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**Diversity Combining for M-ary
Fast Frequency Hopping
in a Multiple-Access
AWGN and Rayleigh Fading Channel**

by

Donna Spilchen, BEng

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Engineering

Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
Department of Systems and Computer Engineering
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Diversity Combining for M-ary
Fast Frequency Hopping
in a Multiple-Access
AWGN and Rayleigh Fading Channel

submitted by Donna Spilchen, BEng
in partial fulfilment of the requirements for
the degree of Master of Engineering

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Abstract

Several diversity combining techniques are evaluated for a Fast Frequency Hopping (FFH) Spread Spectrum communication system. The bandwidth and hop rate are fixed; as a result the diversity, L , the number of available frequencies, Q , and the number of bits per symbol are dependent and optimum values, must be determined. The modulation is M -ary Frequency Shift Keying with non-coherent detection at the receiver. A single cell multiple-user interference model is simulated with thermal noise and Rayleigh fading.

The performance of the Hard Decision Majority Vote, Reduced Rank Sum, Linear, Order Statistics-Normalized Envelope Detection (OS-NED) and Normalized Envelope Detection diversity combining techniques are presented for various values of M and L . OS-NED is shown to be superior and its spectral efficiency is presented.

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List of Symbols and Abbreviations

A_{ui}	users random address for each hop (i)
α	linear combining parameter
α_n	attenuation of the n^{th} received signal
AWGN	Additive White Gaussian Noise
b	values of interference tones (1,... B_I)
β	normalized threshold
BER	Bit Error Rate
B_I	number of Interference tones in the desired time-frequency slot
B_{coh}	Coherent Bandwidth
B_d	Doppler spread
β_o	non-normalized threshold
CDMA	Code Division Multiple Access
dB	decibels
DS	Direct sequence
E_b	Energy per bit
E_c	Energy per hop/chip
E_i	Energy sum over m bins for each hop
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
FFH	Fast Frequency Hopping
FSK	Frequency Shift Keying
f_m	FSK symbol frequency
f_{ui}	user frequency for each hop

f_q	transmitted narrowband frequency
HDMV	Hard Decision Majority Vote
i	values of diversity $(1, \dots, L)$
J_{mi}	Intermediate value used during combining
kb/s	kilo bits per second
k	number of bits in a symbol ($k = \log_2 M$)
L	diversity level
L_{opt}	optimum diversity
λ	center frequency wavelength
m	values of symbol alphabet $(1, \dots, M)$
M	size of symbol alphabet ($M = 2^k = M\text{-ary}$)
MFSK	M-ary FSK
N_0	Gaussian single-sided noise power spectral density
η	spectral efficiency
NED	Normalized Envelope Detection
OS-NED	Order Statistics-NED
P_b	Probability of bit error
P_d	Probability of detection
P_f	Probability of false alarm
P_s	Probability of symbol error
PN	pseudo-noise
Q	number of available channels
$r(t)$	received signal and noise
R_b	bit rate
R_c	chip rate
R_s	symbol rate
R_{mi}	Ranking of the m^{th} symbol for the i^{th} hop

RRS	Reduced Rank Sum
$s(t)$	transmitted signal
SNR	Signal to Noise Ratio
σ_n^2	noise variance
T_b	bit duration
T_c	chip duration
T_{coh}	coherence time
T_m	time delay
T_s	symbol duration
th	threshold
TDMA	Time Division Multiple Access
τ_n	n^{th} path multi path delay
$\phi_{ui}, \theta_1, \theta_b$	random phase angles
u	number of users
U_{max}	maximum number of users allowed
v	vehicle velocity
$\hat{v}$	received symbol decision
W_t	transmission bandwidth
W_t/R_b	bandwidth expansion factor
$x(t)$	time-varying channel impulse response
X_u	symbol address
Y_{mi}	squared output of the m^{th} matched filter for the i^{th} hop
Y_{mi}	magnitude of the m^{th} matched filter output for the i^{th} hop
$Y_{u,i}$	transmission address for user u and chip i
z_m	m^{th} output from the detection device

Section I

1. Introduction

It is estimated that by the year 2002, the United States mobile industry will grow in value to approximately 4 billion dollars [1]. In terms of numbers of subscribers this is a growth of from 4.5 million subscribers in 1991 to more than 15 million in 1994 [2], [3]. In order to keep up with this growth, increased spectral efficiency is paramount. The most spectrally efficient use of the mobile bandwidth follows a cellular concept where service areas are broken into equal geometric cells, with no overlaps or gaps, each containing a central base station [4]. Consequently, the number of users per cell has become the important measure of spectral efficiency.

Various cellular communication systems have been implemented around the globe, however no standard has yet been established to enable inter-operability. A standard

could be established considering one of the many existing multiple access techniques such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), ALOHA, and Code Division Multiple Access (CDMA). Dennis Foster, president of Sprint Cellular feels strongly about the technology that will be embraced with standardization. "I have no idea which technology it will be. I suggest that it hasn't been invented or even dreamed of yet" [5].

A regulation change that allowed the unlicensed use of Direct Sequence (DS) or Frequency Hopping (FH) spread spectrum in the bands of 902-928 MHz, 2.4-2.4835 GHz, and 5.725-5.880 GHz was made in 1985 by the Federal Communications Commission in the United States. The Canadian Department of Communications quickly followed suit and passed a similar regulation [6]. As a result, spread spectrum technologies have enjoyed a great deal of attention in the mobile radio communications area. Some of the spread spectrum advantages are:

Although a system may be designed for a maximum allowable number of users this number may be exceeded. The users will then appear as noise to each other. This increased noise level at the receiver will result in the graceful degradation of performance for all active users [7], [8].

Guard channels which are required by FDMA to avoid spectral overlap and doppler shifts are avoided [9].

The TDMA requirement to have accurate timing so that users do not overlap each other's slots is not necessary [10].

In spread spectrum systems, narrowband signals are transmitted over a large bandwidth. Each user is allowed to use the entire bandwidth for the duration of the call. There are two common types of spread spectrum employed for multiple access applications, namely DS/CDMA and FH/CDMA.

DS/CDMA is implemented with pseudorandom or pseudonoise (PN) carriers where each user has a unique PN spreading code. The modulation is typically Phase Shift Keying. At the transmitter, the modulated signal is multiplied by the spreading code resulting in wideband signal transmission. At the receiver the transmitted signal is de-spread with the same PN sequence and coherently de-modulated. The signals arriving from the other users are not multiplied by their spreading codes, therefore they continue to be wideband signals. As a result, the channel contains noise consisting of the receiver noise and the signals from the other users.

FH/CDMA is implemented with frequency hopped carriers and the modulation is typically Frequency Shift Keying (FSK). The FSK symbol is changed or frequency hopped according to a frequency synthesizer which is driven by a PN sequence. The rate of the frequency synthesizer compared with the symbol duration determines the type of frequency hopping employed. When more than one symbol is transmitted per hop it is considered slow frequency hopping. However, when each symbol is transmitted on one or more hops, it is considered Fast Frequency Hopping (FFH). At the receiver the signal is de-hopped with the same PN sequence and the resultant signal is non-coherently demodulated. Therefore, this modulation is immune to the random phase shift (Doppler frequency shift) caused by the land mobile channel.

FFH/CDMA has not enjoyed the same attention as DS/CDMA for the land mobile application. The inherent diversity which results with FFH, when each symbol is transmitted on several hops, can be exploited through diversity combining at the receiver. It has been demonstrated that optimizing the diversity combining technique can improve FFH/CDMA communication system performance in Rayleigh fading channels [11], [12], [13], [14]. Consequently, when the receiver employs efficient diversity combining, the effects of Rayleigh fading channel is reduced and the ability to accommodate multiple-users is enhanced [9].

The FFH/CDMA multiple-user interference is assumed to be non-Gaussian, consequently, the optimum combining technique is in general non-linear [15]. Typically, Hard Decision Majority Vote (HDMV) combining has been analyzed for FFH/CDMA [10], [13], [16], [17]. However, it was shown in [18], [19] that Reduced Rank Sum (RRS) combining is an alternative to HDMV combining and that it is more robust in a multiple-cell environment. Typically, system performance in a Rayleigh fading environment is lower than in a Gaussian noise environment. However, Gulliver, Ezers, Felstead and Wight [20] have shown that new techniques such as Normalized Envelope Detection (NED) and Order Statistics - NED (OS-NED) can greatly reduce the negative effects of Rayleigh fading in a single user environment.

Considering the aforementioned research, this thesis compares the performance of the linear, RRS, HDMV, NED and OS-NED diversity combining methods. The comparison is carried out for a wide range of system parameters in a fixed bandwidth channel. Both the AWGN and Rayleigh fading channels are considered. It will be shown that OS-NED diversity combining developed by Gulliver [21], performs better in the single cell multiple user environment. Also, the spectral efficiency of the OS-NED combining technique is determined. The following paragraphs describe the FFH/CDMA system requirements for this thesis including: the type of addressing considered, receiver synchronization

requirements and the measure of spectral efficiency.

In a FFH/CDMA communication system, users share the same bandwidth and are assigned specific frequency hopping patterns as their address. These hopping patterns allow the users to be identified at the receiver. Increasing the number of users in a limited bandwidth requires an increase in the number of addresses for transmission. Although more efficient addressing schemes exist, [16], [22], [23], [24], random addressing (which can be considered worst case addressing) has been used extensively to select the number, M -ary, of FSK signal tones, denoted by MFSK, and the diversity, denoted by L , in order to optimize FFH/CDMA systems [10], [15], [17], [25], [26]. In this thesis random addressing is assumed.

Addressing has been considered for two types of FFH/CDMA systems: synchronous and non-synchronous. For the synchronous case, all user signals are aligned in time. Consequently two or more users would have to hop into the same time-frequency slot in order to interfere with each other. The non-synchronous case can result in interference from two users hopping into time-frequency slots which overlap in time. In this thesis, all users are assumed to be synchronous at the receiver.

The performance of a FFH/CDMA system is generally measured by capacity or spectral efficiency. The capacity is determined by the maximum number of users which can be supported given a fixed probability of bit error (P_b) or Bit Error Rate (BER). Alternatively, performance can be measured by the minimum BER that can be achieved given a fixed number of users. Fiebig has shown [17] that in a noisy FFH/CDMA system, the spectral efficiency is dictated by the basic system parameters. When the bandwidth is limited, the number of bits/symbol (M) and the diversity (L) must be optimized to maximize system capacity. For different fixed bandwidths the optimum value of M and the optimum value of L can vary [27]. In this paper, the most spectrally efficient FFH/CDMA system using random addressing would be one that maximizes the number of users in a single cell. This will be achieved by optimizing the diversity combining technique and the system parameters.

1.1 Thesis Outline

The remainder of Section 1 describes the mobile channel and provides some background on FFH spread spectrum.

Section 2 presents the FFH-MFSK system model which includes multiple-user interference, Rayleigh fading and AWGN.

Section 3 includes a description of the combining methods employed in this thesis. More specifically HDMV, Linear, NED, RRS and OS-NED diversity combining methods will be described.

Section 4 contains the simulation results and Section 5 the conclusions.

1.2 The Mobile Channel

The outdoor mobile communication channel contains many obstacles that hinder the propagating radio signal. Due to reflections from buildings, vegetation and other obstructions, signals are diffused. These multi-path signals add constructively and destructively at the receiver causing the signal amplitude and phase to vary. This creates a time-varying channel impulse response which can be described by [28]:

$$x(t) = \sum_n \alpha_n(t) s[t - \tau_n(t)] \quad (1.1)$$

where the propagation delays, τ_n , and attenuation factors,

α_n , are time varying and depend on the properties of the channel. The transmitted signal is $s(t)$ and n denotes a particular multi-path component. The effect of the channel on the signal is considered to be random and can be modelled statistically [29].

The terrain may also cause obstruction of the line-of-sight signal. When the line-of-sight component is absent and only the scattered components are considered, the signal amplitude is Rayleigh distributed [28]. This Rayleigh fading can be frequency selective, where two signals of sufficiently different frequencies fade independently when transmitted over the same multi-path channel. Frequency selective Rayleigh fading occurs when the transmission bandwidth exceeds the coherence bandwidth, B_{coh} , of the channel [4], [30]. B_{coh} is dependent on the size of the delay window, T_m , where the delay window represents the multi-path spread, the relationship is represented as follows [29]:

$$B_{coh} \cong \frac{1}{T_m} \quad (1.2)$$

Further impairment of the propagating signal is caused by losses due to large buildings, mountains and other obstacles. This blocking of the signal, called shadowing,

or lognormal fading is non-frequency selective. Shadowing can add to the near-far effect, i.e. signals closer to the base station are overwhelmed by signals that are further away.

The vehicle motion causes a Doppler shift of the transmitted frequency. The signals arrive at the receiver simultaneously through diverse paths creating a shift in the transmission frequency spectrum. The shift or Doppler spread, B_d , is a continuum between the positive and negative limits of the Doppler bandwidth because of the multi-path propagation through the channel. The impulse response of the channel will change after a minimum time, more specifically the coherence time, T_{coh} , of the channel. Consequently, the vehicle velocity, v , affects the coherence as follows:

$$T_{coh} = \frac{\lambda}{2v} \quad (1.3)$$

λ is the wavelength at center frequency. When the channel coherence time is exceeded by the system data transmission rate, the channel becomes time-invariant and can be approximated by [29]:

$$T_{coh} \cong \frac{1}{B_d} \quad (1.4)$$

Each hop experiences flat fading and no spectral distortion will result when the hopping rate, T_c , is a narrowband transmission and $B_{coh} > 1/T_c$. When the available bandwidth, is larger than the coherence bandwidth, all hops fade independently of each other [4], [31], [7].

1.3 FFH Spread Spectrum Systems

Non-coherent MFSK FFH with diversity combining is a spread spectrum technique that has been used predominately for protection against (unfriendly) jamming interference [32]. In 1979 Viterbi and Jacobs stated that partial band interference results could be applied to the unregulated multiple-access channel [33]. This was based on the assumption that when two users hopped on approximately the same frequency they would appear as Gaussian noise to each other's detectors. The use of the central limit theorem to model the multiple users as Gaussian interference was shown to be optimistic in the MFSK FFH/CDMA case [15]. The multiple user interference is better modelled using random addressing [9]. In a synchronous system with random addressing and N available channels, there is a $1/N$ probability that an interferer will hop to a particular frequency.

A system was presented by Viterbi [10] which used FFH/CDMA with the full available bandwidth utilized by each user. He showed theoretically that for a satellite transponder with multiple-access mobile users this application was not only more robust than coherent PN techniques, it was much easier to acquire and track through large doppler rate motion [10]. Viterbi noted that some form of adaptively

setting the HDMV combining threshold was necessary in the Rayleigh fading channel.

Based on the Viterbi proposal, Einarsson [34] demonstrated that an address consisting of different fixed patterns in time and frequency should be assigned to each user in order to distinguish between them. Einarsson derived error rate bounds for the non-synchronous and synchronous cases. The synchronous bound was shown to have a lower error rate than the non-synchronous bound. The random coding bound, which is upper bounded by the union bound, had a rate of error in-between the synchronous and non-synchronous bounds [34]. It was shown that the number of potential users could than be upper bounded based on the target error probability.

Haskell [22] has shown, through computer simulation, that Einarsson's addressing technique is somewhat better than random addressing. Timor [25] applied several different addressing techniques for FH-Multilevel FSK. He demonstrated, using both upper bounds and simulation, that performance could be substantially improved over random addressing. This improvement resulted when the known structure of the user addresses were exploited and decoding was done in various stages. In the noiseless case, when the number of stages was increased to three the number of users could be increased from 216 to 450. However, implementation of stage three resulted in a significant increase in complexity at the mobile unit.

Goodman, Henry and Prabhu [16] analyzed the FFH/CDMA system with HDMV combining using a random addressing model. Modulation capacity curves and receiver operating curves were used to determine the maximum number of users in a Rayleigh fading channel with AWGN. They showed that in AWGN with or without Rayleigh fading the optimum M-ary FSK design includes an address and diversity of 19 tones with $M = 256$ signal tones available. This is assuming that all users utilize the full bandwidth, 20 MHz, and transmit source data at 32 kb/s. This system led to a maximum number of users equal to 209 in an AWGN channel and in a land mobile telephone system it was approximated at 170.

Viswanathan and Gupta [13] have shown that Reduced Rank Sum (RRS) combining compares favorably to adaptive HDMV combining in a three cell mobile system. Recent results by Gulliver, Ezers, Felstead and Wight [20] demonstrate that newly designed diversity combining techniques developed to counteract worst case partial-band jamming are also effective against the degrading effects of frequency-selective Rayleigh fading. Although the partial-band interference model is not indicative of the multiple access environment, the superior performance demonstrated by OS-NED combining and the comparable performance demonstrated by NED combining show promise for FFH/CDMA applications.

Section II

2. FFH/CDMA System Model

2.1 Transmitter

The M-ary FSK-FFH transmitter is shown in Fig. 2.1. The input is binary data generated at a rate R_b . The data is then converted from binary to M-ary where $M = 2^k$ and k is the number of data bits per symbol. The symbol rate is $R_s = R_b/k = 1/T_s$ where T_s is the symbol duration.

A time-frequency coded system is considered where each user transmits a sequence of L tones per symbol over Q available frequencies. For user u , each symbol X_u is Modulo Q added to a random hopping address A_{ui} L times for $T_s = LT_c$ seconds, as shown in Fig. 2.2, where $i = 1, \dots, L$. Each time-frequency slot is defined as a bin. The random hopping address is PN generated and for every chip interval or hop time, T_c

seconds, the frequency address is changed. The resultant transmission address:

$$Y_{ui} = X_u \oplus A_{ui} \quad (2.1)$$

is used to determine the narrowband FSK transmission frequency, f_q , where $q = 1, \dots, Q$. For a specified bandwidth the number of available transmission frequencies for all users $u = 1, \dots, U$ is the following integer:

$$Q = \frac{W_t}{R_c} = \left\lfloor \frac{\log_2(M) W_t}{LR_b} \right\rfloor \quad (2.2)$$

where $Q \geq M$. The FSK modulated signal is transmitted on an expanded bandwidth $W_t = Q \cdot R_c$ at a rate of $R_c = LR_s = 1/T_c$, where L is the diversity of the system. Fast frequency hopping occurs when $L \geq 1$. For $L = 1$ the hopping rate is equal to the symbol rate and for $L > 1$ each symbol is transmitted on two or more hopping frequencies.

The performance of a narrowband communication system can be characterized by its spectral efficiency, η , where $\eta = R_b/W_t$ is the bit transmission rate over the total system bandwidth, measured as bits/second/Hz. In an FFH/CDMA system, the spectral efficiency is also dependent on the

number of users which can be supported at a given bit error rate [15], [9] which results in:

$$\eta = \frac{U_{\max} R_b}{W_t} \quad (2.3)$$

where $U_{\max}$ is the maximum number of users that can be accommodated with $P_b \leq 10^{-3}$ for a fixed bandwidth and bit rate. Note that $P_b \leq 10^{-3}$ is chosen as the performance criteria because it is sufficient to guarantee adequate voice transmission quality [10]. Combining (2.2) and (2.3) results in the following spectral efficiency for a FFH/CDMA communication system [17]:

$$\eta = \frac{U_{\max} \log_2(M)}{QL} \quad (2.4)$$

If $Q = M$, the CDMA system is called "unconventional" [35] since the M-ary band cannot be hopped to a different set of frequencies. Performance of unconventional FFH/CDMA was shown to be superior to that of conventional FFH/CDMA system ($Q > M$) with HDMV combining in AWGN [17] and Rayleigh fading channels [16].

Fig. 2.1 FFH Transmitter for a single user

Fig. 2.2 Transmitter Addressing for FFH/CDMA

2.2 Receiver

The receiver is shown in Fig. 2.3. The following multiple-user input signal tones are passed through a noise limiting bandpass filter:

$$s_u(t) = \sqrt{\frac{2E_c}{T_c}} \cos(2\pi f_{ui}t + \phi_{ui}) \quad (2.5)$$

where $u = 1, \dots, U$ is the number of users. For each user during the chip interval $i = 1, \dots, L$ the frequency is f_{ui} and ϕ_{ui} is the random phase angle which is uniformly distributed between $(0, 2\pi)$. The signalling interval is $(i-1)T_c \leq t \leq iT_c$ and time synchronous communications is assumed where the chips of all users are aligned. As a result, users will interfere if and only if they hop in the same time-frequency slot.

All users are considered to have the same chip energy, E_c . Since L chips are transmitted for each k bit sequence, the chip energy is related to the bit energy as follows:

$$E_c = \frac{E_b k}{L} \quad (2.6)$$

The bandpass filtered signal is modulo Q subtracted every T_c seconds by the same address A_{ui} that was used at the transmitter. The output of the modulo Q subtracter is the sum of the multiple-user signals and AWGN as follows:

$$r(t) = \sum_{u=1}^U s_u(t) + n(t) \quad (2.7)$$

The AWGN, $n(t)$, has a single sided power spectral density N_0 with variance $\sigma_n^2 = N_0/2T_c$.

At baseband, the in-phase and quadrature components are passed through a bank of filters matched to the M signaling frequencies, as shown in Fig. 2.4. The components are digitized by sampling at twice the hop rate ($2R_c$). The in-phase and quadrature components, denoted by y_{mi} , are squared and then summed. The complex vector $\tilde{y}_{mi} = y_{m1c} + jy_{m1s}$ which is the sum of the real cosine and imaginary sine components of the matched filter can be defined as follows:

$$\tilde{y}_{mi} = \sqrt{E_{c_{m1}}}} e^{j\theta_{m1}} + \sum_b^{B_i} \sqrt{E_{c_{m1b}}} e^{j\theta_{m1b}} + \tilde{n} \quad (2.8)$$

where " $\tilde{\cdot}$ " denotes a vector. The first term represents the

intended signal at f_m and the second term represents the interference tones, $b = 0, \dots, B_I$, which are at the same frequency, f_m , where $m = 1, \dots, M$. B_I is the number of interferers which are in the same time-frequency slot as the desired user. The noise vector n is a complex Gaussian random variable. The random phases θ_{mil} and θ_{mib} are uniformly distributed between 0 and 2π .

Depending on the combining method employed either the magnitude, Y_{mi} , or the summed output, y_{mi} , of the complex vector is used in the diversity combining operation. After combining the output, z_m , is passed through a decision device and a symbol decision, v , takes place.

After LT_c seconds the detection matrix illustrated in Fig. 2.5 is obtained. The desired user signal, denoted by (x) , will complete a row of L bins in the receiver matrix. However, fading, noise and/or interference will cause fluctuations in these values.

Gaussian noise and multiple-user interference, denoted by o , results in undesired energy throughout the receiver detection matrix. As a result, noise appears where no user signal has been transmitted. Fading, noise and interference vary the signal amplitude, consequently the normalized bin energy at the output of the matched filters may be altered. The noise and multiple-user interference can combine to produce a decision error where an incorrect

symbol decision is made at the receiver. To reduce the occurrence of decision errors, diversity combining algorithms are used to manipulate the $M \times L$ decision matrix. These are described in the next section.

Fig. 2.3 FFH Receiver for a single user

Fig. 2.4 Matched Filter - m

Fig. 2.5 Receiver Addressing for FFH/CDMA

Section III

3. Diversity Combining Methods

Numerous parametric and non-parametric diversity combining techniques have been applied to FFH/CDMA communication systems. With parametric combining, each chip is processed separately whereas with non-parametric combining all the data in each $M \times L$ block must be stored before processing [36]. Storing the data prior to processing results in an increase in processing time over parametric techniques. Consequently, parametric receivers such as HDMV have been favoured in FFH/CDMA systems. However, the feasibility of implementing a non-parametric receiver is more viable today due to advances in technology. Also, it has been shown by Viswanathan and Gupta that non-parametric receivers are realistic alternatives to parametric receivers for FFH/CDMA applications [14], [18]. Advantages such as performance robustness against statistical changes in the probability model, and the absence of the adaptive schemes which are

normally required by the HDMV parametric receiver are quoted.

In a single cell Rayleigh fading channel, where interference from adjacent cells is not considered, parametric hard limited combining is superior to non-parametric combining [13], [18]. However, in a three cell FFH/CDMA system, reduced rank sum non-parametric combining did not show a decrease in performance when interference from two adjacent cells was considered [18]. Conversely, in the same three cell interference model the performance of hard limited combining was significantly degraded [19].

In this thesis, the combining techniques will be examined in a bandlimited one cell CDMA communication system. Two bandwidths will be used $W_t = 32 * R_b$ and $W_t = 128 * R_b$ also, the different values of M and L will be examined to determine the optimum parameters for the aforementioned bandlimited systems. In past research, a bandwidth of $W_t = 525 * R_b$ was predominately assumed where $M = 256$ and $L = 19$ were shown to be the optimum parameters. HDMV, linear and RRS combining will be examined to formulate a baseline for the comparison, of past results and the results presented herein. NED and OS-NED combining have both been selected for comparison based on their performance in Rayleigh fading, and in the presence of tone jamming [20]. Also, the potential robustness in a statistically changing

channel makes non-parametric OS-NED combining extremely attractive for the land mobile cellular application. Although there exist many other combining techniques, complexity or past performance resulted in their not being selected for investigation in this thesis.

3.1 Hard Decision Majority Vote

HDMV combining as illustrated in Fig 3.1, has been used extensively in CDMA applications, [16], [10], [4], [17].

The, y_{mi} , outputs of the M matched filters, are fed through M threshold devices. Each threshold device makes a decision, J_{mi} , on each chip where

$$J_{mi} = \begin{cases} 1 & y_{mi} \geq th \\ 0 & y_{mi} < th \end{cases} \quad (3.1)$$

Optimization of the threshold in an FFH environment depends on L and M as well as E_b/N_o and the number of users. The following formulas allow the threshold to be calculated for fixed values of M , L and $SNR = E_c/N_o$ [37]:

$$\beta = \frac{\beta_a}{\sqrt{N_o}} \quad (3.2)$$

where β_0 is the fixed threshold normalized to the rms noise, N_0 .

The analytical approximation for the non-normalized threshold is [37]:

$$\beta = \sqrt{2 + \frac{SNR}{2}} \quad (3.3)$$

for the AWGN case. The approximation for the Rayleigh fading case is [37]:

$$\beta = \sqrt{2 \left(1 + \frac{1}{SNR} \right) \ln(1 + SNR)} \quad (3.4)$$

The calculated normalized thresholds for the AWGN case are shown in Fig. 3.2 for several values of M and L , using $E_b/N_0 = 15$ dB. When a fixed hop energy, $E_c/N_0 = 15$ dB, is employed the calculated threshold is 0.5307 for all values of M and L , since β is solely a function of E_c/N_0 .

Arriving at the optimum threshold using analytical calculations is extremely difficult since knowledge of E_b/N_0 or E_c/N_0 is required at the receiver[10].

Consequently, to optimize the performance of HDMV combining, an adaptive threshold is required to adjust to the fluctuating number of users and varying signal amplitudes. As a result HDMV combining is difficult to implement. This is especially true in a Rayleigh fading channel, with a statistically changing multi-cell environment.

Goodman, Henry and Prabhu [16], computed the maximum number of users as a function of k for the case when $P_f, P_d = 0, 0$. The Probability of false alarm, P_f , is the probability that the bin energy exceeds the threshold even though a signal was not transmitted. This is the case where receiver noise and/or multiple-user interference results in a false signal being detected. The probability of deletion, P_d , is the probability that a signal was transmitted, and fading reduced the signal energy sufficiently to cause it to fall below the threshold for a particular bin.

The following equations were applied in [16] to a Rayleigh fading channel to determine the threshold [37]:

$$P_f = \exp\left(-\frac{\beta^2}{2}\right) \quad (3.5)$$

and

$$P_d = 1 - \exp\left(-\frac{\beta^2}{2(1 + SNR)}\right) \quad (3.6)$$

where $\beta = 2.75$ was shown to be nearly optimum for $W_t = 20$ MHz, $M = 256$, $L = 19$, $SNR = 25$ dB and $U_{\max} = 170$ [16]. The thresholds for several values of M and L are shown in Fig 3.3. The normalized threshold calculated using (3.2) and (3.4) for $L = 19$ and $M = 256$ is 0.1836 and the value which Goodman, Henry and Prabhu derived using the receiver curves, $\beta = 2.75$ and an approximation for the maximum number of users is 0.1685. This demonstrates the validity of the HDMV thresholds used in this thesis.

A comparison of the thresholds, obtained using (3.2), (3.3) and (3.4), in Figs. 3.2 and 3.3, which correspond to AWGN and Rayleigh fading, respectively, reveals that they differ by approximately $\beta = 0.4$. This reduction for the Rayleigh fading case is necessary to accommodate the reduced signal amplitudes which are characteristic of the Rayleigh fading channel.

The detection matrix shown in Fig. 3.1 illustrates typical output values from the energy detectors. In real time, the

outputs of the energy detectors are summed and after LT_c seconds a symbol decision, v , is made, based on the row with the largest output (the largest number of 1's). In the case of a tie, the symbol is selected randomly from the largest values which are tied.

Note that using hard decisions rejects a significant portion of the information available in the $M \times L$ matrix. Using all the bin information could potentially result in an increase in system performance.

Fig. 3.1 Hard Decision Majority Vote Combining

Fig. 3.2 Calculated Threshold for $E_b/N_o = 15\text{dB}$ AWGN Channel

Fig. 3.3 Calculated Threshold for $E_b/N_o = 25$ dB Rayleigh Fading Channel

3.2 Linear

Linear combining is one of the simplest combining methods. It requires the summing of the L bin values for all M filter outputs as follows:

$$z_m = \sum_{i=1}^L Y_{mi}^{\alpha} \quad (3.7)$$

There are two variations of linear combining. The chip values are summed when $\alpha = 1$, or they are squared and then summed when $\alpha = 2$ (also called square law combining). The symbol decision, v , is based on the largest output, z_m , from the summing devices as shown in Fig 3.4.

Square law linear combining is optimum in a Rayleigh fading environment [32]. However, it is only slightly better than linear combining with $\alpha = 1$ [20], and it has been shown that the performance of linear combining in multi-tone jamming is far superior to that of square law combining [20]. As a result, linear combining with $\alpha = 1$ is considered in this thesis.

Fig. 3.4 Linear Combining

3.3 Normalized Envelope Detection

Normalization Envelope Detection (NED) combining has shown similar performance to linear combining in the Rayleigh and tone jamming environments [20]. Therefore it is also considered for comparison. The normalization is achieved by dividing each chip value, Y_{mi} , by the sum of the energy, E_i , in all M bins over the symbol interval, as shown in Fig. 3.5. The normalized signals, J_{1i} , are summed and the symbol decision, v , is based on the maximum z_m .

Fig. 3.5 Normalized Envelope Detection Combining

3.4 Reduced Rank Sum

Reduced Rank Sum (RRS) combining requires that after each hop (every T_c seconds) the M Y_{mi} input values are ranked and the actual rank value from 1 to M is placed in each bin. The bin corresponding to the largest value is assigned the value M , while the bin corresponding with the lowest value is assigned the value 1. The remaining bins are assigned rank values from 2 to $M-1$ accordingly. After L hops, the ranks, R_{mi} , are summed for each of the M rows. The largest sum, z_m , is selected as the symbol decision, v , as illustrated in Fig. 3.6.

Although RRS has the attributes of non-parametric combining, there is no requirement to store the complete $M \times L$ data matrix. Only the data in each column (hop) is considered for ranking, and the data can be summed after each hop for L hops precluding the requirement to store L columns of data. Consequently, the processing time is reduced.

Fig. 3.6 Reduced Rank Sum Combining

3.5 Order Statistics - NED

Order Statistic - Normalized Envelope Detection (OS-NED) is a combination of Order Statistics and NED combining. The L values for each of the Y_{mi} inputs are sorted from smallest to largest as shown in Fig. 3.7. Once sorted, normalization as with the NED receiver is applied and the symbol decision, v , is once again the largest output z_m as illustrated in Fig. 3.5. This method has been shown to be the best overall performer in Rayleigh fading, and in multi-tone jamming [20].

Fig. 3.7 Order Statistics Combining

Section IV

4. Simulation of the FFH/CDMA System

4.1 Model

The assumptions used for simulating the FFH/CDMA communication system are as follows:

To determine performance in AWGN, all users are assumed to have a signal to noise ratio of $E_c/N_o = (k/L) * (E_b/N_o) = 15$ dB.

To determine the performance in Rayleigh fading, all users are assumed to have $E_c/N_o = 25$ dB. Increased signal-to-noise ratios are required to counteract the effects of Rayleigh fading.

The source data rate is chosen to be $R_b = 32$ kbits/sec,

which is adequate for voice transmission [16], [10], [13], [18]. Fixed bandwidths are used where $W_t/R_b = 32$ and 128.

Perfect synchronization of the received signal tones is assumed [16], [17].

Given that for the typical outdoor channel $B_{coh} \approx .1\text{MHz}$ [8] a frequency selective Rayleigh fading channel is assumed where $B_{coh} \leq W_t$. Also, the channel is assumed to be flat for each chip where $B_{coh} > 1/T_c = f_q$. It is important to note that for small values of k and large values of L , more specifically where the ratio of $L/k \geq 3.1252$, $B_{coh} < 1/T_c$. For example, in this thesis the worst case channel spacing is 0.256MHz, this occurs when $k = 2$ and $L = 16$. Also, for both $k = 2$, $L = 8$ and $k = 3$, $L = 12$ the channel spacing is 0.125MHz. Consequently, the narrowband transmission is not less than B_{coh} and frequency selective Rayleigh fading could cause a degradation in system performance. Therefore, the results obtained for the parameters where $L/k \geq 3.1252$ are considered to be optimistic. The Rayleigh fading is modelled as a multiplicative complex Gaussian process [38]. The random numbers are multiplied by the in-phase and quadrature components of the received signal in accordance with [39], as illustrated in Fig 4.1.

Power control is assumed in accordance with [15], [4], [7]. Therefore the near-far effect due to propagation loss, where users close to the base station overwhelm distant users, can be ignored. Also it is assumed that the lognormal component of the fading is slow enough that it can be overcome with power control [15].

The probability of bit error is related to the probability of symbol error by [16], [17], [18]:

$$P_b = \frac{M}{2(M-1)} P_s \quad (4.1)$$

where P_s is the symbol error rate.

Fig. 4.1 Rayleigh Fading Model

4.2 Procedure

All simulations were carried out using 'Matlab'. The programs were run until a specified number of symbol errors occurred. The BER was then calculated using (4.1) and plotted versus diversity for $M = 4, 8, 16, 32$ and $W_t/R_b = 32$. The simulation times were lengthy especially for large values of M and L .

In order to minimize simulation time while maximizing data accuracy, not all the data points were determined using the same number of errors. Trial data points were run for all the combining methods to determine approximate error values. Combining techniques which resulted in a large number of ties were more prone to large deviations in BER, therefore a greater number of symbol errors was sought.

The number of specified errors which were required to reproduce Fiebig's results were used as the baseline. More specifically for a $BER < 10^{-2}$ a minimum of 200 errors were obtained for a minimum of three iterations. Similarly for a $BER < 10^{-4}$ a minimum of 50 errors were obtained for a minimum of three iterations. Trading off run time with data accuracy, the worst case second digit accuracy of ± 4 was established. Consequently, the data had a BER which deviated no more than ± 4 in the second digit regardless of

how many runs were made. The required number of symbol errors sought was determined through trial and error for each of the techniques.

The run time for $W_t/R_b = 128$ was excessive and as a result BER vs diversity curves were not produced. In order to obtain the optimum parameters the curves for $M = 16$ and $M = 32$ were obtained. The resultant optimum parameters were the same as those shown in [17] where HDMV combining was used with infinite signal energy. The optimum parameters were then used to determine the maximum allowable number of users and the spectral efficiency.

When determining the maximum number of users, the runs were made for 30 errors. The number of users was varied until the BER approached but did not exceed 10^{-3} for three consecutive runs.

4.3 Simulation Results

Four different configurations of the aforementioned model were simulated.

The first phase included all the Section III diversity combining techniques with AWGN, a fixed bandwidth of $W_t/R_b = 32$ and a fixed number of users, $U = 4$. Four users were selected in order to compare with the

results in [17]. The resultant BER vs diversity graphs for $M = 4, 8, 16$ and 32 are presented in section 4.3.1.

In the second phase, the three best combining techniques from phase I were simulated in a Rayleigh fading channel with AWGN. The bandwidth was not changed from Phase I, $W_t/R_b = 32$, however the energy was increased to combat the negative Rayleigh fading effects. In phase I the OS-NED combining results were repeatedly below 10^{-4} therefore, the number of users was increased to six to reduce simulation time. This increase in the number of users created a higher error rate due to the increased multiple-user interference. The results are presented in section 4.3.2.

The optimum values of M and L were determined, based on the minimum BER for a fixed number of users, for the optimum phase 2 combining method. These optimum values were then used to determine $U_{\max}$ with $W_t/R_b = 32$. The bandwidth was expanded to $W_t/R_b = 128$. Optimum values were obtained for M and L and used to determine $U_{\max}$ for the expanded bandwidth. These results are presented in 4.3.3.

The spectral efficiency of the optimum combining method at $W_t/R_b = 32$ and 128 is presented in 4.3.4.

4.3.1 AWGN Channel

To verify the simulation model, HDMV diversity combining was simulated for $M = 4, 8, 16$ and 32 , and $L = 2, 4, 6, 8, 10, 12, 14$, and 16 , as applicable in accordance with $Q \geq M$ and (2.2). The Q values are presented in Tables 1 and 2. The optimum parameters are shown in bold and the unconventional FSK/FFH parameters are shown in *italic*. The HDMV simulation results are shown in Fig 4.2. Fig 4.3 is included to provide a baseline comparison with the results obtained in [17]. Note that the curves in Figs. 4.2 and 4.3 have the same shape. However, they vary at $M = 4$ and 8 for large values of L and for $M = 16$ and 32 for small values of L .

The simulations were carried out with a fixed hop energy, where $E_c/N_0 = 15$ dB. However, the curves from [17] were obtained using $E_b/N_0 = 15$ dB which results in a varying hop energy E_c/N_0 . The variation in hop energy for a fixed $E_b/N_0 = 15$ dB is illustrated in Fig. 4.4. Note that the differences between the curves in Figs. 4.2 and 4.3 are small even when the Fig 4.4 E_c/N_0 difference was large. This demonstrates that in the multiple-access application with AWGN fixing the bit energy vice fixing the hop energy does not have a significant effect on the performance. As a result, it can be deduced that the performance was

limited primarily by multiple-user interference in AWGN. Further, in [17] no indication is given of the procedure used to specify the threshold for HDMV combining. In this thesis the threshold was determined for $E_c/N_0 = 15$ dB using the threshold formulas presented in Section II. Based on the AWGN results, this model was considered adequate and was adopted for the simulation of linear, NED, RRS and OS-NED combining for comparison purposes.

As shown in Fig. 4.5, the NED combining curves are similar in shape to those obtained with HDMV combining. However, the NED curves do not have a decreasing bit error rate for increasing M . The optimum parameters $M = 8$ and $L = 8$ allow four users with a $BER < 10^{-3}$. Although NED combining performed the worst of all the considered combining methods, it was modelled in phase two to investigate its performance in the multiple-access Rayleigh fading channel.

The linear combining results, shown in Fig. 4.6, have many points below $BER = 10^{-3}$ for $M = 8$, $M = 16$ and $M = 32$, indicating that more than 4 users could potentially be accommodated. Also, note that the BER does not decrease with increasing values of L . Actually, the unconventional FSK points showed poor performance. Linear combining did not perform well in a Rayleigh fading multiple-user channel in [13], therefore it was not considered for further investigation.

The performance of the RRS and OS-NED methods, shown in Figs. 4.7 and 4.8 respectively, demonstrate better performance than the HDMV, NED and linear methods. This is not surprising since the RRS and OS-NED techniques are both non-parametric. Consequently, more of the available received signal information is being used to determine which symbol was transmitted. The RRS method has a BER $\leq 10^{-3}$ for almost all values of $L > 2$ and $M > 8$. As with linear combining, the BER for RRS does not decrease with increasing L when M is constant, as is generally the case for the HDMV and OS-NED methods. The OS-NED method was the best as $P_b \leq 10^{-3}$ was achieved for all values of M , where $12 > L > 2$.

L	M = 4	M = 8	M = 16	M = 32	M = 64
L = 2	32	48	64	80	96
L = 3	21	32	42	53	64
L = 4	16	24	32	40	M > Q
L = 5	12	19	25	32	
L = 6	10	16	21	M > Q	
L = 8	8	12	16		
L = 10	6	9	M > Q		
L = 12	5	8			
L = 14	4	M > Q			
L = 16	4				

Table 1: Q values for M and L with $W_t/R_t = 32$ and $Q \geq M$

L	M = 16	M = 32	M = 64	M = 128	M = 256
L = 4	128	160	192	224	256
L = 6	85	106	128	149	M > Q
L = 7	73	91	109	128	
L = 8	64	80	96	M > Q	
L = 10	51	64	76		
L = 12	42	53	64		
L = 13	39	49	M > Q		
L = 14	36	45			
L = 20	25	32			
L = 31	16	20			

Table 2: Q values for M and L with $W_t/R_b = 128$ and $Q \geq M$

4.3.2 Rayleigh Fading Channel

The non-parametric OS-NED and RRS and the parametric NED combining methods were simulated in a Rayleigh fading channel. Six users were simulated and the results are shown in Figs. 4.9 to 4.11. The curves for NED were similar to those obtained in the AWGN case, where the BER did not decrease with increasing M and increasing L. Also, NED did not have any parameters that would accommodate six users for $\text{BER} \leq 10^{-3}$. Considering that the increase in signal to noise ratio significantly reduces the negative effects of AWGN, it can be concluded that the poor performance of NED is a result of multiple-user interference. Since NED combining did not prove to be efficient in the multiple-user environment it was not considered for any further investigation.

The RRS curves show that regardless of the M or L chosen six users cannot be supported for a $\text{BER} \leq 10^{-3}$. It should be noted that for $M > 8$ the unconventional FSK parameters were optimum and the BER decreased as L increased. These results indicate that the non-monotonic performance obtained with AWGN simulations was generally a result of AWGN interference. RRS performed well in the multiple-access Rayleigh fading channel, but not as well as OS-NED.

The results obtained using OS-NED combining demonstrate that six users could be supported for several combinations of parameters. It is important to note that with the exception of $M = 4$, where the $Q \times L$ matrix is sufficiently small to be unable to support the number of users simulated, the unconventional FFH/CDMA parameters result in the maximum number of users. OS-NED has shown to be extremely effective in combating AWGN and Rayleigh fading as illustrated in Figs 4.8 and 4.9. Also, OS-NED has shown superior performance to all the combining methods with or without Rayleigh fading. Therefore OS-NED considered for FFH/CDMA bandwidth efficiency investigations.

A comparison of OS-NED performance with fixed hop energy versus fixed bit energy was carried out in Rayleigh fading to determine the limiting performance factor. The varying hop energy which results when a fixed bit energy model is used is shown in Fig. 4.12. For example, when $M = 16$ and $L = 8$, $E_c/N_0 = 21.99$ dB for a fixed bit energy and $E_c/N_0 = 25$ dB for a fixed hop energy. The comparison at $M = 8$ and $L = 12$ is more varied where $E_c/N_0 = 15.879$ dB for a fixed bit energy and $E_c/N_0 = 25$ dB for a fixed hop energy. The comparison curves which were obtained with OS-NED are shown in Fig 4.13. The curves are essentially the same, indicating that in a Rayleigh channel system performance is dependent on the number of users occupying the bandwidth. This verifies that OS-NED combining optimizes performance in AWGN and Rayleigh fading.

4.3.3 Maximum Number of Users

In order to investigate the efficiency of the system the maximum allowable number of users must be obtained. Thus the optimum parameters must be determined. For $W_t/R_b = 32$, the optimum system parameters for OS-NED can be extracted from Fig. 4.9. These values are the same as those obtained in [17] where an infinite bit energy was used with the noiseless model.

When the bandwidth is expanded, the M-ary signalling is increased which results in an increase in system complexity. However, more narrowband channels are available for transmission, as a result, the maximum number of users that the system can accommodate is also increased. To obtain the optimum parameters for $W_t/R_b = 128$, simulations were carried out for $M = 16$ and $M = 32$ using various values of L . As shown in Figs. 4.14 and 4.15, $L_{opt} = 13$ for both values of M . Again these parameters are the same as in [17] where the noiseless model was simulated. Therefore L_{opt} for $M = 64$ and $M = 128$ have been assumed to be the same as [17].

The optimum parameters are shown in Table 3.

$W_t/R_b = 32$			$W_t/R_b = 128$		
M	L_{opt}	Q	M	L_{opt}	Q
4	8	8	16	13	39
8	12	8	32	13	49
16	8	16	64	12	64
32	5	32	128	7	128

Table 3: FFH/CDMA Optimum Parameters

It should be noted that the L_{opt} values obtained in a Gaussian channel, given $E_b/N_o = \infty$ [17], are the same as those obtained in a Rayleigh fading channel given $E_b/N_o = 25$ dB for unconventional MFSK. Lee [40] has shown analytically that for L-diversity branches, as L approaches ∞ , the Rayleigh fading environment L-diversity multi-path channel capacity approaches the Gaussian noise channel capacity when DS/CDMA diversity combining is employed. Whereas, in the FFH/CDMA case the diversity level is limited by the bandwidth of the channel, given by (2.2). Also, the independent multi-path channels that are providing diversity are being collected over time - T_c , instead of simultaneously, as is the case when DS/CDMA is

employed. As the results of this paper show for FFH/CDMA in a Rayleigh fading channel, as L approaches the maximum for each value of $M > 4$, the BER is decreased and the number of users which the system can support is increased. $U_{\max}$ results were obtained for $W_t/R_b = 32$ with OS-NED combining. The FFH/CDMA system capacity in a Rayleigh fading channel, where $E_c/N_0 = 25$ dB was identical to the Gaussian channel where $E_c/N_0 = \infty$ as illustrated in Table 4. This indicates that for large values of M , when unconventional FSK is employed, the capacity of FFH/CDMA in a Rayleigh fading channel matches the infinite energy AWGN FFH/CDMA system capacity.

M	Rayleigh			AWGN		
	L_{opt}	$U_{\max}$	Q	L_{opt}	$U_{\max}$	Q
4	8	4	8	8	4	8
8	12	6	8	12	6	8
16	8	7	16	8	7	16
32	5	6	32	5	6	32

Table 4: FFH/CDMA System Capacity $W_t/R_b = 32$

4.3.4 Bandwidth Efficiency

OS-NED demonstrated the best performance when the bandwidth expansion was 32, therefore it was simulated for a bandwidth expansion of 128. As shown in Fig 4.16 the maximum number of users was obtained when $M = Q = 16$ (unconventional FSK) and $L = 8$ for $W_t/R_b = 32$, and $M = Q = 64$ (unconventional FSK) and $L = 12$ for $W_t/R_b = 128$. In general it can be seen that a selection criteria does exist which enables the optimum parameters to be determined for a fixed bandwidth of 32 or 128. To maximize spectral efficiency the optimum parameters can be selected using the following constraints: $\log_2(M) < L_{\text{opt}} < M$ and $Q = M$. In the case of a tie, the optimum parameters occur at the maximum $\log_2(M)$ as demonstrated in Table 5.

The bandwidth expansion from 32 to 128 increased the bandwidth efficiency by $\eta_{128}/\eta_{32} = 1.357$ as shown in Fig. 4.17, where it is compared to the results in [17] obtained with HDMV combining in the AWGN environment. When unconventional FSK is used, HDMV combining with AWGN and an infinite SNR is equivalent to the OS-NED combining in a Rayleigh fading channel with $E_c/N_0 = 25$ dB.

Bandwidth Expansion	$\log_2(M)$	L_{opt}	Q
$W_t/R_b = 32$	2	14	4
	3	12	8
	4	8	16
	5	5	32
	6	3	64
$W_t/R_b = 128$	4	31	16
	5	20	32
	6	12	64
	7	7	128
	8	4	256

Table 5: Optimum Parameter Criteria: $\log_2(M) < L_{opt} < M$ and $Q = M$; where maximum $\log_2(M)$ is selected from those values which are tied

Fig. 4.2 Performance of HDMV combining with 4 users in AWGN, where $W_t/R_b = 32$

Fig. 4.3 Performance of HDMV combining from [17] with 4 users in AWGN, where $W_t/R_b = 32$

Fig. 4.4 E_c/N_0 vs diversity for fixed bit rate
 $E_b/N_0 = 15$ dB

Fig. 4.5 Performance of NED combining with 4 users in AWGN, where $W_t/R_b = 32$

Fig. 4.6 Performance of Linear combining with 4 users in AWGN, where $W_t/R_b = 32$

Fig. 4.7 Performance of RRS combining with 4 users in AWGN, where $W_t/R_b = 32$

Fig. 4.8 Performance of OS-NED combining with 4 users in AWGN, where $W_c/R_b = 32$

Fig. 4.9 Performance of OS-NED combining with 6 users in Rayleigh fading where $W_t/R_b = 32$

Fig. 4.10 Performance of RRS combining with 6 users in Rayleigh fading where $W_t/R_b = 32$

Fig. 4.11 Performance of NED combining with 6 users in Rayleigh fading where $W_t/R_b = 32$

Fig. 4.12 E_c/N_0 vs diversity for fixed bit energy
 $E_b/N_0 = 25\text{dB}$

Fig. 4.13 Comparison of OS-NED performance in Rayleigh fading for $E_b/N_0 = 25\text{dB}$ and $E_c/N_0 = 25\text{ dB}$ with 6 users, where $W_t/R_b = 32$

Fig. 4.14 Performance of OS-NED combining for $M = 16$,
 $U = 30$ and $W_t/P_N = 128$ in Rayleigh fading

Fig. 4.15 Performance of OS-NED combining for $M = 32$,
 $U = 35$ and $W_t/R_b = 128$ in Rayleigh fading

Fig. 4.16 Maximum allowable users for OS-NED combining with $BER \leq 10^{-3}$ in a Rayleigh fading channel

Fig. 4.17 Spectral efficiency for OS-NED diversity combining in a Rayleigh fading channel

Section V

5.0 Summary and Conclusions

5.1 Summary

In Section I, the problem of M-ary Frequency Shift Keyed Fast Frequency Hopping/Code Division Multiple Access in a Rayleigh fading channel was defined. The ability to reduce the negative effects of Rayleigh fading with efficient diversity combining was presented. In Section II, a typical FFH/CDMA random addressing transmitter and receiver was presented and the system parameters defined. In Section III, the Hard Decision Majority Vote, Linear, Normalized Envelope Detection, Reduced Rank Sum and Order Statistics-NED diversity combining techniques were defined. In Section IV, the simulation model and procedures were described, and the simulation results were presented.

5.2 Conclusions

The performance of HDMV, NED, linear, RRS and OS-NED diversity combining was compared in AWGN with multiple-user interference. The results showed that the RRS and OS-NED techniques were superior to the others. The OS-NED technique had the lowest BER for all values of M .

Past research has shown that linear combining is not effective in the multiple-user Rayleigh fading channel. The HDMV combining technique is complex to implement due to the adaptive threshold requirement, also it was shown not to be robust in a statistically changing channel [14]. The OS-NED, RRS and NED combining techniques demonstrated comparable or better performance than the linear and HDMV techniques, consequently they were selected for comparison in a Rayleigh fading channel.

OS-NED combining was shown to be superior to NED and RRS combining in a Rayleigh fading channel with AWGN and multiple-user interference. NED was shown to be inefficient in the multiple-access environment. For OS-NED and RRS the optimum parameters for $W_t/R_b = 32$ were $M = Q = 16$ and $L = 8$. OS-NED supported seven users with these parameters. Neither NED or RRS could support even six

users. However, the BER for RRS combining at $M = 16$ and $L = 8$ was 1.9×10^{-3} whereas for NED the BER was only 2×10^{-2} .

When the bandwidth was expanded to $W_t/R_b = 128$ the optimum parameters for OS-NED were $M = Q = 64$ and $L = 12$, which resulted in $U_{\max} = 38$ for the OS-NED technique. This demonstrated an improvement in spectral efficiency of $\eta_{128}/\eta_{32} = 1.357$ for a 4-fold increase in bandwidth. It was shown that the spectral efficiency obtained in the Gaussian channel, with infinite energy, is identical to the spectral efficiency obtained in a Rayleigh fading channel, with $E_c/N_0 = 25$ dB. It was also demonstrated that the optimum parameters for a fixed bandwidth and fixed bit rate system can be determined using the following criteria: $Q = M$ and $\log_2(M) < L_{\text{opt}} < M$; where the maximum $\log_2(M)$ is selected from those values which are tied.

It was shown that the non-parametric OS-NED receiver was optimal in both the AWGN environment and a Rayleigh fading channel with AWGN. In addition it was determined that regardless of the technique, unconventional FSK is optimum in a Rayleigh fading multiple access channel.

5.3 Recommendations for Future Work

This thesis concentrated on a limited bandwidth system with random addressing and no adjacent cell interference. To improve on these results, more efficient addressing techniques could be used. Also, the OS-NED receiver could be examined with adjacent cell interference to measure its robustness in a multi-cell model.

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

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