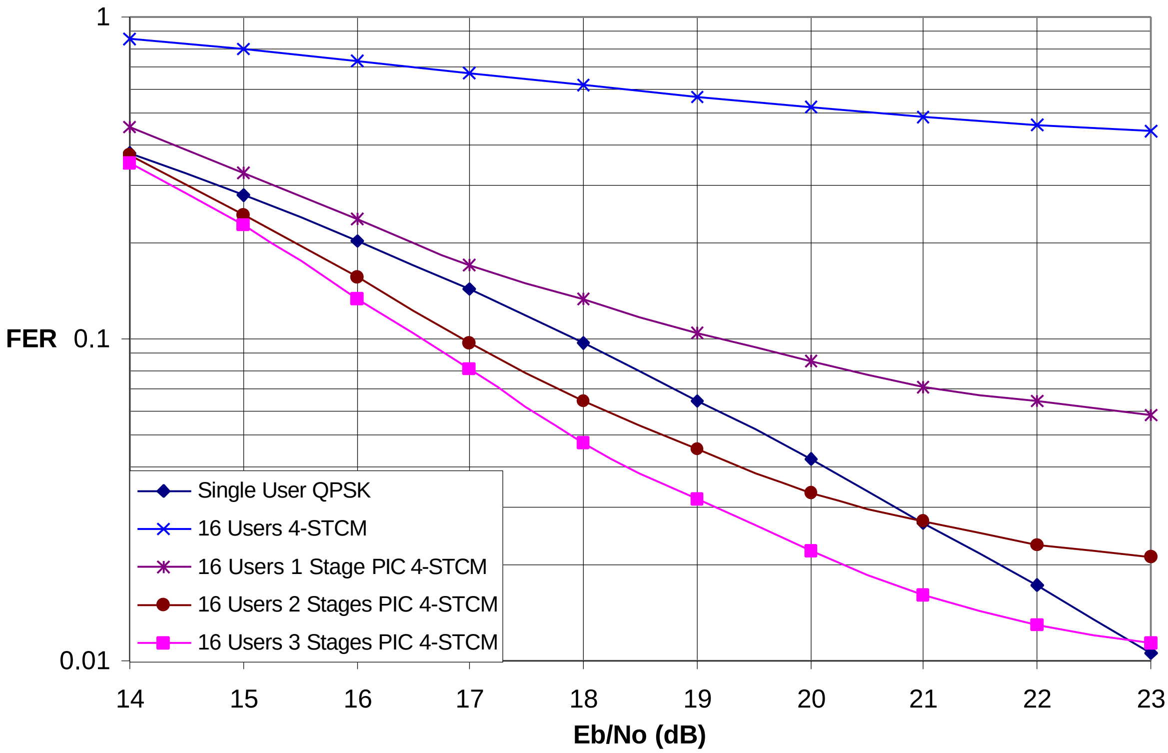

Figure 4.5 FER Comparison of STCM-MC-CDMA Using PIC over Frequency-Selective **Fading Channel with coherence time of 20 Frames**

- It can easily be seen that using only one stage PIC can improve the system performance. More than 10 dB SNR can be obtained around 0.32 FER comparing PIC 1 stage with no PIC. When more stages of PIC sheme are applied, the performance does not linearly improve.

- Due to the error floor the performance of 3 stages PIC will be worse than uncoded case eventually.

- Figure 4.6 shows the performance of MC-CDMA using multiuser detection for faster fading than in Figure 4.5.

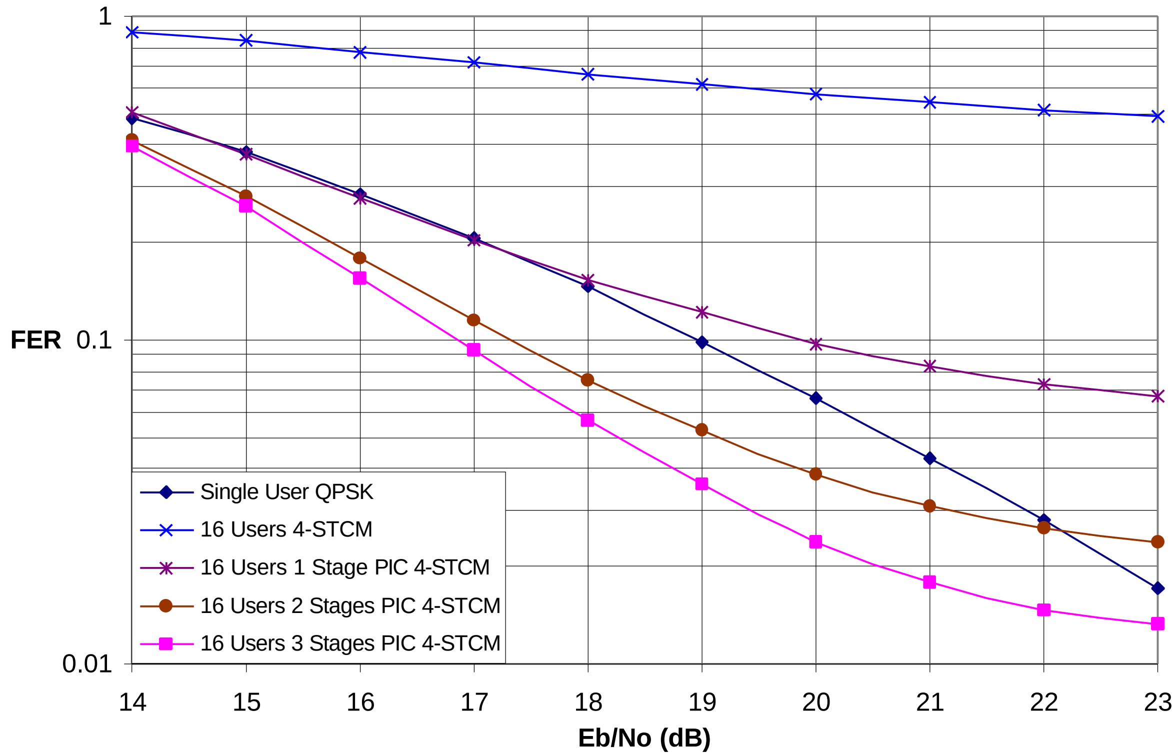

Figure 4.6 FER Comparison of STCM-MC-CDMA Using PIC over Frequency-Selective **Fading Channel with coherence time of 20 Symbols**

- The performance of the proposed system does not much depend on the receiver-movement speed but for uncoded case the performance of the system strongly depends on the receiver movement. However, it is clear that still at very high SNR, the performance of STCM-MC-CDMA with PIC for 16 users is not better than uncoded case for a single user.

- Figure 4.7 shows the performance of the proposed system when PIC is employed for 4, 8 and 16 users over slow frequency-selective fading channel.

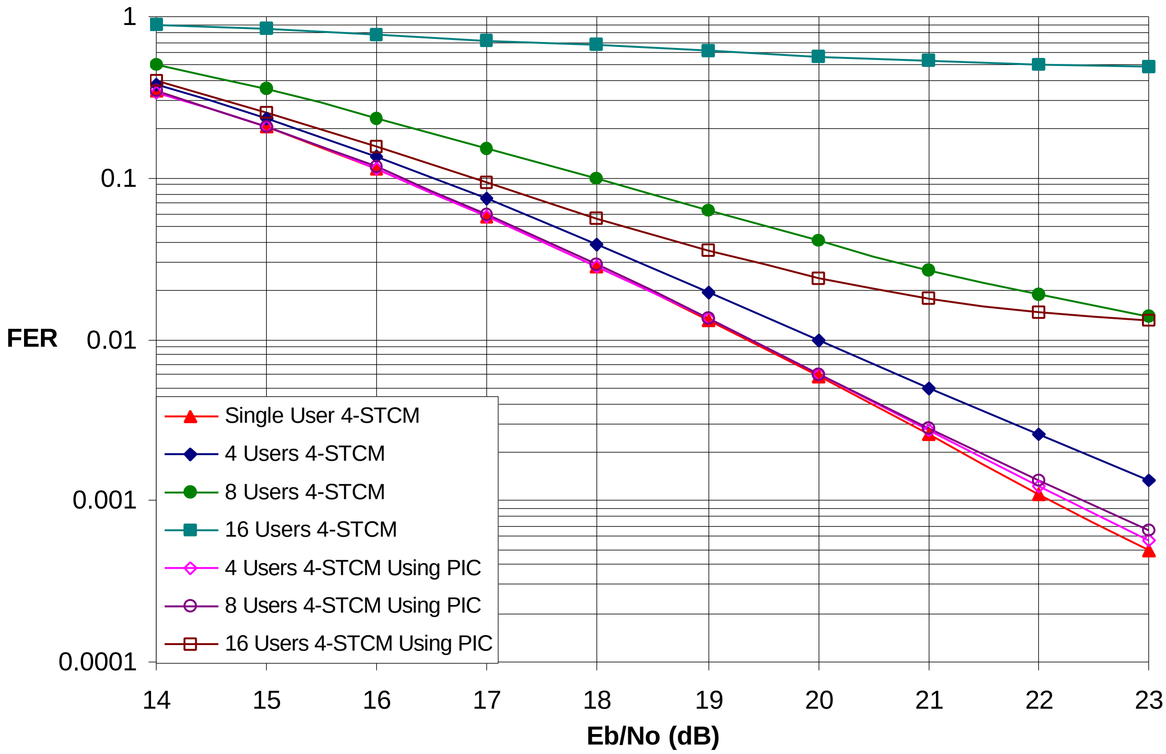

Figure 4.7 FER Performance Comparison of MC-CDMA Using 4-STCM with and without PIC over Multipath Fading Channel with coherence time of 20 Symbols

- The performance of 4 and 8 users can be improved closely to single user case. For 4 users, use of PIC can obtain 1 dB gain at 0.0013 FER compared to no PIC. For 8 users, use of PIC can reach 4 dB gain at 0.013 FER compared to no PIC. For 16 users, a significant gain can be achieved compared to no PIC. However, there is obviously a floor in 16 users curve while there is no floor in others cases.

- As the performance of the proposed system over the longer coherence time is always better than the shorter one, we do not include the simulation result with the same parameters over the longer coherence time channel.

- Figure 4.8 shows the performance comparison of sensitivity of the proposed system and MC-CDMA using TCM over multipath channel with both 20 symbols (Fast in the Figure 4.8) and 20 frames (Slow in the Figure 4.8) coherence time.

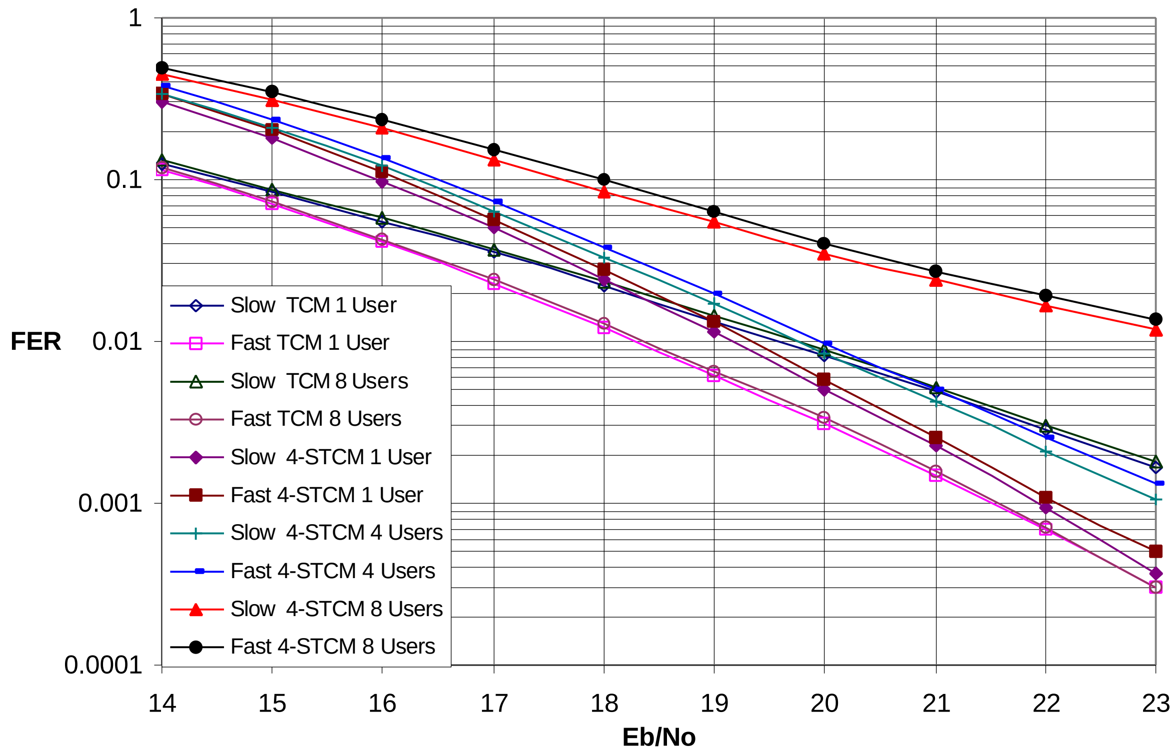

Figure 4.8 FER-Performance Sensitivity Comparison of Number of Users of MC-CDMA Using 4-STCM and TCM over Multipath Fading Channel with Different Values of coherence time

- For TCM (**Schlegel and Costello**, 1989), the performance is less sensitive to the number of users but more sensitive to the receiver movement. There is more than 2 dB degradation in SNR at 0.002 FER when compared the movements of the receiver but there is only a little bit degradation of FER performance with 8 users compared to single user are in the system.

- For 4-STCM, the performance is more sensitive to the number of users as no combining technique can be used but less sensitive to the receiver movement. There is no more than 0.5 dB degradation in SNR for all cases of FER when compared the movements of the receiver. However, there is about 4 dB degradation in FER performance when there are 8 users in the system compared to single user case.

Conclusions

- The FER performance of the proposed system is much dependent on the multiple access scheme due to the need of a combining technique. As no combining scheme can be used, the performance of the system is severely degraded even only one active user is in the system and much more weak due to MAI whenever more than four active users are in the system. This is confirmed from the FER comparison in the single user cases with and without MC-CDMA.

- There is no gain when using STCM compared to uncoded case over AWGN channel. Eventually, the performance of 2-STCM is also better than 4-STCM. As STCM holding the concept of diversity has designed for fading channel, TCM in the simulation shows the best performance over AWGN channel.

- When considering the receiver movement, the performance of the proposed system for all cases of number of users are not much different compared to TCM and uncoded cases. In STCM, the performance for all numbers of users degrades when the receiver moves faster. These trends are the same as in uncoded cases. The performance for all uncoded cases are weaker than STCM when the receiver moves faster. Surprisingly, when using TCM as an encoder, the performances are different when the receiver moves faster. TCM shows a better performance for less coherence time.

- If delay, weight and power consumption are negligible at the receiver, multiuser detection or interference cancellation can be introduced. Based on the simulation results, multiuser detection can significantly improve the performance of the proposed system. Considring 16 active users, a gain of more than 10 dB SNR at 0.5 FER can be achieved when comparing MC-CDMA using 1 stage PIC 4-STCM with MC-CDMA no PIC 4-STCM.

- In a real environment, the proposed system with increased the processing gain and multiuser detection can be considered as a possible scheme for data transmission due to the robustness over various Doppler shifts in practical channels of interest.

APPENDIX D

CONSTRUCTION OF SPACE-TIME CODED MODULATION

To achieve the Gaussian capacity when considering outage capacity, we have chosen a code similar to delay diversity codes corresponding to 4 transmit antennas. The output signal $x_1^k x_2^k x_3^k x_4^k$ at time k is given by

$$\begin{aligned}(x_1^k, x_2^k, x_3^k, x_4^k) = & \, b_{k-3}(0,0,0,3) + a_{k-3}(0,0,0,1) \\ & + b_{k-2}(0,0,2,0) + a_{k-2}(0,0,3,0) \\ & + b_{k-1}(0,1,0,0) + a_{k-1}(0,2,0,0) \\ & + b_k(2,0,0,0) + a_k(1,0,0,0)\end{aligned} \tag{D.1}$$

In a single user system, 4 space-time code using 4 transmit antennas and QPSK modulation achieves spectral efficiency of 2 b/s/Hz. The trellis complexity is then at least 64 (**Tarokh et al.**, 1997).

$$\mathbf{B}(\bar{c},\bar{e}) = \begin{bmatrix} e_1^1 - c_1^1 & e_2^1 - c_2^1 & \cdots & e_l^1 - c_l^1 \\ e_1^2 - c_1^2 & e_2^2 - c_2^2 & \cdots & e_l^2 - c_l^2 \\ e_1^3 - c_1^3 & e_2^3 - c_2^3 & \cdots & e_l^3 - c_l^3 \\ e_1^4 - c_1^4 & e_2^4 - c_2^4 & \cdots & e_l^4 - c_l^4 \end{bmatrix} \tag{D.2}$$

Rank Criterion:

For diversity advantage of 4, the matrix $\mathbf{B}(\bar{c},\bar{e})$ must have rank 4. Hence, the associated paths of the codewords $\bar{c}$ and $\bar{e}$ in the trellis that diverges at time t_1 and remerges at a later time $t_2 \leq l$ have to be linearly independent at time t_1, t_1+1, t_2-1 and t_2.

From the trellis diagram, it can be claimed that $e_{t_1}^4 - c_{t_1}^4$, $e_{t_1+1}^3 - c_{t_1+1}^3$, $e_{t_2-1}^2 - c_{t_2-1}^2$ and $e_{t_2}^1 - c_{t_2}^1$ can likely be any elements of the ring of integer modulo 4 except 0. $e_{t_1+1}^4 - c_{t_1+1}^4$ and $e_{t_2-1}^1 - c_{t_2-1}^1$ can possibly be any elements of the ring of integer modulo 4. All others are normally equal to 0. Therefore, the matrix $\mathbf{B}(\bar{c},\bar{e})$ can be expressed as

$$\mathbf{B}(\bar{c},\bar{e}) = \begin{bmatrix} 0 & 0 & 0\cdots3 & 1\cdots3 \\ 0 & 0 & 1\cdots3 & 0 \\ 0 & 1\cdots3 & 0 & 0 \\ 1\cdots3 & 0\cdots3 & 0 & 0 \end{bmatrix} \tag{D.3}$$

Hence, it can be seen that the t_1^{th}, t_1+1^{th}, t_2-1^{th} and t_2^{th} columns of $\mathbf{B}(\bar{c},\bar{e})$ are independent. Consequently, the diversity advantage of 4 is achieved.

Determinant Criterion:

For coding advantage, we need to find codewords $\bar{c}$ and $\bar{e}$ such that

$$\det\left[\sum_{k=1}^{l}(e_k^1-c_k^1,e_k^2-c_k^2,e_k^3-c_k^3,e_k^4-c_k^4)^*(e_k^1-c_k^1,e_k^2-c_k^2,e_k^3-c_k^3,e_k^4-c_k^4)\right] \qquad \text{(D.4)}$$

is minimized.

Referring that the codes are QPSK, then the codes is geometrically uniform. We can assume that $\bar{c}$ is all zero codewords. We can place the edge label (x_1, x_2, x_3 and x_4) by complex forms into equation above and replace each element to be

$$\begin{bmatrix} a_k & m_k & n_k & o_k \\ m_k^* & b_k & p_k & q_k \\ n_k^* & p_k^* & c_k & s_k \\ o_k^* & q_k^* & s_k^* & d_k \end{bmatrix} \qquad \text{(D.5)}$$

At time t_1, t_1+1, t_2-1 and t_2, the matrices are respectively contributed as follows

$$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & d_0 \end{bmatrix}, \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & c_0 & s_0 \\ 0 & 0 & s_0^* & d_0 \end{bmatrix}, \begin{bmatrix} a_0 & m_0 & 0 & 0 \\ m_0^* & b_0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \begin{bmatrix} a_0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad \text{(D.6)}$$

Finally, the determinant can be written as

$$\det\left[\begin{bmatrix} a_0 & 0 & 0 & 0 \\ 0 & b_0 & 0 & 0 \\ 0 & 0 & c_0 & 0 \\ 0 & 0 & 0 & d_0 \end{bmatrix} + \sum_{k=1}^{3}\begin{bmatrix} a_k & m_k & n_k & o_k \\ m_k^* & b_k & p_k & q_k \\ n_k^* & p_k^* & c_k & s_k \\ o_k^* & q_k^* & s_k^* & d_k \end{bmatrix}\right] \qquad \text{(D.7)}$$

where $a_0 = b_0 = c_0 = d_0 = 2$

a_k, b_k, c_k and $d_k \geq 0$, $m_k \cdot p_k \cdot s_k \cdot o_k^* \geq 0$

$n_k \cdot q_k \cdot n_k^* \cdot q_k^* \geq 0$, $m_k^* \cdot p_k^* \cdot s_k^* \cdot o_k \geq 0$

$o_k^* \cdot o_k \cdot p_k^* \cdot p_k \leq a_k \cdot b_k \cdot c_k \cdot d_k$, $q_k^* \cdot c_k \cdot q_k \cdot a_k \leq m_k \cdot p_k \cdot s_k \cdot o_k^*$

$s_k^* \cdot s_k \cdot m_k^* \cdot m_k \leq n_k \cdot q_k \cdot n_k^* \cdot q_k^*$, $n_k^* \cdot b_k \cdot n_k \cdot d_k \leq m_k^* \cdot p_k^* \cdot s_k^* \cdot o_k$.

Consequently, the minimum determinant of these codes is 16.

Figure D.1 shows trellis diagram used to describe diversity and coding advantages of the 4-STCM codes.

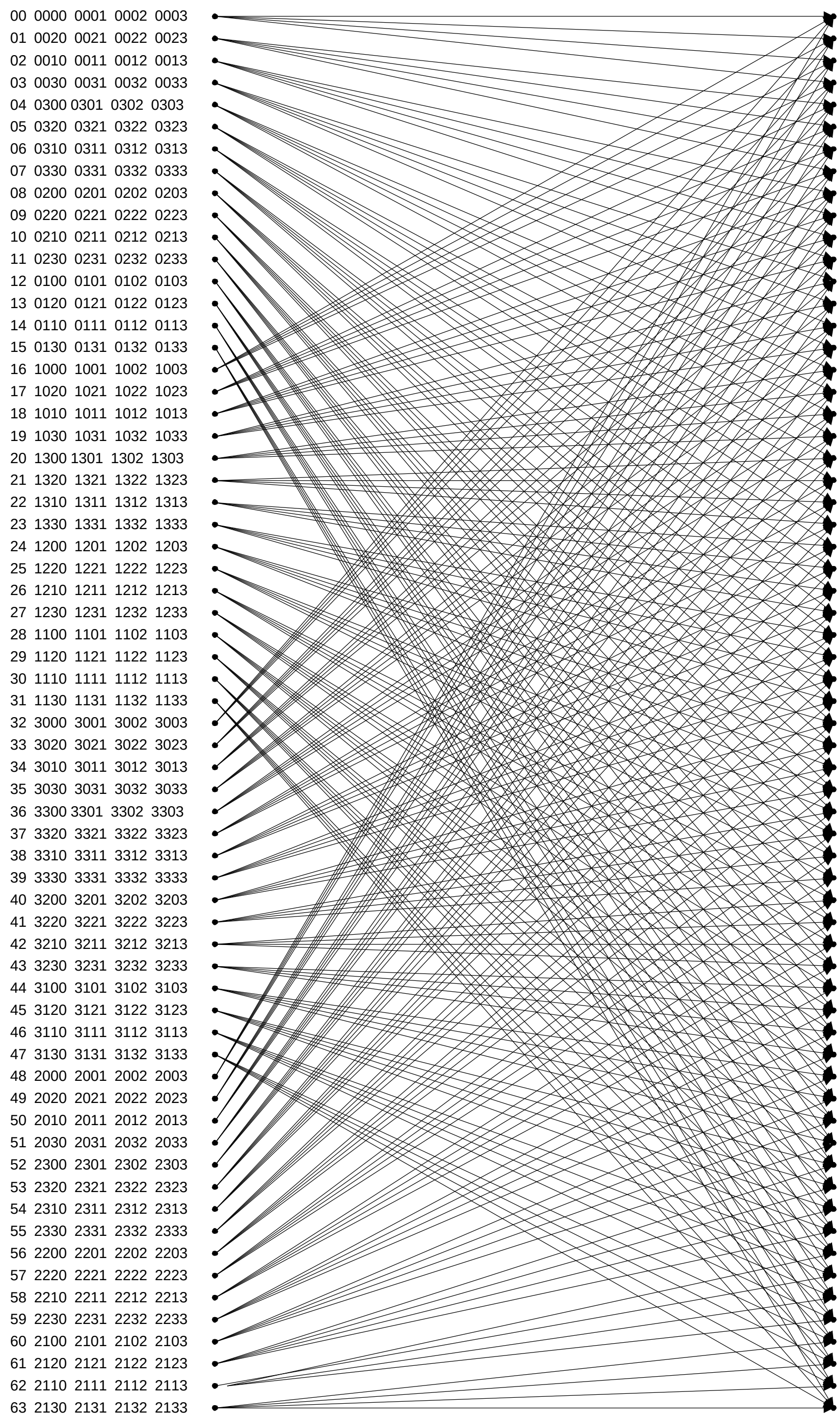

Figure D.1 Trellis Diagram of 4-STCM Code

Figure D.2 shows trellis diagram used to describe complexity of the 8-PSK TCM code with rate of 2/3.

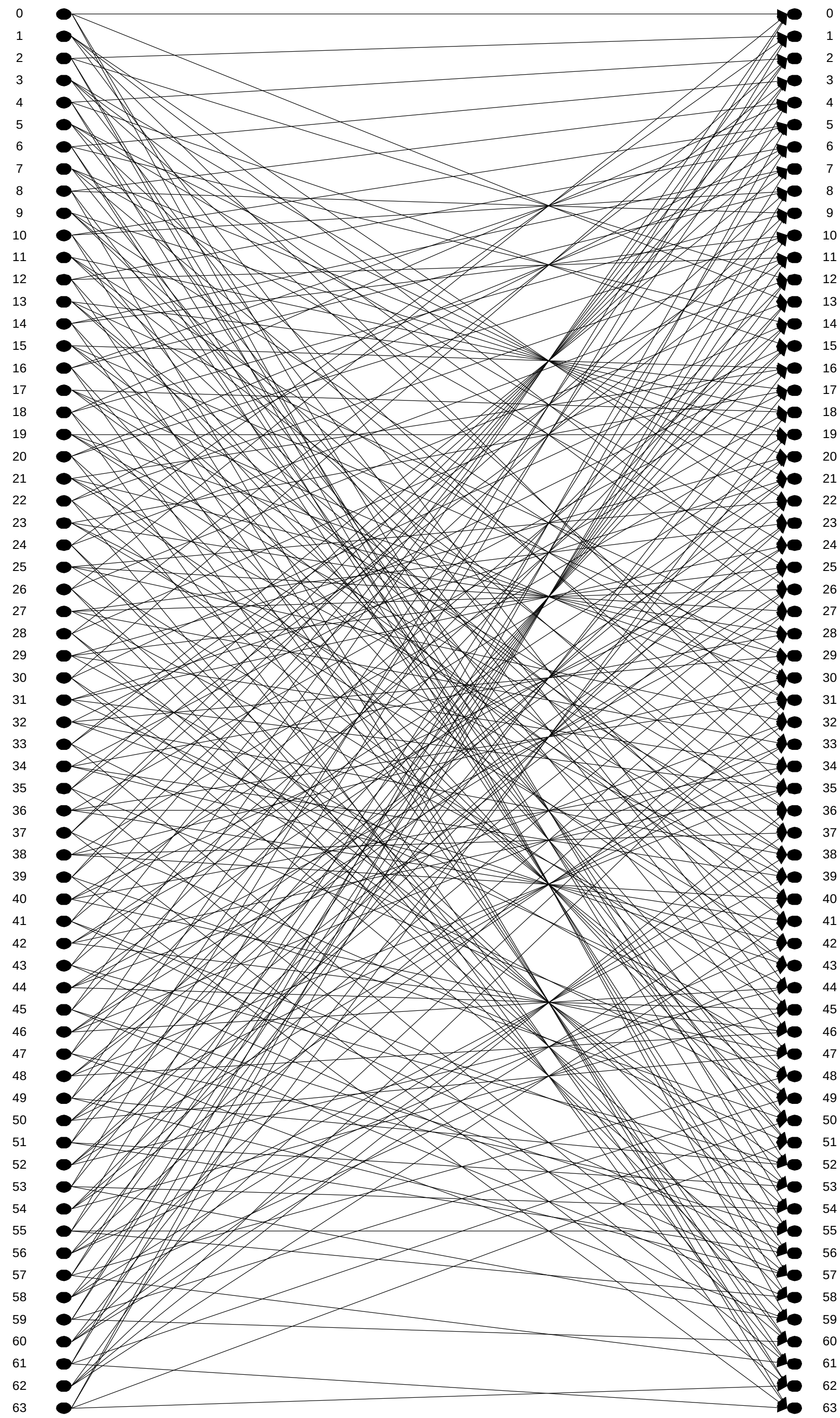

Figure D.2 Trellis Diagram of 8-PSK TCM with rate 2/3