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Fuzzy Signal Detection in Multiple-access Ultra-wide Band Communication Systems

模糊信號偵測在多功存取超寬頻通訊系統

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Abstract

Ultra-wide band (UWB) communications transmits a wide bandwidth signal with an extremely low power spectral density. This property of UWB makes it possible to co-exist with the current narrowband communication systems operating at dedicated frequency bands. UWB can also serve multiple users by using the Spread Spectrum (SS) technique. However, with the number of multiple users increasing, signals associated with users will interfere with each other, resulting in Multi-Access Interference (MAI), a drawback in MA-UWB systems, which could adversely affect the system performance. In practice, the exact transfer function of MAI from other users is rarely known due to the security property of the SS system. Therefore it is difficult to represent the characteristics of MAI by any statistical model. Lacking such information of MAI would cause *imprecision* to the signal model, which could adversely degrade the performance of UWB communications.

Fuzzy logic is a conceptually simple, flexible and effective way to handle the imprecision of the signal model. In this thesis, fuzzy detection techniques are investigated in solving the problem of MAI in Multiple-Access (MA) UWB communication system. In chapter 2, signal detection of MA-UWB using fuzzy integration is presented. Fuzzy Integration (FI) detector, by mapping the input vectors of detector to a fuzzy space using a fuzzy membership function, would alleviate the performance degradation due to MAI. This chapter also illustrates that the FI detector has a very simple hardware design, and it can be applied into practical systems directly.

A signal detection method for MA-UWB using Fuzzy Inference system (FIS) is presented in chapter 3. This FIS detector modifies the fuzzy space of the FI detector and further improves the detection performance of UWB communication systems. The enhancement in performance after applying the FIS detector is also illustrated in this chapter. Result has indicated that a significant performance improvement could be obtained by using the FIS detector.

Multistage interference cancellation (PIC) is one of the common multi-user detection techniques, and an effective method to cancel the MAI from other users within the same communication network. The principle of the PIC is to estimate the signal of interfering users, and then subtract the estimated interference from the received signal.

This approach can be further iterated by using a larger number of stages.

The effectiveness of the PIC, however, is related to, and is sensitive to the reliability of the decision involving the interference estimation process. The performance of PIC could therefore be severely degraded if the interference estimation is not reliable, resulting in non-robustness in the PIC. In chapter 4, a fuzzy PIC detector for MA-UWB application is developed in order to address this problem. This fuzzy PIC detection estimates the reliability of the signals and assigns a cancellation weight to each interference cancellation path to minimize the error. The cancellation weight is chosen depending on the reliability of the received signal. The concept of this fuzzy PIC detection is discussed and the performance of this detector is also presented in chapter 4.

In chapter 5, a general discussion in these three detectors, i.e FI, FIS, and FPIC is presented. This chapter also concludes the use of fuzzy detection techniques in UWB communications and summarizes the detection performance of the fuzzy detection techniques by comparing with the conventional approaches.

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Chapter 1

Introduction

Ultra wide Band (UWB) impulse radio (IR) is a recent innovation for commercial communication application. UWB-IR transmits its signal using a series of narrow base-band impulses instead of a fixed-frequency sinusoidal wave. The pulse widths of these base-band pulses are only in the order of sub-nanoseconds and hence the energy of UWB signal is spread over an extremely wide bandwidth, resulting in a low spectral content signal [*Win*, 00]. This low spectral content signal behaves as white-noise to the current communication systems, ensuring that UWB-IR does not interfere the narrowband and wideband systems of which the frequencies are allocated within the UWB bandwidth. This characteristic allows the UWB-IR systems to be implemented in communication applications and to co-exist with the communication systems when the propagating signals are appropriately designed [*Win*, 98a].

UWB signal occupies a bandwidth from dc to several gigahertzes. Operating at the lowest possible frequency, UWB-IR could penetrate materials that tend to be more opaque at higher frequencies [*Win*, 97]. It is also an advantage that the narrow pulse width with an extremely wide bandwidth means that the multi-path is resolvable down to the path differential delay to the order of 1 nanosecond, which reduces the multi-path fading that the traditional narrowband systems are severely suffered in indoor environments [*Win*, 98b]. UWB-IR transmits its signal only in base-band, which provides the advantage of the system by omitting the expensive IF to RF converters in both the transmitters and receivers [*Ghavami*, 04]. The UWB-IR also transmits a very low power signal, which provides the added bonus of avoiding the necessity of a power amplifier in the transmitter [*Ghavami*, 04]. The reduction of component hence reduces the implementation cost and the device size of UWB transceiver. Due to the mentioned advantages of UWB technology, UWB-IR is particularly well suited for high speed, indoor hand-held wireless applications.

1.1 Review of UWB-IR communications

The technique of UWB was firstly applied in the field of radar in last century [*Fowler*, 90]. Because of its high penetrating power, high jamming resistance and the security property, several kinds of radars such as impulse, terrain profiling and ground penetrating radar are developed using UWB technique [*Fowler, 90*]. This carrier-free, base-band technique has also been applied in other applications such as automobile collision avoidance, liquid-level sensing, positioning systems and altimetry by US government [*Mitchell*, 01]. Recently, UWB was under development in the communication applications. For examples, IEEE 802.15 working group are working to standardize the UWB wireless personal area networks (WPANs); Nakagawa combined the standard of IEEE 1394 together with UWB, to provide a high speed high performance home entertaining network that is able to support digital multi-media contents and full motion video transfer [*Nakagawa, 03*], while Xu has proposed a radio resource control method in UWB MAC Protocol Design that could obtain a significant improvement of maximum throughput over random access scheme [*Xu, 03*].

While some of the researches focus on the standardization and implementation of UWB-IR communications, in the meantime, works on analyzing and mitigating the effect of interference and imprecision to the UWB systems have also been carried out [*Forgac*,03; *Klein*,03]. The interference and noise which are mainly concerned are Multi-Access Interference (MAI) from other UWB users, co-channel interference from the existing conventional narrowband and wideband system, Inter-symbol Interference (ISI) from the delay replica of the original signal and the time imprecision between the transmitter and receiver [*Welborn,* 01; *Ghavami*, 04]. The interference issues are briefly described in the following sections.

1.1.1 Multiple Access Interference (MAI)

UWB-IR communications using Spread Spectrum (SS) techniques support Multiple-Access (MA). UWB-IR systems are conceptually similar to asynchronous Code Division Multiple Access (CDMA). The UWB users share the common spectrum and the set of signaling waveforms across each user are not necessarily orthogonal [*Yoon*, 02]. Since the signaling waveforms of the operating users are not completely orthogonal, the signals among users sometimes collide, resulting in MAI [*Win*, 00]. MAI is a drawback in UWB systems and could adversely affect the system performance.

In general, when both the duty cycle of UWB signaling and the number of active users are low, the probability of signal collisions between users could be significantly reduced. However, the trade-off will be the slow transmission rate and low bandwidth efficiency. The performance degradation of the UWB-IR communications due to MAI was analyzed in terms of BER in [*Hu*, 03], illustrating that the system performance could be heavily degraded by MAI when the number of users is large or the transmission rate is high [*Hu*, 03].

1.1.2 Co-channel Interference from existing systems

Existing wideband systems such as wideband CDMA and the narrowband system such as PCS and AM/FM radio are operating within the bandwidth of UWB systems. UWB-IR transmits a signal with low power spectral density, which ensures that the UWB signal does not affect the current radio systems [*Win*, 00]. However, the existing systems could potentially interfere the operation of UWB-IR and therefore the potential interference among the systems is worth to be concerned [*Zhao,* 02]. Detailed studies on the interaction between the UWB and the current communications systems must be undertaken to ensure the coexistence of UWB and current system. The effect of interference and coexistence issues of UWB with UMTS, GPS and DCS1800 were examined in [*Giuliano*, 05].

1.1.3 Inter-Symbol Interference (ISI)

UWB is cited as "highly immune to multipath" due to its fine delay resolution, however, Inter-Symbol Interference (ISI) from the delayed replica of signal due to multi-path fading are sometimes unavoidable, especially in the high data rate applications [*Win*, 98b]. UWB has been proposed for use in WPANs, which requires a data rate in excess of 110Mbps per user. Therefore a required symbol period for a binary signaling system will at least need to be less than 10ns [*Klein*, 03]. Several

UWB indoor channel measurement campaigns have demonstrated that the delay spreads are far beyond 30ns [*Win*, 98b], indicating that UWB system is also suffering a significant ISI.

1.1.4 Time imprecision of pulse detection

The signal transmission of UWB-IR relies on a series of very narrow pulses. UWB-IR systems that employ a range of pulse shapes requires very fast, power efficient, and wideband components to differentiate between the distorted pulses, as well as highly stable clocks and accurate synchronization [*Gargin*, 04; *Win*, 99]. Therefore only tens of pico-seconds of the time imprecision between the transmitter and receiver could seriously affect the reliability of communication. Recently, Rowie presented an IC which contains analog, digital and RF functions that is capable of operating at a clock rate of up to 2.5 Ghz with clock jitter less than 10ps [*Rowie,* 99]. However, the clock jitter is not the only source of the time imprecision; tracking error is also a component of time imprecision. Lovelace investigated the effects of timing jitter and tracking error on the system performance, and the relationship between BER and the time imprecision was formulated in [*Lovelace,* 02].

1.2 Signal detection of UWB-IR in the presence of MAI

The conventional UWB detector introduced in [*Win*, 00; *Yoon*, 02] is a correlation detector, which consists of a bank of filters matched to pulses for each possible pulses position followed by a decision device selecting the argument of the largest input. This detector assumes that the noise is only a Gaussian random process, and that it has no process to reduce or to mitigate the MAI amongst users [*Win*, 00]. The advantage of this detector is its simplicity in receiver structure, which provides practical implementation in general applications.

However, the combined noise including MAI is not a Gaussian random process indeed, and the conventional detector becomes un-optimal as pointed out in [*Win*, 00]. Many works focused on the BER of a MA-UWB in the presence of MAI in order to investigate the performance of this conventional detector [*Durisi*, 02; *Hu*, 03]. Durisi devised a numerical expression of the Bit Error Rate (BER) using the Gaussian approximation method in [*Durisi*, 02], and then compared the value given by the expression with the BER obtained by simulation. The result comparison illustrates that the BER by simulation is often higher than that given by the numerical expression for a fixed number of active users. Hence Durisi concluded that the Gaussian approximation is not valid to characterize the system performance of MA-UWB. The inaccuracy of the Gaussian approximation is resulted in a certain degree of *uncertainty*, or *imprecision* in the signal model.

In engineering and science, complex physical models are usually described by mathematical logic or statistical models. A usual difficulty of constructing a precise model is that considerable information is necessary and required to be precise. However, according to the discussion of the author in [*Klir*, 88], "Uncertainty is an inseparable companion of almost any measurement", and it is unavoidable in almost all of the practical systems. Moreover, even the information is precise in a high degree, the complexity of the system design would be very high (sometimes unacceptable) for managing a more and more complex system [*Kruse*, 94].

A system using crisp information, which is objective knowledge based, would generally suffer imprecision [*Kruse*, 94]. Fuzzy logic is a conceptually simple, flexible and effective way to handle the vague, uncertainty and imprecision [*Klir*, 98]. Fuzzy logic attempts to coordinate the objective knowledge of the crisp information and the subjective knowledge such as the human experience and linguistic information that the crisp logic could not represent [*Kaufmann*, 85]. Therefore it is not surprising that fuzzy logic could perform better than the traditional system in an imprecise environment [*Kruse*, 94].

Fuzzy logic is widely used in the signal detection of communication systems. Leung developed a Fuzzy Integration scheme based on the Binary Integration in radar signal detection [*Leung*, 96; *Leung*, 00a; *Leung*, 00b; *Leung*, 02]. Minett developed a method to detect the fixed amplitude signal of a PSK system in a fuzzy Gaussian environment [*Minett*, 99]. Naidoo speeded up the iteration process of a multi-user detector for a DS-SS communication system [*Naidoo,* 98]. In this thesis, fuzzy detection techniques are investigated in handling the imprecision of UWB-IR communications in the presence of Multi-Access Interference.

1.3 Outline of thesis

In chapter 2 of this thesis, Fuzzy Integration detector for the MA-UWB communication systems is discussed and presented. Fuzzy Integration (FI) detector, by mapping the input vectors to a fuzzy space using a fuzzy membership function, would alleviate the performance degradation due to MAI. The performance of the FI detector has been analyzed and it has been illustrated that the FI detector has simplicity in the hardware design, and it can be applied to practical systems directly.

In chapter 3, a fuzzy signal detection method in MA-UWB using a Fuzzy Inference system (FIS) is presented. This FIS detection modifies the fuzzy space of the FI detector, resulting in a further improvement in detection performance. The enhancement in performance after applying the FIS detector is also illustrated in this chapter. The result has indicated that a significant performance improvement could be obtained by using the FIS detector.

In chapter 4, a fuzzy sub-optimal multi-user detection transmission method: fuzzy multi-stage Parallel Interference Cancellation (FPIC) is presented. The principle of the multi-stage PIC in MA-UWB is first introduced in this chapter. The multi-stage PIC has shown the ability of mitigating MAI among the interfering users; however, when the interference estimation is not reliable, the effectiveness of the PIC could be severely degraded, resulting in non-robustness in the PIC [*Correal*, 97]. A multi-stage FPIC detection technique aiming at obtaining a robust performance is then introduced and discussed. This multi-stage FPIC detector estimates the reliability of the signals first and then assigns proper cancellation weights, which chosen by a fuzzy system, to individual interference cancellation path to minimize the said error. The performance of this detector is then analyzed by comparing with the conventional and partial multi-stage PIC.

The last chapter draws the conclusion regarding the fuzzy detection techniques used in signal detection of UWB-IR in the presence of MAI. This chapter also summarizes the investigation of this thesis, and the effectiveness of using fuzzy detection techniques to improve the performance of MA-UWB is discussed.

Chapter 2

Fuzzy Integration detector in Multiple-Access UWB communications

2.1 Background

Noise and interference of UWB communications could consist of many components. It includes Multiple Access Interference (MAI) from the active users of the network, timing jitter between the transmitter and receiver, Co-channel interference from the existing narrowband systems and Inter-Symbol Interference (ISI) from the delayed replica of signal itself [*Ghavami*, 04]. In practice, these noises are unable to be described by any precise model due to their randomness, or the lack of their complete information. In general, they can be classified as *imprecision* [*Leung*, 02].

In order to overcome these imprecision, a high Signal-to-Noise Ratio (SNR) is desirable to maintain a reliable communication. In general, increasing the emission power of the UWB impulse generator could effectively increase the SNR. However, due to the laws and regulatory concerning the interference issues, the output signal power of UWB impulse generator is restricted to a maximum of -41.6dbm in the main target area of UWB spectrum, i.e. from 3.1GHz to 10.6GHz [*FCC*, 02], to prevent

UWB from interfering existed narrowband systems. In an alternative way, UWB-IR uses an over-sampling technique to increase the effective Signal-to-Noise Ratio [*Zhao, 02*]. A number of impulses are used to over-sample a symbol, and the symbol decision is made after the integration of the over-sampling pulses collected by the detector [*Win,* 98a]. However, this over-sampling technique is vulnerable to the occasional *catastrophic collisions* with other UWB active users [*Win,* 98a]. Catastrophic collisions occurs when a large number of pulses from two signals are received simultaneously, resulting in Multi-Access interference (MAI). This problem becomes serious when the UWB pulses are transmitted with uniform spacing [*Win*, 00].

Spread Spectrum (SS) techniques allow UWB-IR communications to support multi-users, minimizing the catastrophic collisions [*Win*, 00]. Two most common Spread Spectrum techniques introduced in UWB communications are Time Hopping Spread Spectrum (TH-SS) with Pulse Position Modulation (PPM), and Direct Sequence Spread Spectrum (DS-SS) with Binary Phase Shift Keying (BPSK) [*Canadeo,* 03]. Both SS techniques assign a distinct pseudo-noise (PN) sequence to each user. TH-SS PPM modulates the signal by shifting the pulses to possible referenced time positions; while DS-SS BPSK modulates the signal by assigning a polarity (± 1) to pulses according to the PN sequence [*Canadeo,* 03]. Each detector knows the exact replicas of the PN sequences of its corresponding transmitters, thus the symbol detection is made according to its own assigned code, as in the case of CDMA systems [*Yue,* 03]. Spread Spectrum techniques could eliminate catastrophic collisions significantly, and hence maintain a reliable communication in multiple-access environment.

The use of the TH-SS technique in UWB-IR is more popular as reviewed in the literature [*Win*, 98a; *Win*, 00]. The key motivations for using TH-SS PPM impulse radio are the ability of resolving multi-path fading, and that the technology of implementing UWB signals with relatively low complexity is available immediately [*Win*, 00]. A typical TH-SS UWB detector was the correlation detector [*Win*, 98a]. The correlation detector is equipped with the information of its assigned PN sequence and it makes the symbol decisions by comparing the decision statistics to a threshold. This detector has an advantage of simplicity suggesting practical implementation in general applications [*Win*, 00].

This conventional detector assumes the overall noise structure is simple Additive White Gaussian Noise (AWGN) and it is optimal when the number of other active users is zero, or the pulses from any two users will never be over-lapped [*Verdu*, 98]. However, MAI is not gaussian distributed in general; hence the conventional detector is no longer optimal in the MA-UWB system. It is difficult to obtain a complete orthogonal PN sequence among users due to their asynchronous characteristics [*Win*, 98a]. More importantly, with the number of users increasing or with the processing gain decreasing, MAI could become a major source of interference.

Yoon has proposed an optimum detection in the TH-SS UWB application [*Yoon*, 02]. This detector requires the complete knowledge of the MAI, and the complexity of this optimum receiver design grows exponentially with the number of active users. In general, the knowledge of MAI is rarely known in single user detection applications, and therefore this approach becomes impractical when there is a large number of active users in the network.

In this chapter, a Fuzzy Integration (FI) detector applying to UWB system mitigating the performance degradation due to MAI is presented. A typical THSS UWB signal model and the conventional UWB single user detector are described. The principle of the FI detector is also presented. In the last part of this chapter, the performance of the conventional detector and the FI detector are compared.

2.2 Signal Modeling of TH-SS UWB communications

The typical TH-SS UWB communications system was introduced in [*Win*, 98a]. This simulation model is widely used in the literatures [*Win*, 00; *Yoon*, 02], and it forms the basic simulation model for this work. When there are Ns active users in the network, the overall received signal is expressed as

$$r(t) = A_1 s^{(1)}(t) + \sum_{k=2}^{N_u} A_k s^{(k)}(t) + n(t) \tag{2.21}$$

This received signal composes of three components; the signal from the desired transmitting user, $s^{(1)}(t)$, the combined signal of other N_u-1 transmitting users , $\sum_{k=2}^{N_u} s^{(k)}(t)$, and the non-MAI type interference, $n(t)$. The signal of each user will be attenuated over the propagation path, and A_k is the attenuation of the k-th user. Hence the total noise $n_{tot}(t)$ is represented by

$$n_{tot}(t) = \underbrace{A_k \sum_{k=2}^{N_u} s^{(k)}(t)}_{Multiple\ \ Access\ Interference} + \underbrace{n(t)}_{thermal\ \ noise} \tag{2.22}$$

The signal of the k-th user, $s^{(k)}(t)$, is given by

$$s^{(k)}(t) = \sum_{j=-\infty}^{+\infty} w_{rec}\left(t - \tau_k - jT_f - c_j^{(k)}T_c - \delta d_j^{(k)} - \varepsilon_n^{(t)}\right) \tag{2.23}$$

The signal of the k-th user starts to transmit from $t-\tau_k$, where τ_k is the time delay between the desired user and the k-th user. Each symbol of the k-th user is over-sampled by N_s impulses, which are spaced by a pulse repetition time, T_f. The shape of impulse waveform is represented by $w_{rec}(t)$. Each user uses a distinct time hopping sequence $\{c_j^{(k)}\}$, and the pulses are shifted followed by these TH sequence to eliminate catastrophic collision in multiple accessing. These TH sequences are pseudorandom with a period N_p, where each element is an integer in the range between $0 < c_j^{(k)}(u) < N_h$, and N_h is the number of time slots within T_f. T_c is the addressable time pin, and $c_j^{(k)}T_c$ is the time shift of the j-th impulse provided by TH sequence, where $N_h T_c \le T_f$. The additional timing jitter between the transmitter and receiver is given by a zero-mean normally distributed random variable $\varepsilon_n^{(t)}$.

UWB uses over-sampling modulation scheme transmitting N_s impulses per symbol. The modulating data symbol changes only every N_s hops. To distinguish different transmitting symbols, N_s impulses corresponding to the symbol will be shifted by an additional delay, $\delta d_j^{(k)}$, where $\delta d_j^{(k)} \in \{\delta_1, \delta_2, ..., \delta_M\}$ for M-PPM, δ_1 =0 and $\delta_1 < \delta_2 < ... < \delta_M < T_c$. The distances between any adjacent symbols are sufficiently widely spaced, to ensure the signals are orthogonal among symbols.

2.3 Conventional detector of TH-SS UWB communications

A common UWB single user detector is the correlation receiver which was introduced in [*Win*, 00]. The correlation receiver is composed of a bank of correlators, each of which convolutes the received RF signals by a reference template waveform. The outputs of the correlators are then integrated, and the symbol decision is made by choosing the largest output among the bank of correlators [*Yoon*, 02]. A block diagram of the correlator bank is shown in figure 2.1.

The reference template signal for the desired user could be expressed as:

$$v_i(t) = w_{rec}(t - jT_f - c_j^{(1)}T_c - \delta_i) \tag{2.31}$$

where $\delta_i = 0, \delta_1, ...\delta_m$ is used to distinguish different symbols.

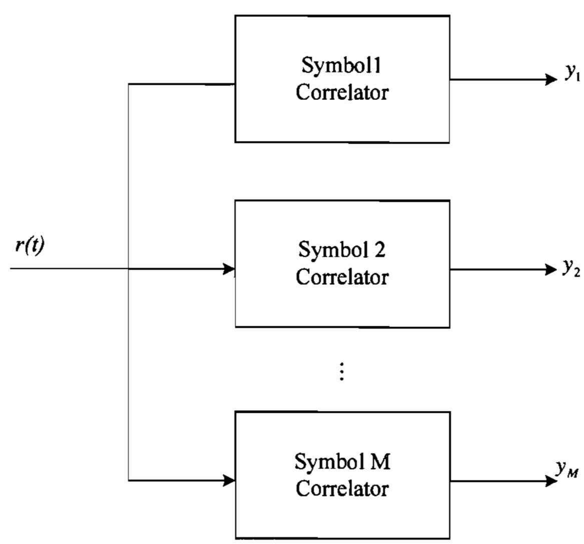

Figure 2.1: Block diagram of a correlator bank.

The convolution outputs of the correlators for each symbol, y_i, is then calculated by:

$$y_i = \sum_{j=0}^{Ns-1} \int_{\tau_1 + jT_f}^{\tau_1+(j+1)T_f} r(t)v_i(t)dt \tag{2.32}$$

The decision of each received symbol is made depending on the magnitude of the output, which are yielded by summing the corresponding N_s correlator outputs between the template and the received impulses. By choosing the largest output among the correlators, the symbol estimation a_i can be obtained by:

$$a_i = \begin{cases} 1, & if\ y_i = \max(y_1, y_2, ..., y_m) \\ 0, & if\ y_i \neq \max(y_1, y_2, ..., y_m) \end{cases} \tag{2.33}$$

The below figure is the block diagram of the conventional UWB single user detector.

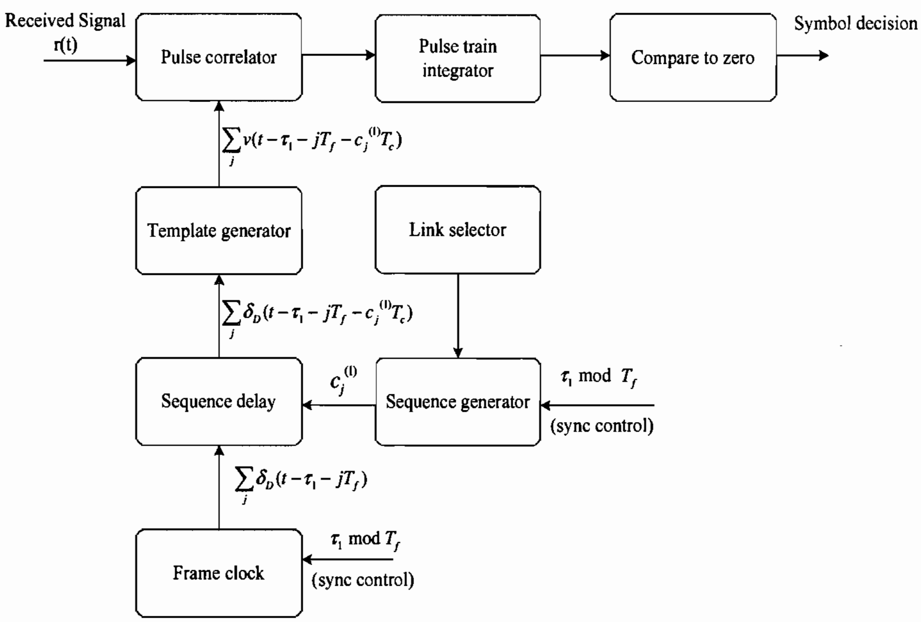

Figure 2.2: Block diagram of the desired users' receiver (from [Win, 00])

2.4 Fuzzy Integration (FI) detector in TH-SS UWB communications

The Fuzzy Integration detector is developed based on the fuzzy detection scheme for radar detection [*Leung*, 00; *Leung*, 02]. FI is different from the optimum detector introduced in [*Yoon*, 02], and does not require the knowledge of MAI, and it has an extremely low design complexity. Moreover, the design complexity of FI is independent of the number of active users.

The basic concept of FI is to suppress the MAI from each over-sampling pulses, by transforming the individual correlator output of the pulses to a fuzzy value. Similar to the conventional detection scheme, FI adapts the integration process by summation of the correlator outputs of N_s over-sampling pulses, and it improves the detection by transforming the correlator outputs of each over-sampling pulse using a fuzzy membership function, to a continuous value within [0,1] before integration. The transformed value within [0,1] represents the degree of *presence-of-pulse*, where the degree of *presence-of-pulse* represents the degree of existing of signal pulses in that locatable time positions. The block diagram of FI detector is illustrated in figure 2.3.

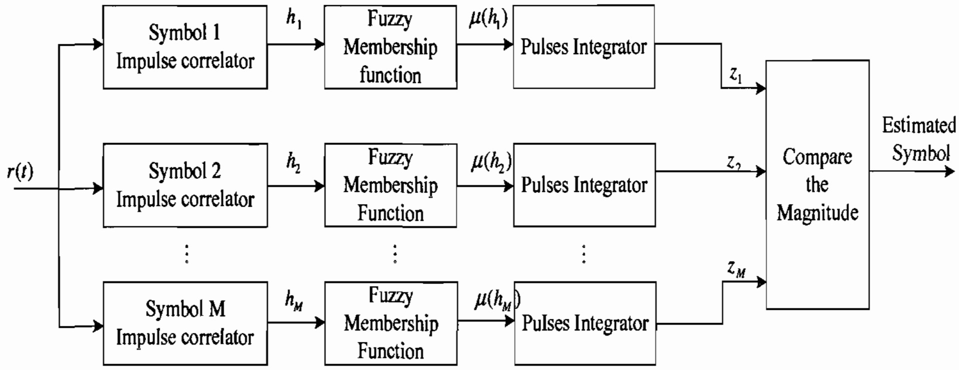

Figure 2.3: Block diagram of the FI Detector

The correlator output of the j-th over-sampling pulse of the i-th bit, h_{ij}, is obtained by the convolution between the received impulses and the template, which can be expressed by:

$$h_{ij} = \int_{\tau_1 + jT_f}^{\tau_1 + (j+1)T_f} r(t) v_i \left(t - \tau - jT_j - c_j T_c\right) dt \qquad (2.41)$$

where $i = 1,2,\ldots M$ for different symbol locations

Since the FI detector uses a single membership function to transform the correlator output to the degree of *presence-of-pulse*, the performance of the FI detector depends on the choice of the membership function. Basically, the membership function of the FI detector should obey the following rules:

$$\mu(x) \geq \mu(y) \Leftrightarrow x \geq y \tag{2.42a}$$

$$\lim_{x \to -\infty} \mu(x) = 0 \tag{2.42b}$$

$$\lim_{x \to +\infty} \mu(x) = 1 \tag{2.42c}$$

Rule (2.42a) suggests that the detector has a characteristic of monotonicity, which ensures that a greater membership value would be assigned to a stronger signal. In TH-SS UWB system, some over-sampling pulses will collide with one other, resulting in MAI. Due to the impulsive nature of UWB signals, those corrupted pulses may have large magnitudes as a result of the superposition of pulses. Rule (2.42b) and (2.42c) provide the boundary conditions to the FI detector, which limits the correlator outputs of over-sampling pulses within [0,1], preventing the domination of the symbol decision by those corrupted pulses with large magnitudes. These rules suggest the characteristics of the membership function for the FI detector, and an example, which is also being used for our investigation, is shown in figure 2.4. This piecewise linear membership function can be represented by:

$$\mu(x) = \begin{cases} 0 & : x \leq 0 \\ \dfrac{x}{S} & : 0 < x < S \\ 1 & : x \geq S \end{cases} \tag{2.43}$$

where S is the correlator output of only one over-sampling pulse without noise and interference, which is given by:

$$S = \int_0^{T_f} A_1 w_{rec}^2(t)\,dt \qquad (2.43)$$

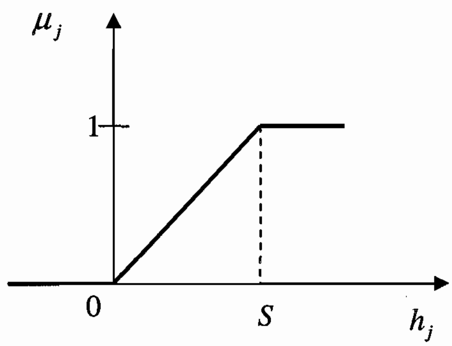

Figure 2.4: Membership function of the FI detector

After assigning the fuzzy membership function to the correlator outputs of individual impulses, the total membership value of N_s pulses for the *i*-th correlator is integrated as:

$$z_i = \sum_{j=1}^{N_s} \mu(h_{ij}), \qquad i = 1,2,\ldots,M \;\; for\ M-PPM\ . \qquad (2.44)$$

Similar to the conventional detector, by choosing the largest output among z_i, the symbol estimation $\boldsymbol{B}=[b_1, b_2 \ldots b_m]$ can be obtained by the following decision rule:

$$b_i = \begin{cases} 1, & if\ z_i = \max(z_1,\ldots,z_m) \\ 0, & if\ z_i \neq \max(z_1,\ldots,z_m) \end{cases} \qquad (2.45)$$

2.5 Performance comparison between Fuzzy Integration Detector and conventional UWB detector in multiple-access scenario

To demonstrate the performance of the presented FI detector, a simulation model of TH-SS UWB in multiple-user scenario has been carried out. Monte-Carlo method is used to obtain the performance results. The simulation model of this work is illustrated in Figure 2.5. This simulation model consists of the transmitting signal of K users, the noise channel and the desired user's detector. The template generator of the transmission unit generates a train of short pulses with a single basic pulse shape. This pulse is widely used in the Literature [*Scholtz*, 97; *Win*, 00; *Yoon*, 02], and the shape of this single basic pulse is shown in Figure 2.5.

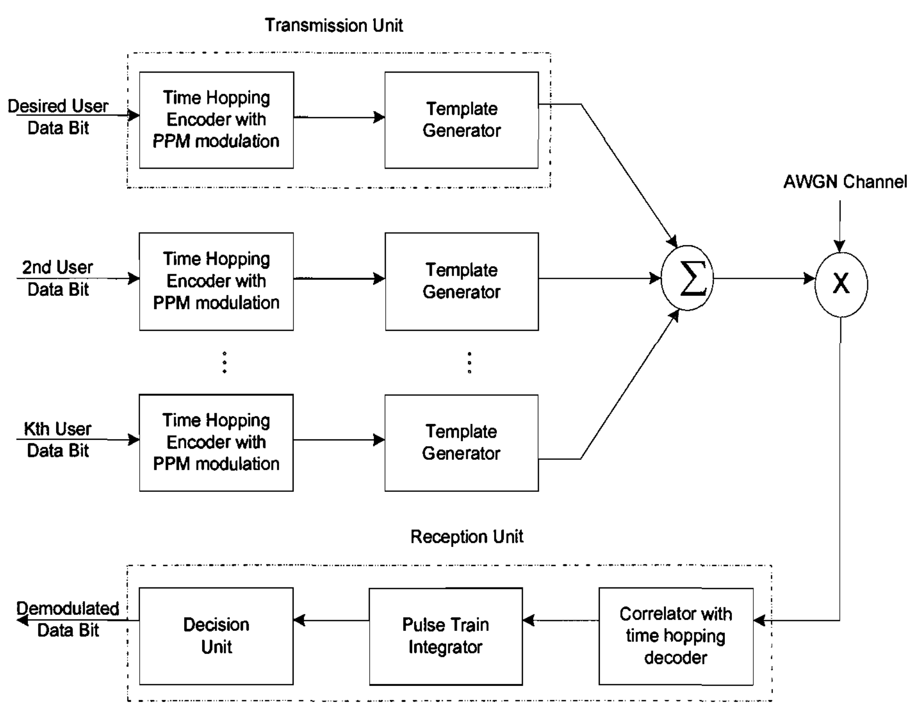

Figure 2.5: Block diagram of the simulation model

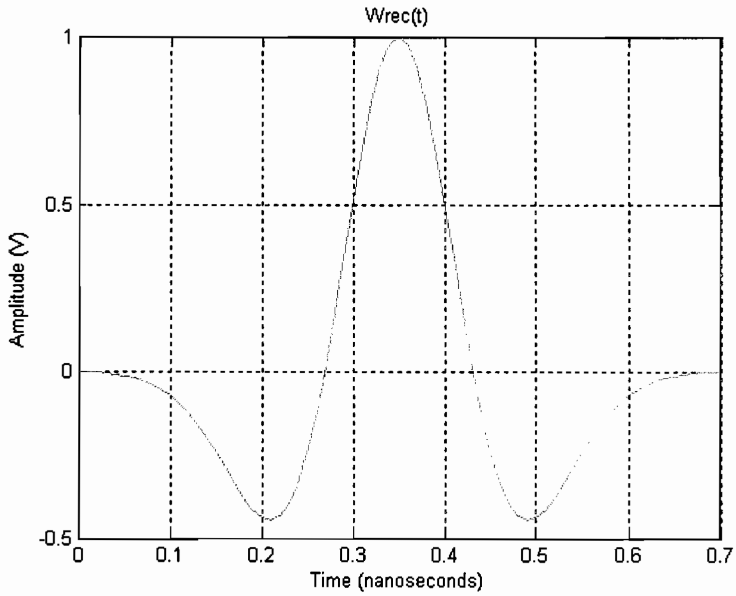

Figure 2.6: Pulse shape of the transmitting impulse

In our simulation, we set the number of time slots within a frame time, N_h, to be 100. The number of over-sampling pulses, N_s, is 5. All the active users in the network have the same N_s and N_h. The distinct time hopping sequence $\{c_j^{(k)}\}$ for all active users are generated randomly. The simulation parameters are listed in the table below:

Parameters	***Notations***	***Value***
Pulse Width	T_p	1ns
Pulse/Symbol	N_s	5
Number of Users	N_u	varies from 1 -100
Number of time slot within a frame	N_h	100
Period of periodic sequence	N_p	∞

Table 2.1: Table of simulation parameters

In general, the effect of MAI will be increased as N_u increases or N_h decreases [*Win*, 98a; *Win*, 00]. By fixing N_h and varying N_u, we can investigate the performances of presented FI detector with different levels of MAI, and all signals are transmitted in AWGN channel.

By observing the single link experiment without any operation of other users, the single user signal-to-noise ratio, SNR_1, could be defined by:

$$SNR_1 = \frac{(N_s A_1 m_p)^2}{\sigma^2{}_{rec}}. \qquad (2.51)$$

where $m_p = \int_{-\infty}^{\infty} \omega_{rec}(x-\tau)v(x)dx$.

When the number of active users or pulse repetition frequency (PRF) increases, the total output signal-to-noise ratio, SNR_{Nu}, will be degraded due to increased MAI. SNR_{Nu} are defined [*Win*, 00] by:

$$SNR_{Nu} = \frac{(N_s A_1 m_p)^2}{\underbrace{\sigma^2{}_{rec}}_{receiver\ noise} + \underbrace{N_s \sigma^2{}_a \sum_{k=2}^{Nu} A_k^2}_{MAI}}. \qquad (2.52)$$

In our analysis, we assume perfect power consumption by all users, i.e. the transmitting powers of all users are equal. The single user signal-to-noise ratio, SNR_1, which is defined in equation 2.41, is set to 13, 16 and 19dB. The number of users, N_u is varied from 1 to 100, and N_h is set to 100. This enables us to investigate the performance of the FI detector with different SNR_{Nu}, as it is obvious that SNR_{Nu} varies with the N_u and N_h. Figure 2.7 and 2.8 shows the BER of the detectors against the number of active users for 2-ppm and 4-ppm; while Figure 2.9 and 2.10 show the BER of the detectors against SNR_{Nu} for 2-ppm and 4-ppm, respectively.

Figure 2.7 and 2.8 illustrate the BER performance of 2-ppm and 4-ppm against N_u. In figure 2.7, with a specific SNR_I equal to 16dB, the 2-ppm FI detector can maximally support 32 users with a constant BER of 10^{-4}, while the 2-ppm conventional detector can only support 17 users with the same BER. In figure 2.8, with a specific SNR_I equal to 16dB, the 4-ppm FI detector can support 30 users with a constant BER of 10^{-4}, and the 4-ppm conventional detector can support 22 users.

Figure 2.9 and 2.10 illustrate the BER performance against SNR_{Nu}. In figure 2.9, with a specific SNR_I equal to 16dB, the required SNR_{Nu} for 2-ppm FI detector to maintain a BER 10^{-4} is 7.8dB, while 11dB is required for 2-ppm conventional detector, indicating an improvement gain of 3.2 dB is obtained by using FI detector. For 4-ppm, the required SNR_{Nu} is 8dB for FI, while 9.4dB is required for a conventional detector, indicating an improvement gain of 1.4 dB is obtained by using FI detector.

Observed from these figures, FI detectors can obtain a better BER performance than that of the conventional detector when the number of users is significant. In general, with a high collision rate in multiple accessing, i.e., a significant number of pulses are received from more than one signal in the same time slot, FI detector could perform much better than the conventional detector. In 2ppm, the possible time positions to represent different symbols are 2, while there are 4 possible time positions for 4-ppm. Therefore the rate of collision of 2-ppm is double of that of 4-ppm, and hence a larger improvement is obtained by 2-ppm rather than 4-ppm.

It is obvious that the conventional detector is optimal when Nu equals to 1. In a multiple-access environment, the proposed detector can only perform more or less the same, or even worse compared with the conventional detector, if the number of users is very small. Taking for example, with SNR_1= 13dB, the 2-ppm FI detector performs better than the conventional detector when $N_u>3$. While 4-ppm FI detector performs better than the conventional detector when $N_u>7$.

In this chapter, a Fuzzy integration detector alleviating the degradation due to MAI was presented. Performance evaluation proved that, FI detector could out-perform the conventional detector when the number of users is significant. Moreover, this detector does not require any knowledge of MAI, and it has very simple hardware complexity which can be directly implemented in practical applications.

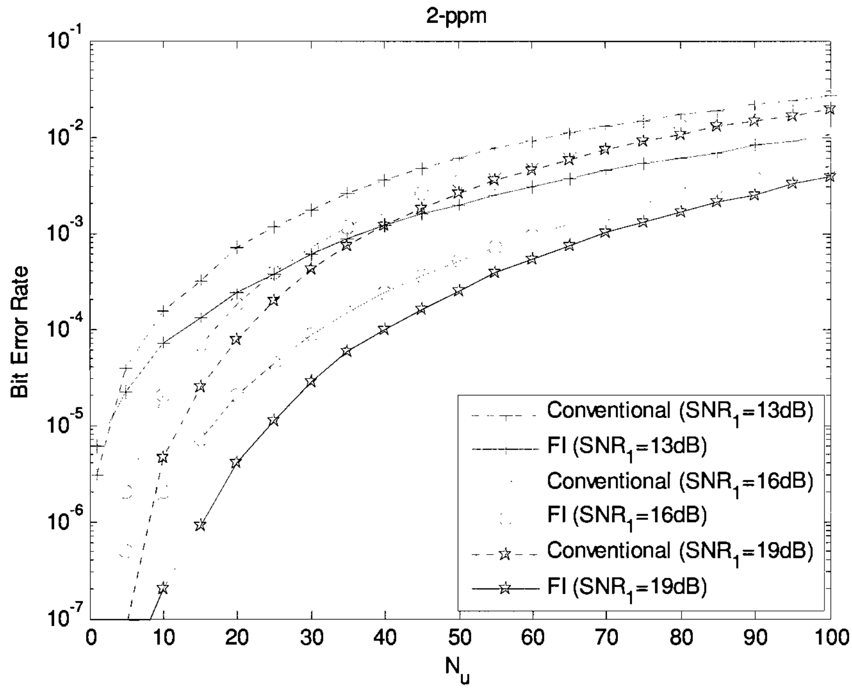

Figure 2.7: BER of the detectors against the number of active users for 2-PPM

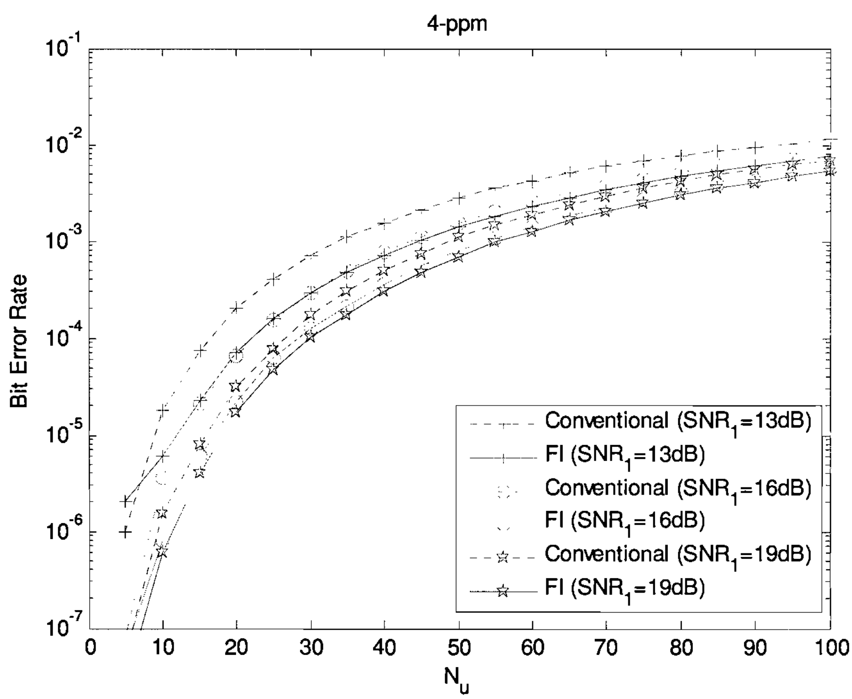

Figure 2.8: BER of the detectors against the number of active users for 4-PPM

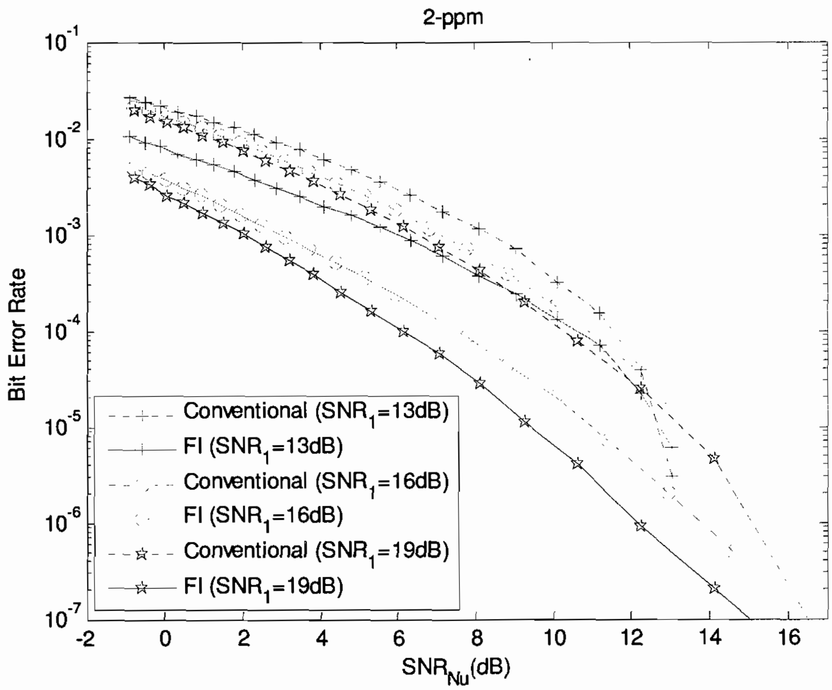

Figure 2.9: BER of the detectors against SNR_{Nu} for 2-PPM

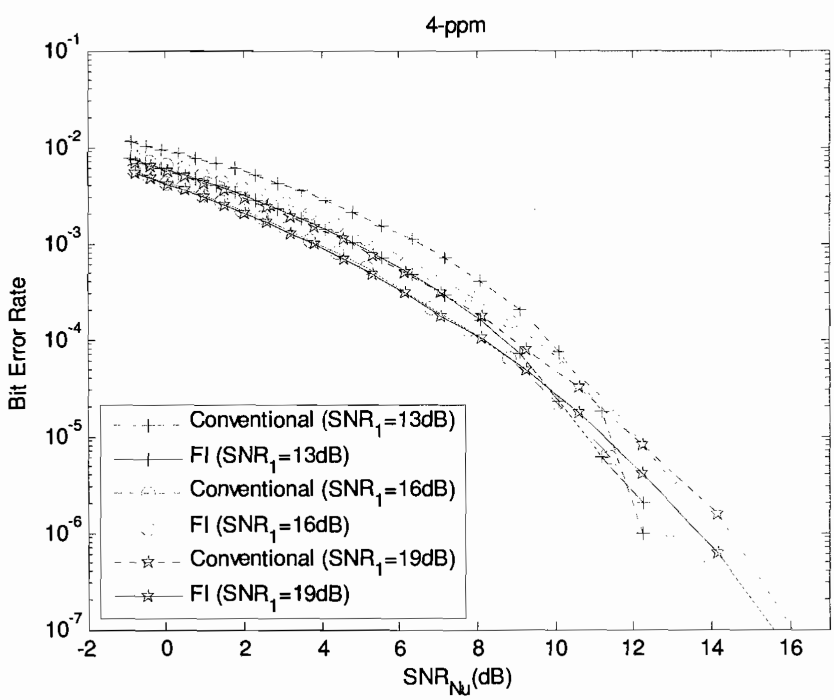

Figure 2.10: BER of the detectors against SNR_{Nu} for 4-PPM

Chapter 3

Fuzzy signal detection method in MA-UWB communications using Fuzzy Inference System

3.1 Background

Fuzzy integration (FI) detector could significantly improve the system performance of UWB-IR communications in the presence of MAI as discussed in the previous chapter. The FI detector keeps the simplicity by using only a single membership function fuzzifing the individual correlator outputs to fuzzy membership values between [0, S], where S is the correlator output of one over-sampling pulse without noise and interference, to improve the detection performance of TH-MA UWB system. The fuzzification process of FI detector, in effect, performs a clipping-like process with the thresholds 0 and S, in order to prevent any corrupted pulses with high amplitude from dominating in the decision process.

The FI detector could significantly out-perform the conventional detector, however, only when the system load is very light, i.e. the number of users is very small. The performance of the FI could only approach that of the conventional detector. The simplicity of the FI detector using a single membership function is a traded off to the system performance when the number of users is very low.

In general, for obtaining a further performance improvement, the thresholds of the membership function can be dynamically adjusted according to various operation environments. Obviously, the conventional detector is optimum when the number of other users is zero [*Win*, 00]. In such situation, the thresholds of the membership function of could approaches $\pm\infty$, i.e. the detector performs no process on the received signal as the conventional detector would have done. When the number of users grows, the thresholds could tend to 0 and S, i.e. the detector performs a clipping process on the received signal, as the FI detector would have done. On the other hand, when both the single user signal-to-noise ratio, SNR_1, and the number of users are high, i.e. MAI is dominant, the thresholds would approach 0 and S. When the single user signal-to-noise ratio, SNR_1, is low, i.e. the thermal noise is dominant, the thresholds would approach $\pm\infty$.

To carry out the clipping process with variable thresholds for further performance improvement, a detection algorithm using Fuzzy Inference System (FIS) has been developed and is presented in this chapter. The FIS detector aims at improving the detection performance by selecting appropriate thresholds in various operation environments. In this chapter, the algorithm for this FIS detector is described, and the performance is evaluated via Monte-Carlo simulation. Performance comparison among the FIS, FI and the conventional detector is then illustrated in order to investigate the performance of the presented detector.

3.2 FIS detection Scheme in TH-SS UWB communications

Fuzzy inference system is a systematic method to adopt the human experience and linguistic concepts into the decision process based on the principle of fuzzy logic [*Mamdani*, 85]. The FIS adopts the subjective knowledge into the system by formulating a mapping from certain crisp inputs to an output, and the output of the mapping then provides a basis upon which the decisions can be made [*Kruse*, 94]. FIS has been successfully applied in many fields such as automatic control, data classification and decision analysis [*Kruse*, 94].

There are several fronts of research in the use of FIS in communications systems. Homnan [*Homnan*, 00] established an algorithm to adjust the soft handoff thresholds in CDMA systems using FIS. The soft handoff thresholds are chosen depending on the traffic load of the system. Lee [*Lee*, 03] presented a novel fuzzy pre-distorter technique. The phase and amplitude inversion of the WCDMA power amplifier are estimated using FIS, and the linearity of this power amplifier is hence improved. Naidoo [*Naidoo,* 98] used FIS to speed up the iteration process of a multi-user detector in DS-SS communication system. The iteration process is forced to converge quickly by choosing a large step-size when the error statistic is low.

In this section, the algorithm of the FIS adopted in the detection process is discussed and presented. The components of the FIS system, namely the crisp inputs, fuzzification, fuzzy inference machine, defuzzification and the crisp outputs are introduced. Fuzzification fuzzifies the crisp inputs to fuzzy values by the defined membership functions. Fuzzy inference machine operates the fuzzy arithmetic according to the *if-then-rules* using fuzzy operators. Defuzzification maps the operated fuzzy values into crisp outputs, and the crisp outputs provide a basis for system decision making [*Kruse*, 94]. In the following section, the components of the FIS would be discussed in detail.

3.2.1 Fuzzification

The first step of the FIS is to take the appropriate inputs and determine, via the membership functions, the degree to which they belong to each of the suitable fuzzy sets [*Kruse*, 94]. For a general FIS, the input of the fuzzification is always a crisp numerical value limited to the universe of discourse of the input variable, and the output of the fuzzification is a fuzzy degree of membership in the qualifying linguistic set (the interval is always between 0 and 1) [*Siler*, 05]. For the presented FIS detector, the optimal threshold which clips the magnitudes of over-sampling pulses varies with SNR_I (dB) and the rate of collision N_u/N_h, where N_h is the number of time slots within a frame time. The rate of collision N_u/N_h is the ratio between the number of operating users and the number of time slots within a frame time, representing the probability of the pulses collision occurring in the same slot; while SNR_I is the Signal-to-Noise Ratio without any other operating users.

The first step in the presented FIS is to fuzzify the crisp inputs SNR_I and N_u/N_h by fuzzification. Fuzzification of the crisp inputs is generally evaluated by fuzzy membership functions. Fuzzy membership functions define the grades of membership of linguistic variables corresponding to the inputs of fuzzification [*Mamdani*, 85]. In general, membership functions could be of almost any shape. Some of the common shapes of membership functions are triangular (piecewise linear), s-shape (piecewise quadratic), normal bell-shaped or trapezoidal [*Siler*, 05]. All of these membership functions are associated with an interval within [0,1] indicating its grade of membership. It is common to define the fuzzy membership function as a triangular function because piecewise linear functions are easy to handle by computers [Kruse, 94]. A typical triangular membership function is illustrated in figure 3.1, which is given by:

$$\mu(x)=\begin{cases} 0, & x\le a \\ (x-a)/(b-a), & a<x\le b \\ (c-x)/(c-b), & b<x\le c \\ 0, & x>c \end{cases} \tag{3.21}$$

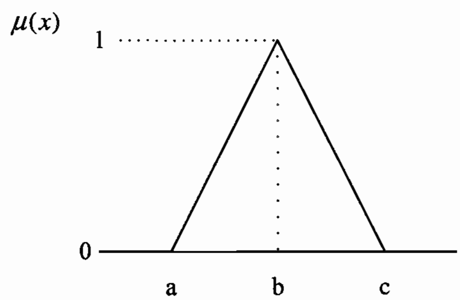

Figure 3.1 A typical triangular membership function

The membership functions of the crisp inputs N_u/N_h and SNR_1 used by the FIS detector are illustrated in figure 3.2a and 3.2b respectively.

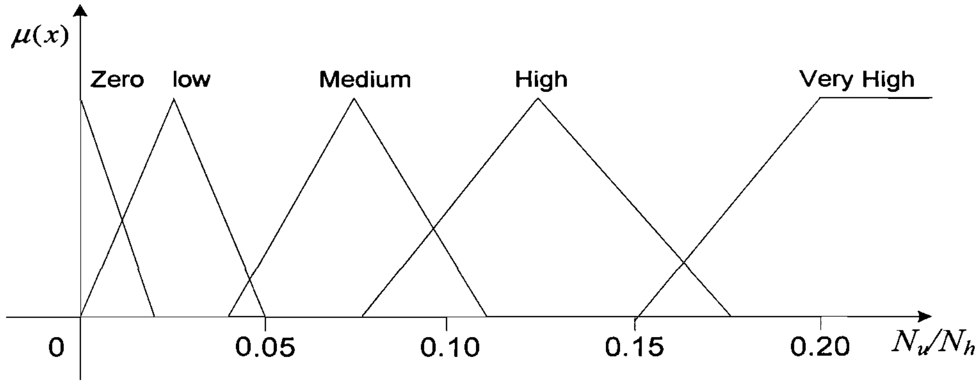

Figure 3.2a Membership functions of the collision rate N_u/N_h

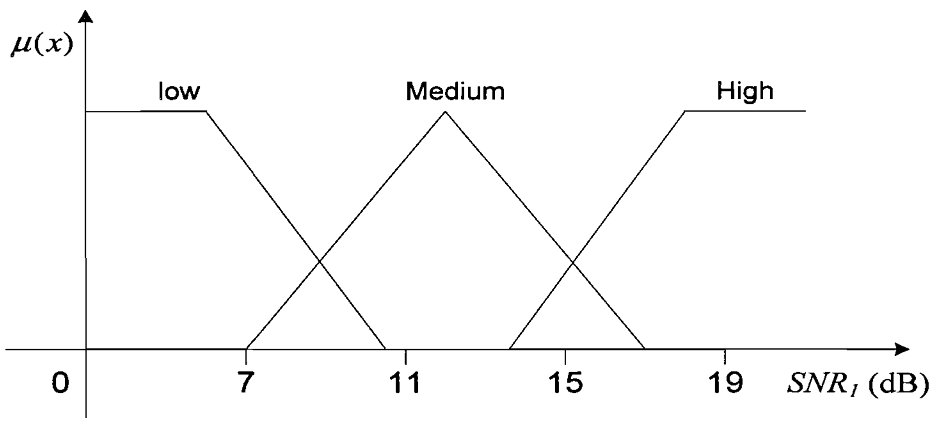

Figure 3.2b Membership functions of the SNR_I

3.2.2 Fuzzy Inference Machine

After the crisp input is fuzzified by fuzzification interface, the fuzzy inference machine of the presented FIS will perform fuzzy operations according to the pre-defined fuzzy *if-then-rules*. The fuzzy *if-then-rules*, which could be formulated as:

If X is A **then** Y is B (3.22)

$X = A^{'}$ infer that $Y = B^{'}$

where A and $A^{'}$ are the fuzzy sets defined in the same universe, and B and $B^{'}$ are also fuzzy sets defined in the same universe, which may be different from the universe in which A and $A^{'}$ are defined.

The fuzzy inference machine performs fuzzy operations on the fuzzified inputs by the fuzzy operators, obtaining one number that represents the result of the antecedent (fuzzified inputs) for each rule. The input to the fuzzy operator is two or more membership values from fuzzified input variables. The most common fuzzy operators are fuzzy intersection or conjunction (AND), fuzzy union or disjunction (OR), and fuzzy complement (NOT) [*Kruse*, 94]. The fuzzified inputs of the collision rate N_u/N_h and the single user signal-to-noise ratio SNR_1 are then operated by the fuzzy operators. An example of applying a fuzzy intersection operator (AND) is illustrated in figure 3.3.

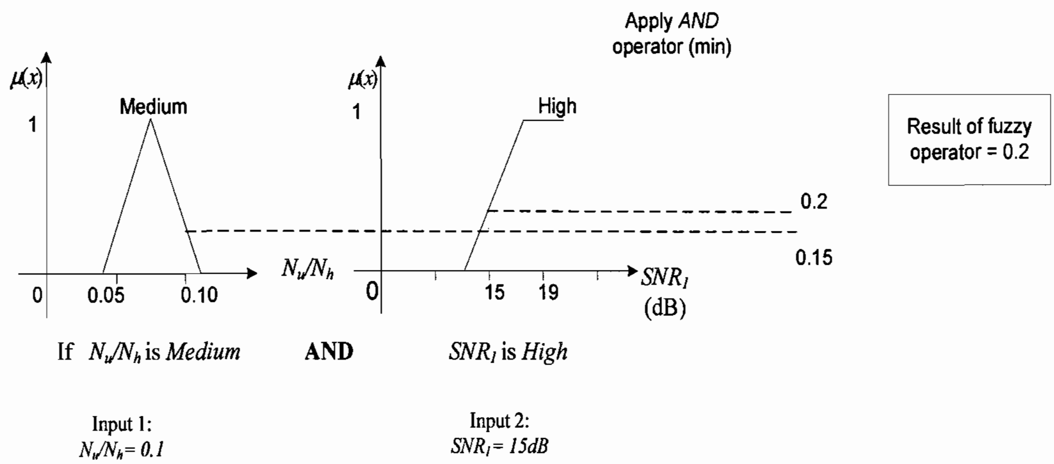

Figure 3.3 Example of operating a fuzzy operator ***AND.***

The results of the fuzzy operator represent the degree of the fuzzified inputs satisfying each fuzzy *if-then-rule*. Implication process is then operated to define the output memberships for each *if-then-rule*. The input for the implication process is a single number obtained by applying the fuzzy operator, and the output is a fuzzy set representing the output membership of the rule [*Kruse*, 04]. The implication operator used in this work is the Zadeh operator, which is given by

$$\text{P } \textbf{AND} \text{ Q} = \min(\text{P,Q}) \tag{3.23}$$

An example of implication in the fuzzy inference machine of this work is illustrated in the figure 3.4.

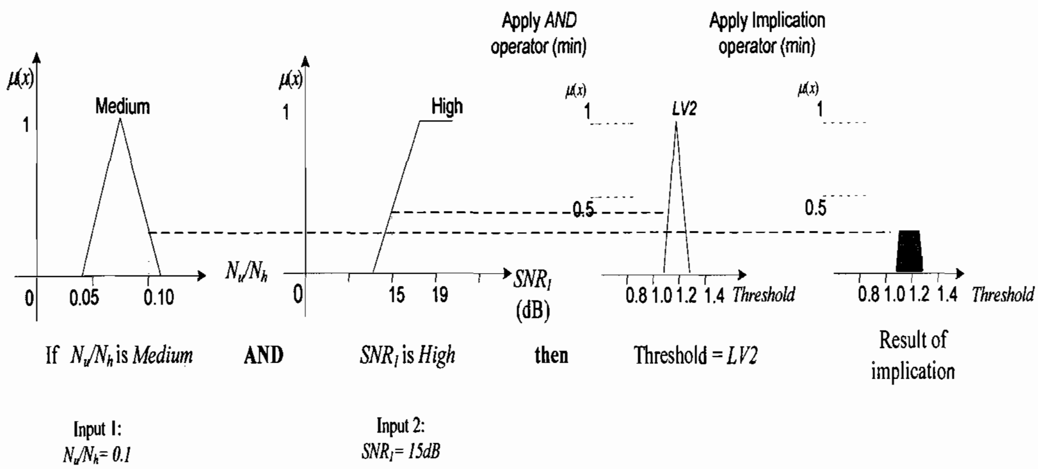

Figure 3.4 Example of operating implication.

A process is required to combine the results of implication of all rules in order to make the final decision [*Kruse*, 04]. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set μ_{output}. The single fuzzy set μ_{output} is then applied in the final step of the FIS system, i.e. defuzzification. The aggregation method is commutative and therefore the order in which the rules are executed is unimportant. The aggregation method used in this work is max. (maximum), which holds the maximum value along the fuzzy sets obtained by the fuzzy implication processes. An example of aggregation of the operated fuzzy sets with $SNR_I=12dB$ and $N_u/N_h=0.1$ is illustrated in figure 3.5.

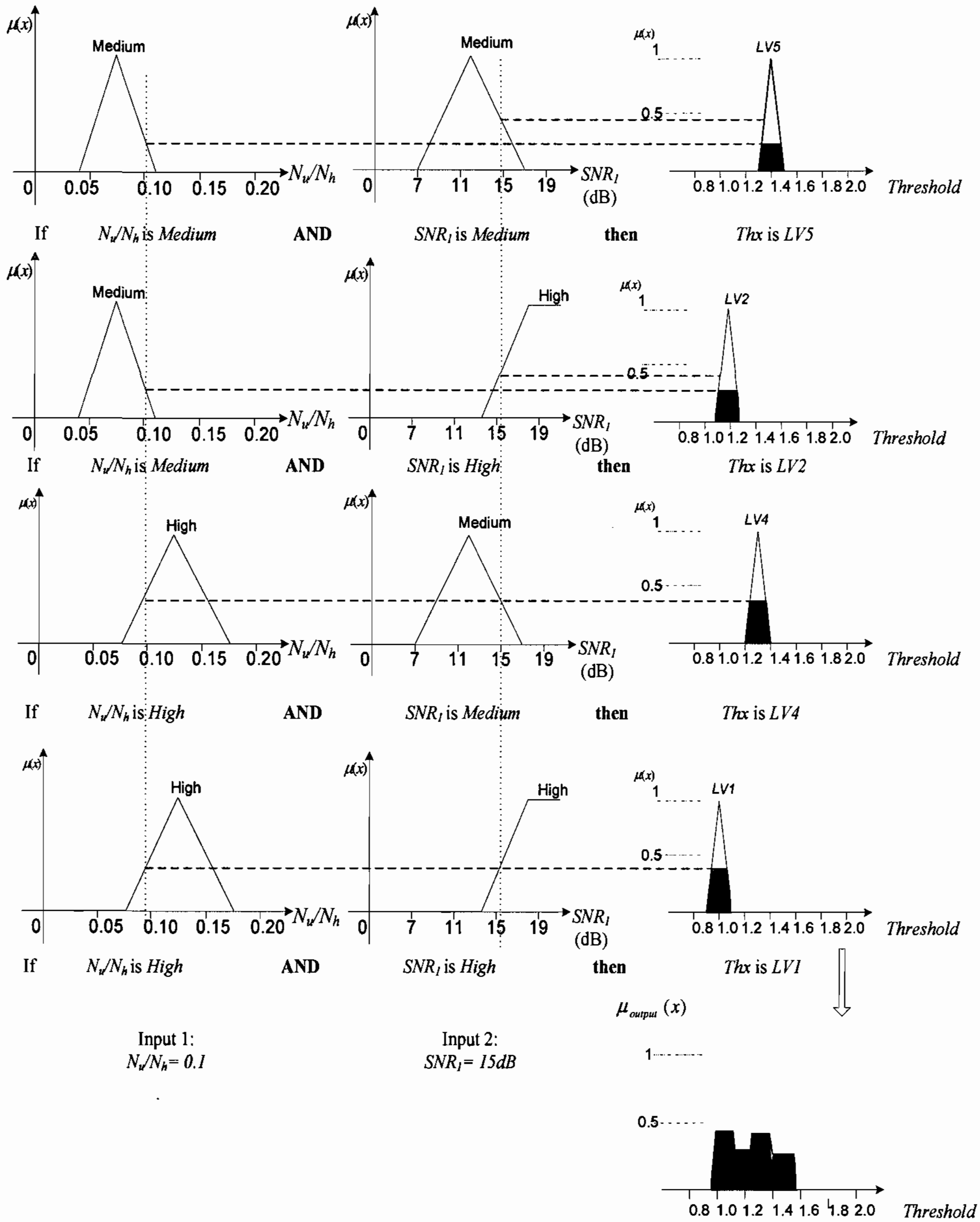

Figure 3.5 Aggregation of operated fuzzy sets with N_u/N_h=0.1, SNR_I=12dB

The process of applying fuzzy operator and implication are based on a number of fuzzy *if-then-rules*. The fuzzy *if-then-rules* are established based on the ideas below: When the rate of collision N_u/N_h tends to zeros, the thresholds should approach $\pm\infty$, and the magnitudes of the thresholds should be set smaller when N_u/N_h grows. When both SNR_1 and N_u/N_h are high, the thresholds should approach -S and S, and the magnitudes of the thresholds should be set larger when the SNR_1 or N_u/N_h decrease. When the SNR_1 is low, the thresholds should approach $\pm\infty$. Based on the above conclusion upon the appropriate thresholds and SNR_1 and N_u/N_h, a number of fuzzy *if-then rules* are established. The linguistic representations of the fuzzy *if-then-rules* are given by

Rule 1: **If** (N_u/N_h is *Zero*) **then** (*Thx* is *Infinite*)

Rule 2: **If** (N_u/N_h is *low*) **AND** (SNR_1 is *low*) **then** (*Thx* is *LV12*)

Rule 3: **If** (N_u/N_h is *low*) **AND** (SNR_1 is *Medium*) **then** (*Thx* is *LV7*)

Rule 4: **If** (N_u/N_h is *low*) **AND** (SNR_1 is *High*) **then** (*Thx* is *LV4*)

Rule 5: **If** (N_u/N_h is *Medium*) **AND** (SNR_1 is *low*) **then** (*Thx* is *LV11*)

Rule 6: **If** (N_u/N_h is *Medium*) **AND** (SNR_1 is *Medium*) **then** (*Thx* is *LV5*)

Rule 7: **If** (N_u/N_h is *Medium*) **AND** (SNR_1 is *High*) **then** (*Thx* is *LV2*)

Rule 8: **If** (N_u/N_h is *High*) **AND** (SNR_1 is *low*) **then** (*Thx* is *LV9*)

Rule 9: **If** (N_u/N_h is *High*) **AND** (SNR_1 is *Medium*) **then** (*Thx* is *LV4*)

Rule 10: **If** (N_u/N_h is *High*) **AND** (SNR_1 is *High*) **then** (*Thx* is *LV1*)

Rule 11: **If** (N_u/N_h is *Very High*) **AND** (SNR_1 is *low*) **then** (*Thx* is *LV8*)

Rule 12: **If** (N_u/N_h is *Very High*) **AND** (SNR_1 is *Medium*) **then** (*Thx* is *LV3*)

Rule 13: **If** (N_u/N_h is *Very High*) **AND** (SNR_1 is *High*) **then** (*Thx* is *LV1*),

The output membership functions of the presented FIS are illustrated in figure 3.6.

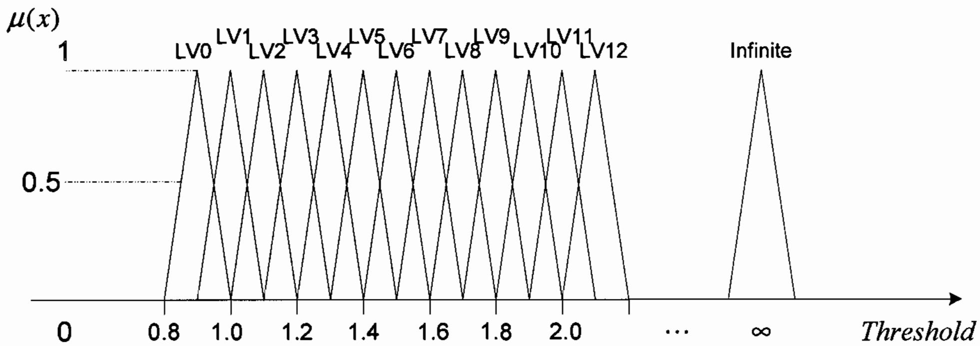

Figure 3.6 Output membership functions of the presented FIS

The output membership functions define the amplitude of the threshold, where the minimum amplitude of the threshold would be 1.0 and the maximum amplitude of the threshold would be infinite. The thresholds are then adopted into the detection algorithm to alleviate MAI.

3.2.3 Defuzzification

Defuzzification of the FIS computes the crisp output C_{output} from the μ_{output} obtained by the implication process [*Siler*, 05]. The crisp output C_{output} is the final output of the FIS system, and it defines the thresholds that will be adopted into the detection process. There are several choices for defuzzification, and many different methods have been proposed in literature [*Siler*, 05]. They are the Max Criterion Method (MC), Mean of Maxima method (MOM) and Centre of Area method (COA). The COA method, one of the most popular methods for the defuzzification strategies, is chosen to evaluate the crisp output of the FIS. The COA method returns the center of area under the curve of μ_{output}, and C_{output} could be evaluated as

$$C_{output} = \frac{\int_a^b x\mu_{output}(x)dx}{\int_a^b \mu_{output}(x)dx} \tag{3.24}$$

where [a,b] are the supported interval of the aggregated membership function.

An example of defuzzification with N_u/N_h=0.1, SNR_l=12dB is illustrated in figure 3.7. In this example, the crisp output C_{output} is 1.2 and it defines the new thresholds for the FIS detector.

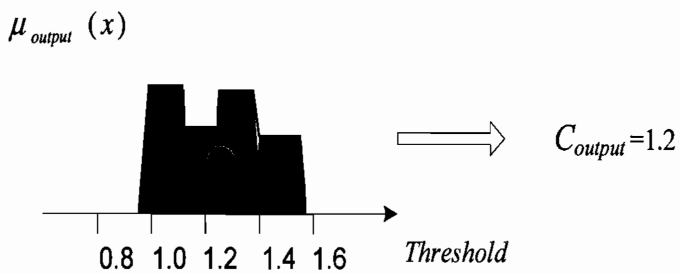

Figure 3.7 Example of defuzzification of the presented FIS

The crisp output of the FIS C_{output} is then adopted to be the threshold of the presented detector, to limit the amplitude of the correlator outputs of the over-sampling pulses.

3.3 Performance analysis of the FIS detector in multiple-access UWB-IR system

The TH-SS MA-UWB model is introduced in [*Win*, 00] and it is used to analyze the detector performance in this thesis. In order to demonstrate the effectiveness of the FIS detector in the presence of MAI, Monte-Carlo simulation was used to obtain the BER performances of the three detectors: the conventional detector, FI detector and FIS detector.

The difference between the FI and the FIS detector presented in this chapter is that the FI detector uses a single membership function to limit the correlator outputs within the fixed thresholds 0 and S, while the FIS detector limits the amplitudes of the correlator outputs of over-sampled pulses by thresholds decided by FIS. Figure 3.8 shows the block diagram of the presented FIS detector.

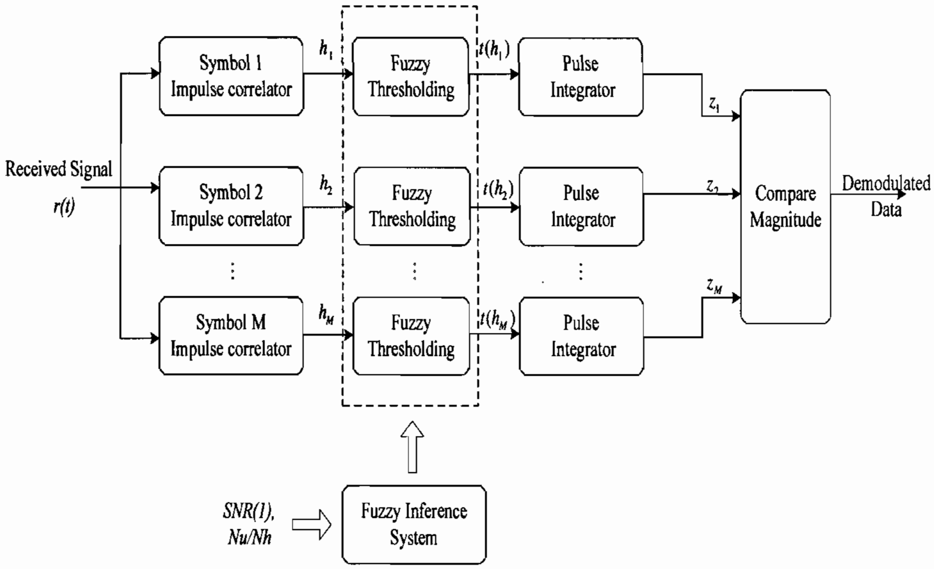

Figure 3.8: Block Diagram of the FIS detector

The fuzzy inference system has to know the value of crisp inputs N_u/N_h and SNR_1 to determine the thresholds of the FIS detector. According to [*Win*, 00], the SNR_1 could be obtained by the single-link experiment, and it is assumed to be known in this work. The number of users N_u is obtained by estimation, which is given by

$$\frac{1}{S}\sum_{i=1}^{S}\sum_{j=1}^{N_h}\sum_{k=1}^{2}\int_{x_1}^{x_1+ST_f} r(t)w_{rec}(t-iT_f-jT_c-\delta_k)dt \tag{3.25}$$

where S is the number of sampling frame for estimation of N_u and N_h is number of time slot within a frame time.

After the input parameters N_u/N_h and SNR_1 are known (by estimation and single-link experiment), the fuzzy inference system chooses the appropriate threshold depending on the input parameters, and the corresponding outputs could be evaluated according to the defined fuzzy *if-then-rules*. The relationship between the output threshold and the inputs SNR_1 and N_u/N_h, which are obtained by evaluating a range of input parameters by the FIS, is illustrated in figure 3.9.

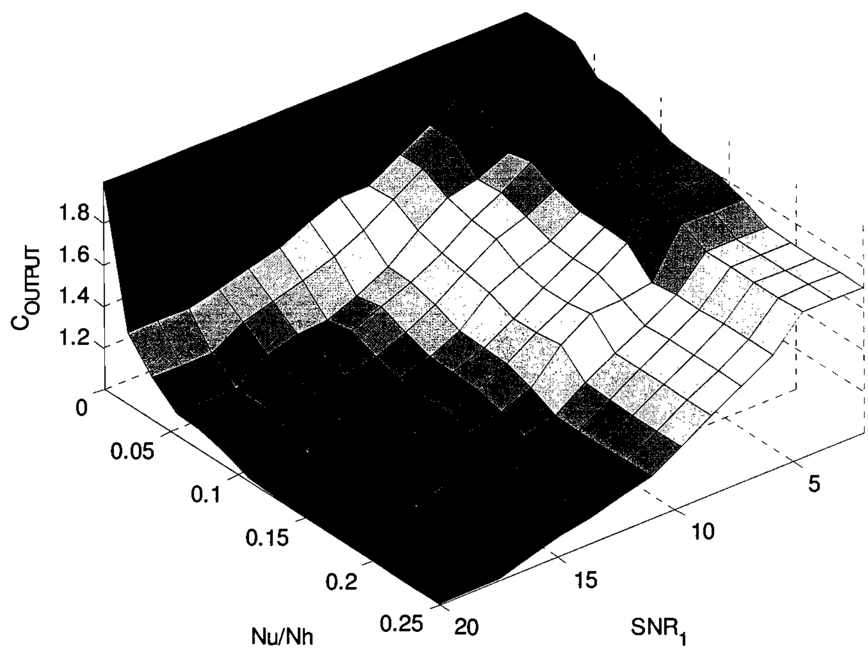

Figure 3.9: Output Surface of FIS: Thresholds against N_u/N_h and SNR_1

After the fuzzy thresholds were determined, the amplitudes of the correlator output of individual over-sampling pulses will be in effect clipped. Again, the individual correlator output of the j-th over-sampling pulse of i-th, h_{ij}, is obtained by the convolution between the received impulses and the template, given by:

$$h_{ij} = \int_{\tau_1 + jT_f}^{\tau_1+(j+1)T_f} r(t) v_i (t - \tau - jT_j - c_j T_c) dt \tag{3.31}$$

where $i = 1,2,...M$ for different symbol locations.

The correlator outputs h_{ij} will then be thresholded by C_{output}, and the processed correlator output C_{ij} could be evaluated by

$$C(x) = \begin{cases} -C_{output} & : x \leq -C_{output} \\ x & : -C_{output} < x < C_{output} \\ C_{output} & : x \geq C_{output} \end{cases} \tag{3.32}$$

The decision statistic for the i-th correlator is then calculated by summation of C_{ij}, which could be expressed as:

$$s_i = \sum_{j=1}^{N_s} C(h_{ij}), \qquad i = 1,2,...,M \ \ for\ M - PPM\ . \tag{3.33}$$

The final symbol decision $\boldsymbol{B}=[b_1, b_2 \ldots b_m]$ is then made by choosing the largest output among s_i, expressed as:

$$b_i = \begin{cases} 1, \ if\ s_i = \max(s_1, ..., s_m) \\ 0, \ if\ s_i \neq \max(s_1, ..., s_m) \end{cases} \tag{3.34}$$

In this work, a time hopping UWB-IR system with 2-ppm modulation scheme has been investigated. The single user signal-to-noise ratio SNR_1 of the system was set to 10, 13 and 16dB. The BER performances of the conventional, FI and FIS detector against number of users N_u are illustrated in figures 3.10, 3.11 and 3.12, while the BER performances of the conventional, FI and FIS detector against the overall signal-to-noise ratio SNR_{Nu} are illustrated in 3.13, 3.14 and 3.15.

Near-far problem due to different distances among the base station and mobile stations [*Win*, 00] would further degrade the performance of UWB systems. In order to analyze the performance of the presented detectors under the influence of near-far effect, an additional simulation with the amplitudes of the operating users are randomly selected in the range from 0 to 6dB, was carried out. The performances were illustrated in figure 3.16 and 3.17.

Figure 3.10-12 shows the BER performances of the detectors against the number of users N_u. Simulation results illustrated that the FIS detector always outperforms the conventional and the FI detector. Figure 3.11 shows the performance of the detectors with a specific SNR_1 equal to 13dB. The conventional detector and the FI detector can maximally support 15 and 25 users respectively, with a constant BER equals to 10^{-4}, while the FIS detector can support 30 users with the same BER. Figure 3.12 shows the performance of the detectors with a specific SNR_I equal to 16dB. The conventional detector and the FI detector can maximally support 16 and 30 users, while the FIS detector can support 35 users.

Figure 3.13-15 shows the BER performances of the detectors against SNR_{Nu}. Figure 3.14 shows the performance of the detectors with a specific SNR_I equal to 13dB. The required SNR_{Nu} for the conventional and FI detector to maintain a BER of 10^{-4} is 11dB and 10dB respectively, while only 9.5dB is required for FIS detector, indicating that a further 0.5dB improvement is obtained. Figure 3.15 shows the performance of the detectors with a specific SNR_I equal to 16dB. The required SNR_{Nu} for the conventional and FI detector to maintain a BER equal to 10^{-4} is 12.4dB and 10.8dB respectively, while only 10.2dB is required for FIS detector, indicating that a further 0.6dB improvement is obtained.

Figures 3.16-3.17 show the BER performances of the presented detectors in an imperfect power control channel with amplitude varies from 0 to 6 dB, with SNR_I equals to 16dB. Similar improvement is observed, that verify the effectiveness of the FIS detector in the imperfect power control channel.

Observed from figures 3.10 and 3.13, FI detector performs worse than the conventional detector when the system load is light. FIS detector could overcome the drawback of the FI detector and FIS performs better than the conventional detector even when the number of other users is small. When the number of other users is zero, the FIS detector simply reduces to the conventional detector by setting the thresholds to $\pm\infty$.

In this chapter, the detection algorithm of the FIS detector was discussed and presented. Performance evaluation illustrated that the FIS detector could obtain a further improvement compared with the FI detector. Moreover, the FIS detector could perform better then the FI and conventional detector when the number of users is significant, and FIS could perform more or less the same as the conventional detector when the number of other users is very small or zero. Results illustrated that the performance of the FIS detector is more robust along a range of number of users.

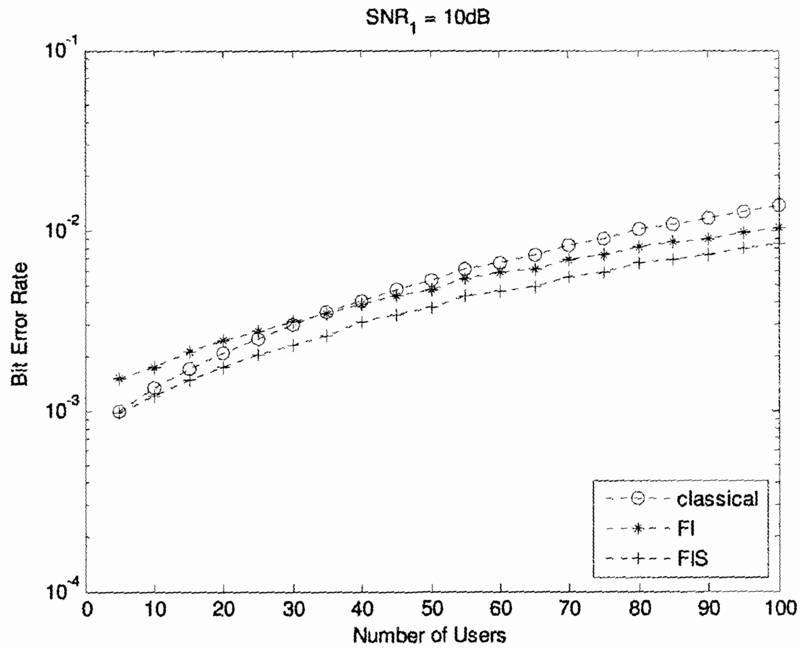

Figure 3.10: BER of the detectors against N_u with SNR_1 =10dB

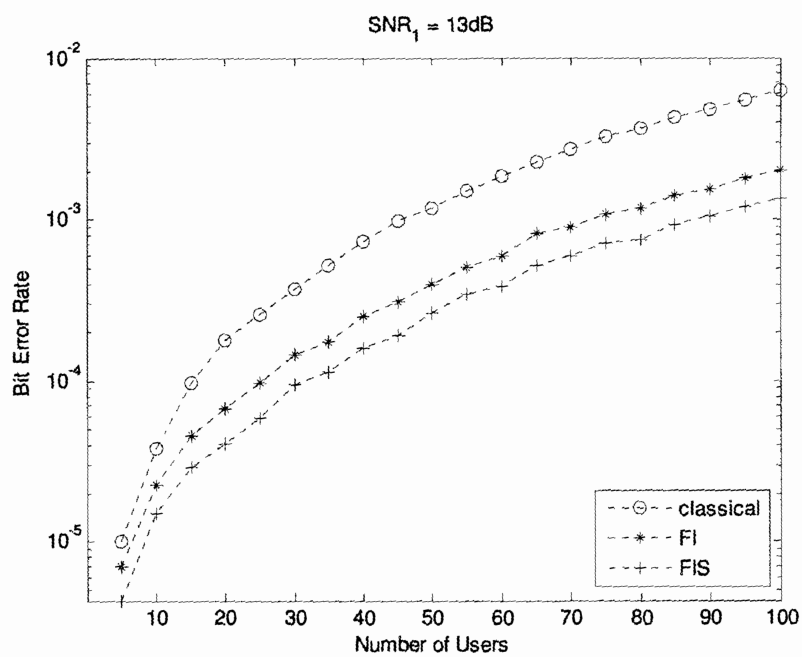

Figure 3.11: BER of the detectors against N_u with SNR_1 =13dB

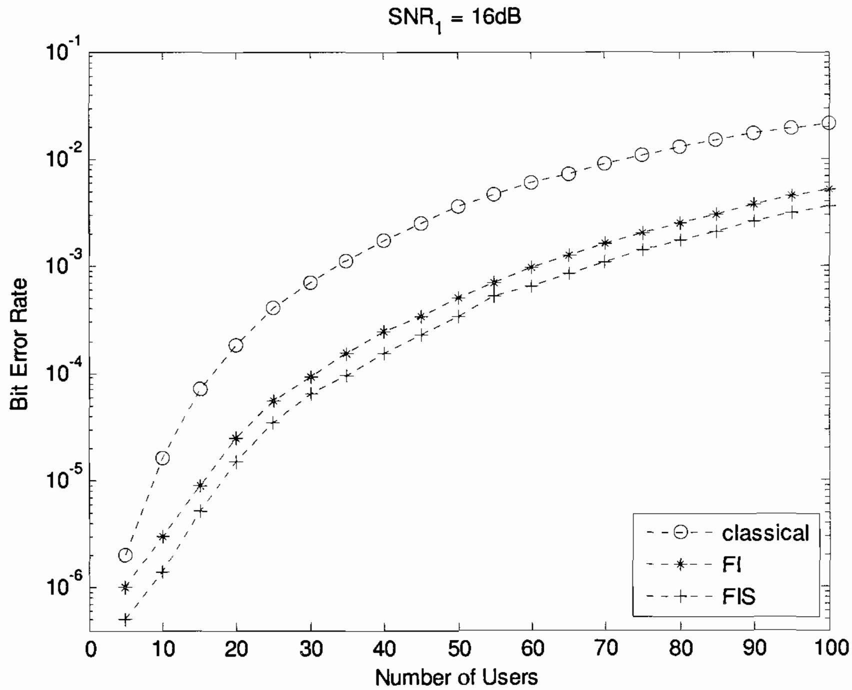

Figure 3.12: BER of the detectors against N_u with SNR_1 =16dB

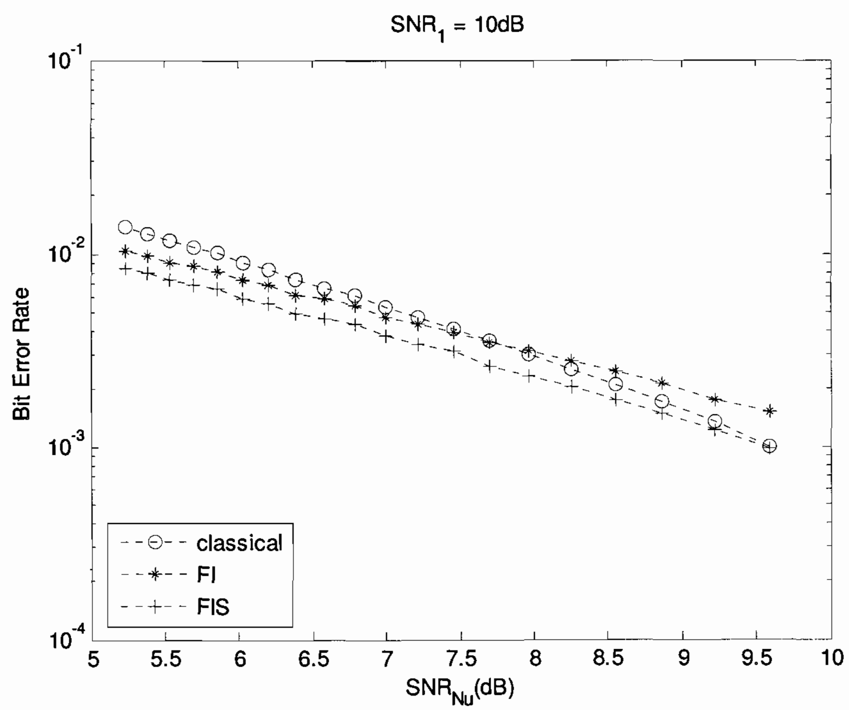

Figure 3.13: BER of the detectors against SNR_{Nu} with SNR_1 =10dB

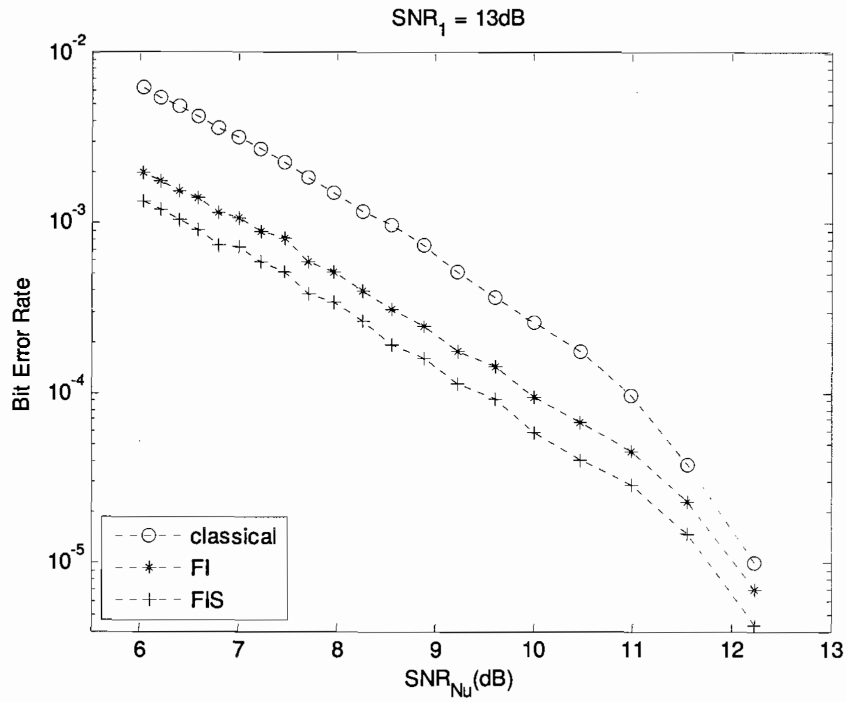

Figure 3.14: BER of the detectors against SNR_{Nu} with SNR_I =13dB

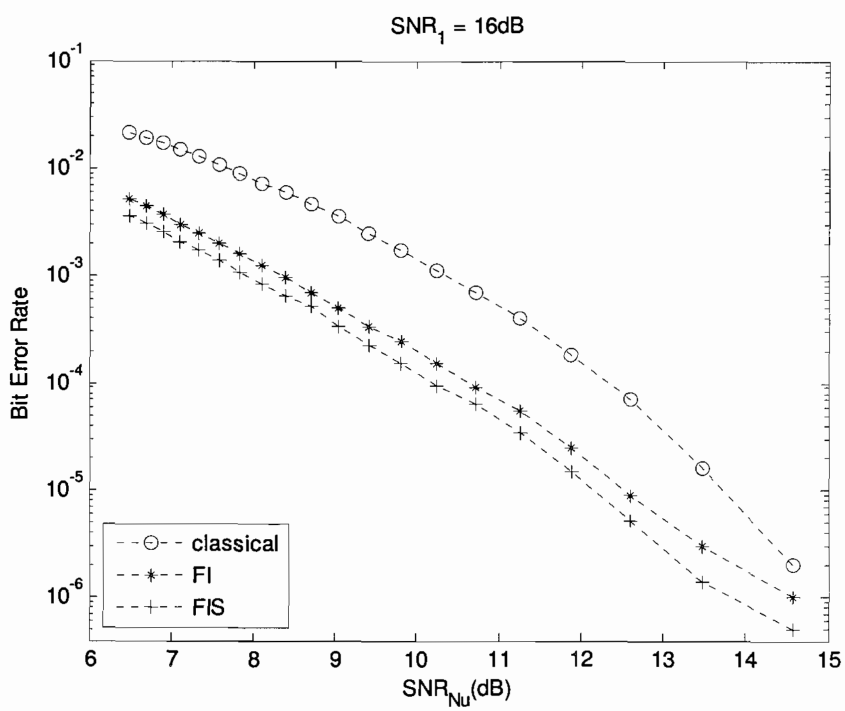

Figure 3.15: BER of the detectors against SNR_{Nu} with SNR_I =16dB

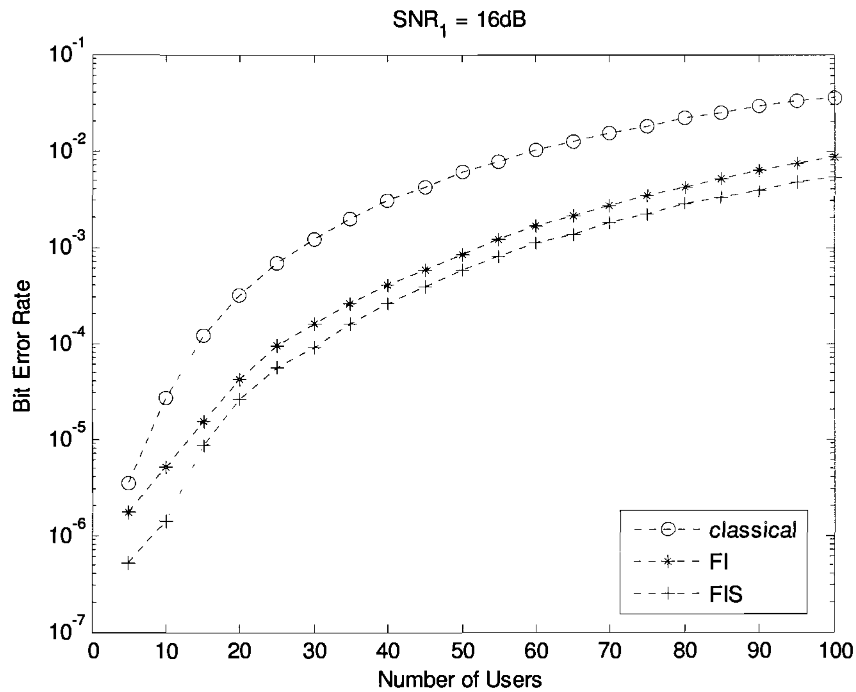

Figure 3.16: BER of the detectors against SNR_{Nu} (imperfect power control)

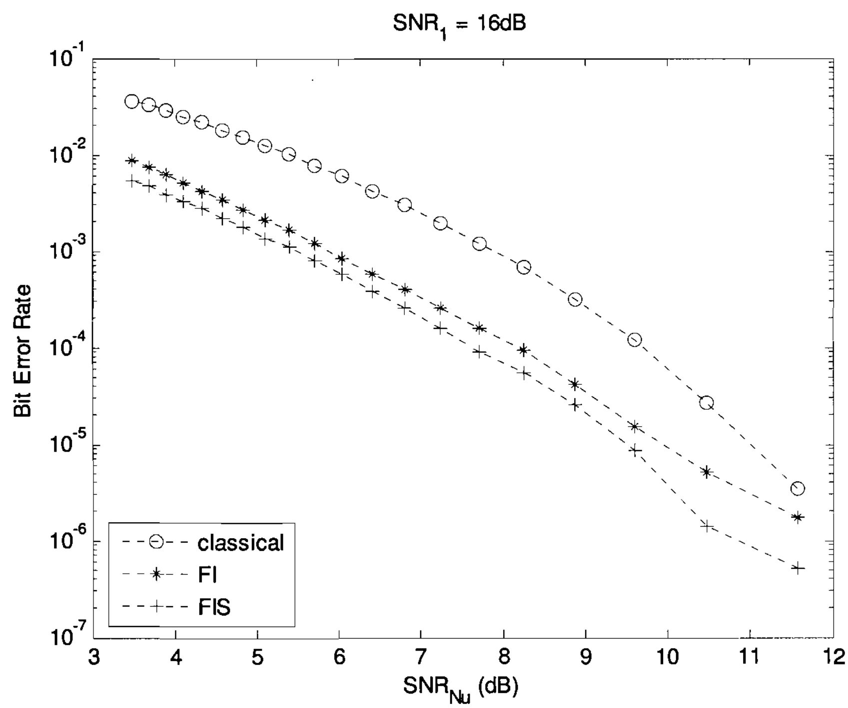

Figure 3.17: BER of the detectors against SNR_{Nu} (imperfect power control)

Chapter 4

Fuzzy multistage Parallel Interference Cancellation in MA-UWB communications

4.1 Background

The detection performance of the conventional UWB receiver can be adversely affected by MAI among users, and be further degraded by the near-far problem due to different distances among the base station and mobile stations [*Win*, 00]. Multi-user detection schemes are effective in alleviating the MAI and the near-far effect. A comprehensive study in multi-user detection to improve the performance of CDMA system has been carried out in [*Verdu*, 98]. Various multi-user detection schemes have been applied in a variety of applications such as radio networks, satellite communications and other multipoint to multipoint network [*Varanasi*, 00]. The performances of some multi-user detection schemes for Time Hopping MA-UWB system were particularly examined in [*Muqaibel*, 02], and results illustrated that the detection performance of UWB-IR system could be improved dramatically.

The initial work of multi-user detection is an optimal detector based on the maximum likelihood method [*Verdu*, 98]. Nevertheless, the complexity of this optimal detector grows exponentially with the number of users, and the requirement of an intensive software complexity for a maximum likelihood solution results in variable decoding delay, which is unacceptable in many applications [*Varanasi*, 00]. Due to the limitations of the maximum likelihood detector, a number of sub-optimal multi-user detection techniques providing a reliable performance with an acceptable complexity have been examined and presented in [*Verdu*, 98].

Among the sub-optimal multi-user detection schemes proposed in [*Yoon*, 93; *Verdu*, 98], multistage Parallel Interference Cancellation (PIC) is one of the efficient methods to combat MAI. The basic principle of the multistage PIC is to estimate the interference from the undesired users, and then subtract the estimated interference from the received signal to clear up the interference [*Varanasi,* 00]. By applying multistage in PIC, the interference could be further cleaned up.

In most of the practical situations, the multistage PIC could achieve dramatic improvement over the conventional detector. In a multiple-access system with well-designed code waveforms, the performance of the PIC detector could match that of the optimum detector [*Varanasi*, 00]. Moreover, the computational complexity of PIC is linear to the number of users, contrasting to complexity of the optimum detector which grows exponentially to the number of users [*Verdu*, 98]. This suggests that PIC could well be implemented in practical multi-user applications.

The conventional multistage PIC could significantly improve the detection performance in the multiple-access system. However, the conventional multistage PIC scheme canceling the entire interference of other users would suffer performance degradation when the number of users in the system is large,. This is a result of a high BER in the temporary bit decisions in the initial stage due to a high MAI [*Correal*, 97]. Divsalar suggests that in this case, total interference cancellation of the estimated interferences is not preferred, and a partial cancellation is suggested [*Divsalar*, 98]. The partial multistage PIC could be simply implemented by multiplying a cancellation factor into the interference cancellation path, to improve the system performance when the temporary decision is not reliable [*Divsalar*, 98].

The optimal cancellation factor for each interferer, in general, is dependent on the reliability of the signal itself. However, the reliability of signal is easily affected by several parameters such as the number and the amplitude of other operating users, and the signal-to-noise ratio of the desired user [*Correal*, 97]. Therefore the cancellation factor should be adaptively adjusted in order to achieve an optimal performance of the

PIC scheme.

In this chapter, we adopt the multistage PIC detection technique in a Time hopping MA-UWB system, and we further improve the performance of the PIC using a fuzzy approach. In the following sections, the principle of the conventional and partial PIC detection is first described. A Fuzzy multistage Parallel Interference Cancellation (FPIC) scheme is then presented. This FPIC adjusts the cancellation weights of individual interferers adaptively according to the reliability of their estimation statistics by a fuzzy approach. In order to analyze the performance of a FPIC detector under the near-far fading, an imperfect power control channel among users has been adopted in the simulation. The detection performance of the conventional PIC (CPIC), the partial PIC (PPIC) and the FPIC is evaluated.

4.2 Conventional and Partial multistage PIC detection Scheme

The principle of the multistage PIC detection is to estimate and regenerate the interfering signal waveforms of other users, and subtract these waveforms from the overall received signal to clean up the interference [*Verdu*, 98]. To estimate the signal of interfering users, multistage PIC detection has to make various temporary decisions for each user in consecutive stages before the final symbol decision is made [*Yoon*, 93]. This multistage PIC detection utilizes a bank of single-user correlation detector, and an initial decision of all users in the network would be made by its corresponding correlation detector in the first stage. After the initial decisions have been made, the signals of users will be regenerated and a symmetry successive cancellation is then operated for all of the users in the second stage. This approach can be further iterated by using multiple stages [*Verdu*, 98].

A block diagram of the multistage PIC detection scheme with K users is illustrated in figure 4.1.

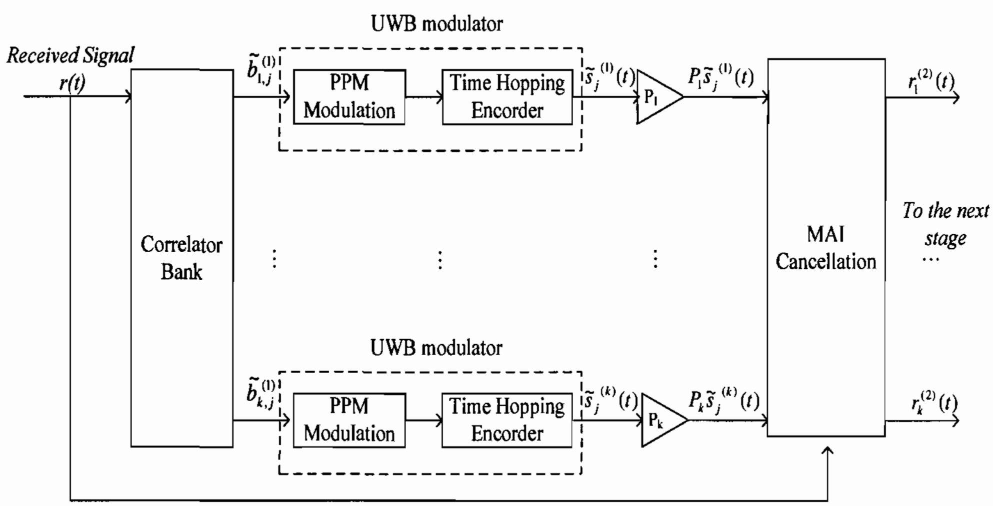

Figure 4.1 Block diagram of multistage PIC detection scheme

$v^{(k)}(t)$ is the reference template for the k-th user, $b_{k,j}^{(n)}$ is the temporary symbol decision of the j-th symbol of the k-th user in the stage n, and $\tilde{s}_j^{(k)}(t)$ is the regenerated waveform according to $b_{k,j}^{(n)}$. P_k is the cancellation weight that decides the volume of the interference to be cancelled for the k-th user. P_k is always equal to 1 for the CPIC to cancel the entire estimated interference, while P_k is a factor of 1 for the PPIC to cancel the interference partially.

The received signal *r(t)* of an imperfect power control system is expressed as:

$$r(t) = A_k \sum_{k=1}^{N_u} s^{(k)}(t) + n(t) \tag{4.21}$$

where A_k is the amplitude of the received signal of the k-th user.

The decision statistics of the j-th bit of the k-th user in the first stage could be obtained by

$$y_{k,j}^{(1,m)} = \sum_{i=0}^{Ns-1} \int_{\tau_1+iT_f}^{\tau_1+(i+1)T_f} r(t) v^{(k)}(t - m\delta) dt \tag{4.22}$$

where $m = 0,1,\ldots M$ to distinguish different symbols

The initial symbol decision of the k-th user is then made according to

$$\tilde{b}_{k,j}^{(1)} = \begin{cases} 1, & if\ y_{k,m}^{(1,j)} = \max(y_{k,1}^{(1,j)}, y_{k,2}^{(1,j)}, \ldots, y_{k,m}^{(1,j)}) \\ 0, & if\ y_{k,m}^{(1,j)} \neq \max(y_{k,1}^{(1,j)}, y_{k,2}^{(1,j)}, \ldots, y_{k,m}^{(1,j)}) \end{cases} \tag{4.23}$$

To decide the amplitude of the received signal of the k-th user, estimation is required. The signal amplitude of the j-th bit of the k-th user in the stage S could be estimated by the decision statistic $y_{k,j}^{(S)}$, which could be expressed as

$$\tilde{A}_{k,j}^{(S)} = E[|y_{k,j}^{(S)}|] \tag{4.24}$$

The estimated signal of j-th bit of the k-th user is given by:

$$\tilde{s}_j^{(k)}(t) = \tilde{A}_{k,j}^{(s)} s_j^{(k)}(t)$$

The k-th user signal after stage n is reduced to $r_k^{(S)}(t)$ by subtracting the received signal from the estimated interference. $r_k^{(S)}(t)$ could be evaluated by:

$$r_k^{(S)}(t) = r(t) - \sum_{l=1, l\neq k}^{K} \tilde{s}^{(l)}(t) \tag{4.25}$$

For PPIC, the estimated waveforms of other users are multiplied by a cancellation factor P_k before the signal reconstruction. The reduced signal could be evaluated by:

$$r_k^{(S)}(t) = r(t) - \sum_{l=1, l \neq k}^{K} P_l^{(S)} \tilde{s}^{(l)}(t) \tag{4.26}$$

where $P_k^{(S)}$ is the cancellation factor for the k-th user at stage S and $0 < P_k^{(S)} \leq 1$. By repeating the above procedures, the CPIC and PPIC detection could be further iterated to clean up the interference from the original correlator output, hopefully, increasing the reliability of the tentative decisions of operating users. The final symbol decision is made by the correlation result between the finalized reduced signal and the template waveform of the desired user.

4.3 Fuzzy multistage PIC detection Scheme

The fuzzy multistage PIC improves the detection performance by choosing the optimal cancellation weights for each cancellation path using fuzzy inference system. The FPIC aims at selecting an adequate cancellation weight for each path, in order to reduce the effect of cancellation error caused by the wrong estimation in the previous stages. A block diagram of the FPIC is illustrated in figure 4.2.

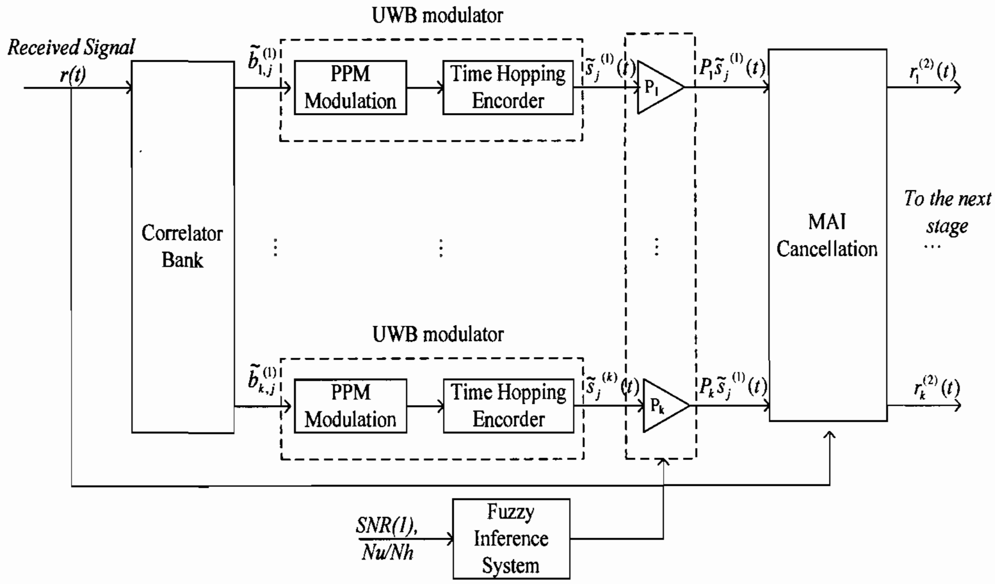

Figure 4.2 Block diagram of Fuzzy multistage PIC detection scheme

A Fuzzy Inference System (FIS) is adopted in the multistage FPIC detection to select the adequate cancellation weight P_k. In general, the optimal cancellation weight of a multistage PIC detector depends on the reliability of the interference estimation. The reliability of the interference estimation is dependent on the overall signal-to-noise ratio SNR_{Nu}. Nevertheless, SNR_{Nu} is dependent on the single user signal-to-noise ratio SNR_1, number of the interfering users N_u and the amplitudes of the interfering users. Therefore the FIS selects the P_k according to SNR_1 and N_u/N_h. The principle and the algorithm of a typical FIS have already been discussed in the chapter 3 and the FIS adopted in the FPIC detection will only be described briefly in this chapter.

The membership functions of the crisp inputs N_u/N_h and SNR_l are illustrated in figure 4.3a and 4.3b respectively.

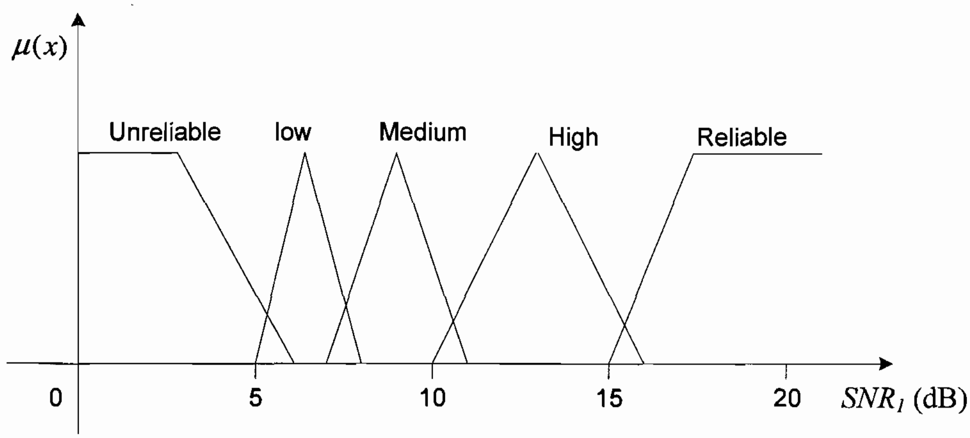

Figure 4.3a Input membership functions of SNR_l

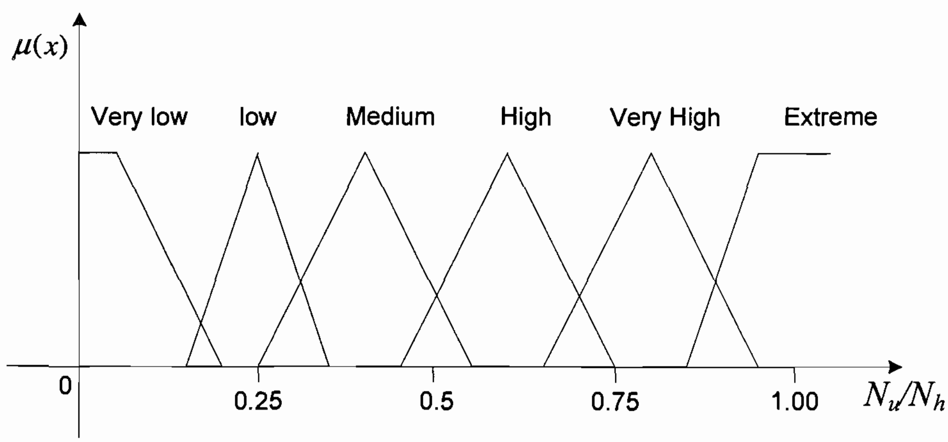

Figure 4.3b Input membership functions of collision rate N_u/N_h

The fuzzy inference system determines the appropriate cancellation weight according to the fuzzified inputs. In general, the cancellation weight P_k should be set large if the interference estimation is reliable, while the P_k should be set small if the interference estimation is unreliable. Intuitively, the reliability of the interference estimation will decrease when SNR_I decreases; thus the cancellation factor P_k should be decreased to achieve the optimal performance of the PIC, whereas when N_u increases, the reliability of the interference estimation will decrease intuitively, thus the cancellation factor P_k should be decreased to achieve the optimal performance of the PIC Based on the relationship between the optimal cancellation weight and the system parameters SNR_I and N_u/N_h, a number of fuzzy *if-then-rules* have been set up. The linguistic representations of the fuzzy *if-then-rules* are given by:

Rule 1: **If** (SNR_I is *Unreliable*) **AND** (*Collision rate* is *Very_low*) **then** (*CW* is *CW4*)

Rule 2: **If** (SNR_I is *Unreliable*) **AND** (*Collision rate* is *low*) **then** (*CW* is *CW4*)

Rule 3: **If** (SNR_I is *Unreliable*) **AND** (*Collision rate* is *Medium*) **then** (*CW* is *CW3*)

Rule 4: **If** (SNR_I is *Unreliable*) **AND** (*Collision rate* is *High*) **then** (*CW* is *CW2*)

Rule 5: **If** (SNR_I is *Unreliable*) **AND** (*Collision rate* is *Very_High*) **then** (*CW* is *CW1*)

Rule 6: **If** (SNR_I is *Low*) **AND** (*Collision rate* is *Extreme*) **then** (*CW* is *CW1*)

Rule 7: **If** (SNR_I is *Low*) **AND** (*Collision rate* is *Very_low*) **then** (*CW* is *CW4*)

Rule 8: **If** (SNR_I is *Low*) **AND** (*Collision rate* is *low*) **then** (*CW* is *CW4*)

Rule 9: **If** (SNR_I is *Low*) **AND** (*Collision rate* is *Medium*) **then** (*CW* is *CW3*)

Rule 10: **If** (SNR_I is *Low*) **AND** (*Collision rate* is *High*) **then** (*CW* is *CW2*)

Rule 11: **If** (SNR_I is *Low*) **AND** (*Collision rate* is *Very_High*) **then** (*CW* is *CW1*)

Rule 12: **If** (*SNR_1* is *Low*) **AND** (*Collision rate* is *Extreme*) **then** (*CW* is *CW1*)

Rule 13: **If** (*SNR_1* is *Medium*) **AND** (*Collision rate* is *Very_low*) **then** (*CW* is *CW5*)

Rule 14: **If** (*SNR_1* is *Medium*) **AND** (*Collision rate* is *low*) **then** (*CW* is *CW5*)

Rule 15: **If** (*SNR_1* is *Medium*) **AND** (*Collision rate* is *Medium*) **then** (*CW* is *CW5*)

Rule 16: **If** (*SNR_1* is *Medium*) **AND** (*Collision rate* is *High*) **then** (*CW* is *CW4*)

Rule 17: **If** (*SNR_1* is *Medium*) **AND** (*Collision rate* is *Very_High*) **then** (*CW* is *CW3*)

Rule 18: **If** (*SNR_1* is *Medium*) **AND** (*Collision rate* is *Extreme*) **then** (*CW* is *CW2*)

Rule 19: **If** (*SNR_1* is *High*) **AND** (*Collision rate* is *Very_low*) **then** (*CW* is *CW6*)

Rule 20: **If** (*SNR_1* is *High*) **AND** (*Collision rate* is *low*) **then** (*CW* is *CW5*)

Rule 21: **If** (*SNR_1* is *High*) **AND** (*Collision rate* is *Medium*) **then** (*CW* is *CW5*)

Rule 22: **If** (*SNR_1* is *High*) **AND** (*Collision rate* is *High*) **then** (*CW* is *CW5*)

Rule 23: **If** (*SNR_1* is *High*) **AND** (*Collision rate* is *Very_High*) **then** (*CW* is *CW4*)

Rule 24: **If** (*SNR_1* is *High*) **AND** (*Collision rate* is *Extreme*) **then** (*CW* is *CW3*)

Rule 25: **If** (*SNR_1* is *Reliable*) **AND** (*Collision rate* is *Very_low*) **then** (*CW* is *CW7*)

Rule 26: **If** (*SNR_1* is *Reliable*) **AND** (*Collision rate* is *low*) **then** (*CW* is *CW7*)

Rule 27: **If** (*SNR_1* is *Reliable*) **AND** (*Collision rate* is *Medium*) **then** (*CW* is *CW6*)

Rule 28: **If** (*SNR_1* is *Reliable*) **AND** (*Collision rate* is *High*) **then** (*CW* is *CW5*)

Rule 29: **If** (*SNR_1* is *Reliable*) **AND** (*Collision rate* is *Very_High*) **then** (*CW* is *CW4*)

Rule 30: **If** (*SNR_1* is *Reliable*) **AND** (*Collision rate* is *Extreme*) **then** (*CW* is *CW4*)

By operating the defined fuzzy *if-then-rules* with various inputs, the output surface of the FIS adopted in the FPIC could be evaluated. The output surface of the FIS against the SNR_1 and N_u/N_h is illustrated in figure 4.4.

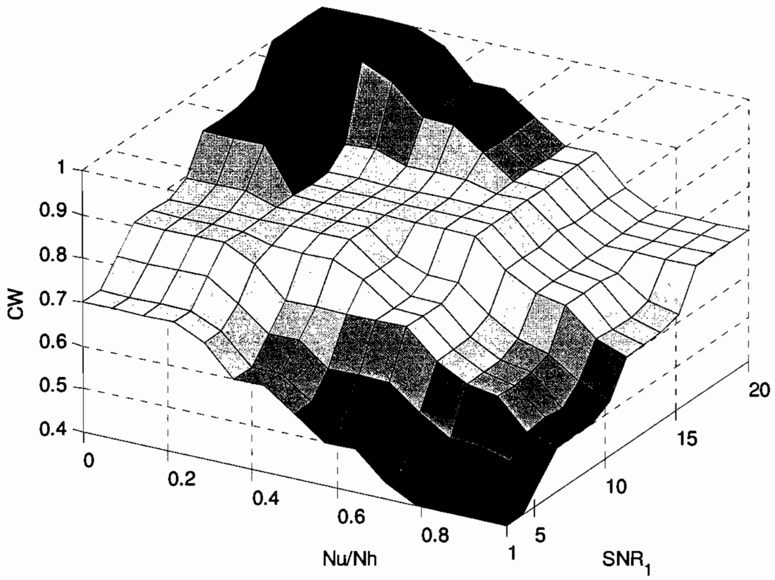

Figure 4.4 Output Surface of FIS: Cancellation weight against N_u/N_h and SNR_1

4.4 Performance evaluation of the fuzzy PIC detection scheme

In this section, several numerical examples have been used in order to analyze the detection performance of the three detection schemes: the multistage CPIC, the PPIC introduced in [*Divsalar*, 98], and the presented FPIC detection scheme. The typical model of a time hopping MA-UWB system with 2-ppm modulation scheme is considered in this work. In many situations, the near-far problem can be a limiting factor of the performance of a multiple-access system. In order to analyze the near-far resistance of the multistage FPIC detection, an imperfect power control model with K users is adopted to examine the performance of FPIC. In this work, K is varied from 0 to 100 and the amplitude of the operating users is randomly selected in the range from 0 to 6dB through out the simulation. The amplitude of the desired users' signal is set to weakest (0dB) among the users and the time slot within a frame time is set to 100.

The performance of the 2-stage and 3-stage of CPIC, PPIC and FPIC detection have been investigated. The cancellation factor P_k in the second stage of the CPIC and PPIC are equal to 1 and 0.7 respectively, while the P_k for FPIC is dyanmic and selected by the FIS. The cancellation factors P_k in the third stage of the CPIC and PPIC are equal to 1 and 0.8 respectively, while the P_k in the third stage is 0.8 for FPIC. The performances of these three detectors are illustrated in figures 4.5-4.10.

Figures 4.5-4.7 show the BER versus the number of users for various PIC detection schemes with SNR_I equal to 10, 13 and 16dB respectively. Figures 4.8-4.10 show the BER versus the overall signal-to-noise ratio including MAI. Observed from the figures 4.5-4.7, the 2-stage CPIC detection scheme always performs better than the 2-stage PPIC detection scheme when the number of operating users is small. It can be concluded that if the number of users is small, the interference estimation is reliable and therefore an entire interference cancellation could effectively combat the MAI. On the other hand, the 2-stage PPIC performs better than the 2-stage CPIC when the number of users is high. It can be concluded that if the number of users is large, the interference estimation is bias, resulting in an unreliable estimation and therefore a partial interference cancellation is preferred in this case. Similar case occurs in the 3-stage CPIC and PPIC detection schemes, but the interference is further cleaned up, and a lower BER could be obtained.

Figures 4.5-4.7 show the BER of various PIC detections versus N_u. In figure 4.6, when the SNR_I equals 13 dB, the 2-stage CPIC and PPIC could maximally support 15 and 17 users respectively, while the 2-stage FPIC could maximally support 18 users with a constant BER equal to 10^{-4}. For the 3-stage PIC detection schemes, the CPIC and PPIC could maximally support 25 users while the FPIC could maximally support 29 users with a constant BER equal to 10^{-4}. In figure 4.7, when the SNR_I equals 16 dB, the 2-stage CPIC and PPIC could maximally support 21 users while the 2-stage FPIC could maximally support 25 users with a constant BER equal to 10^{-4}. For the 3-stage PIC detection schemes, the CPIC and PPIC could maximally support 30 users while the FPIC could maximally support 35 users with a constant BER equal to 10^{-4}. Therefore a larger system capacity could be obtained by applying FPIC detection scheme as shown by the results.

Figures 4.8-4.10 show the BER of various PIC detections versus SNR_{Nu}. Illustrated in figure 4.9, when the SNR_I equals 13 dB, the 2-stage CPIC and PPIC requires a SNR_{Nu} equal to 8.8 and 8.9dB respectively, to keep a constant BER of 10^{-4}, while the 2-stage FPIC only requires a SNR_{Nu} equal to 8.3dB to keep the same BER, indicating that an improvement of 0.5dB is obtained. For the 3-stage detection schemes, the CPIC and PPIC require a SNR_{Nu} equal to 7.8dB to keep a constant BER of 10^{-4}, while the 3-stage FPIC only requires a SNR_{Nu} equal to 7.1dB, indicating that an improvement of 0.7dB is obtained. Illustrated in figure 4.10, when the SNR_I equals 16 dB, the 2-stage CPIC and PPIC required a SNR_{Nu} equal to 8.3dB to keep a constant BER of 10^{-4}, while the 2-stage FPIC only requires a SNR_{Nu} equal to 9dB to keep the same BER, indicating that an improvement of 0.7dB is obtained. For the 3-stage detection schemes, the CPIC and PPIC require a SNR_{Nu} equal to 7.8dB to keep a constant BER of 10^{-4}, while the 3-stage FPIC only requires a SNR_{Nu} equal to 7dB, indicating that an improvement of 0.8dB could be obtained.

In this chapter, we investigated the performance of various PIC detection schemes in time hopping MA-UWB system. Results illustrated that the multistage CPIC performs better than the PPIC when the number of operating users is small, while the multistage PPIC performs better than the CPIC when the number of operating users is large. Results also illustrated that, the FPIC always offer a better performance over a large range of number of users. The FPIC is particularly superior to the conventional PIC when the number of users is large, while the FPIC is particularly superior when the number of users is low.

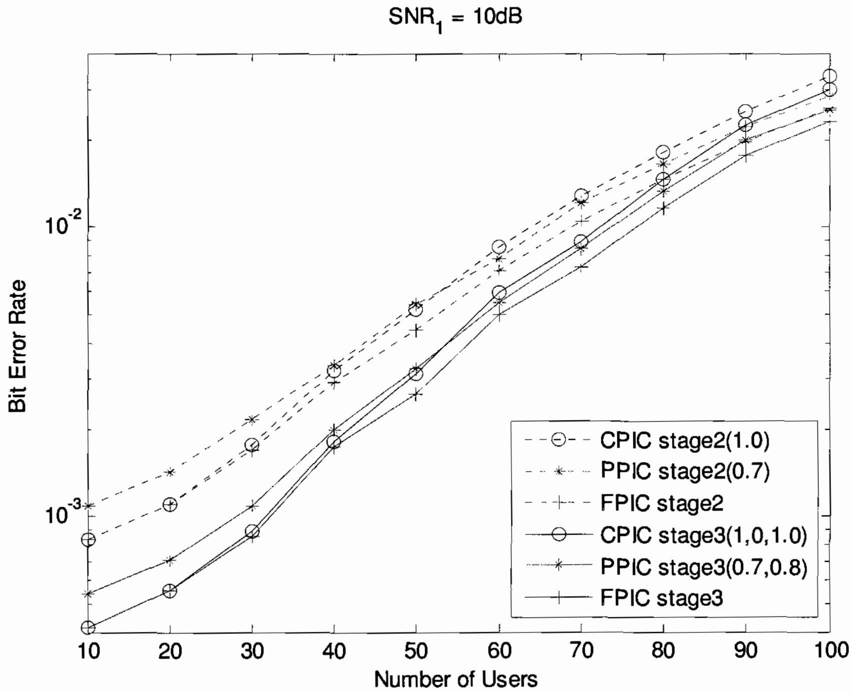

Figure 4.5: BER of the detectors against N_u with SNR_1 =10dB

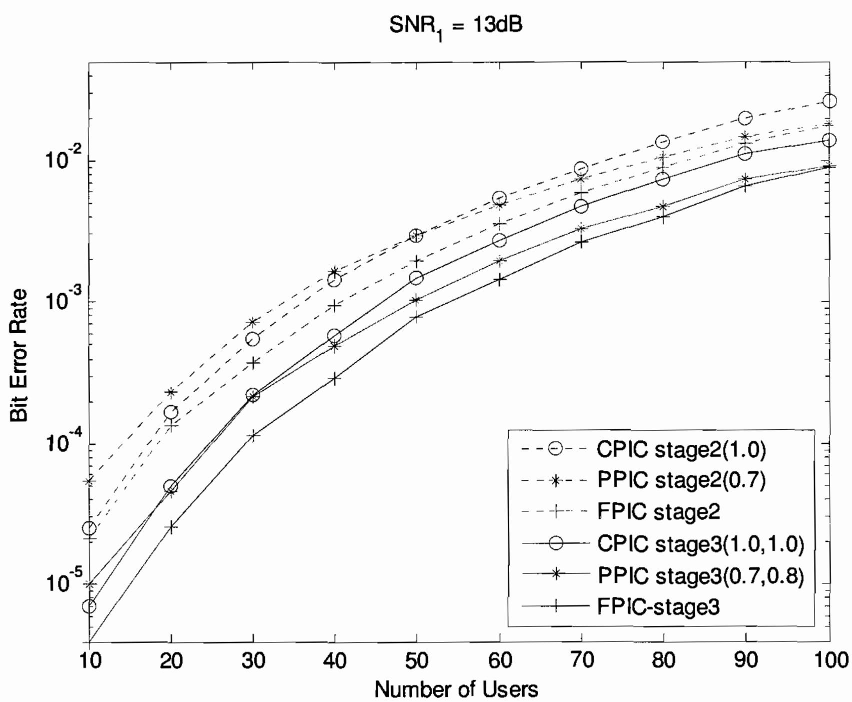

Figure 4.6: BER of the detectors against N_u with SNR_1 =13dB

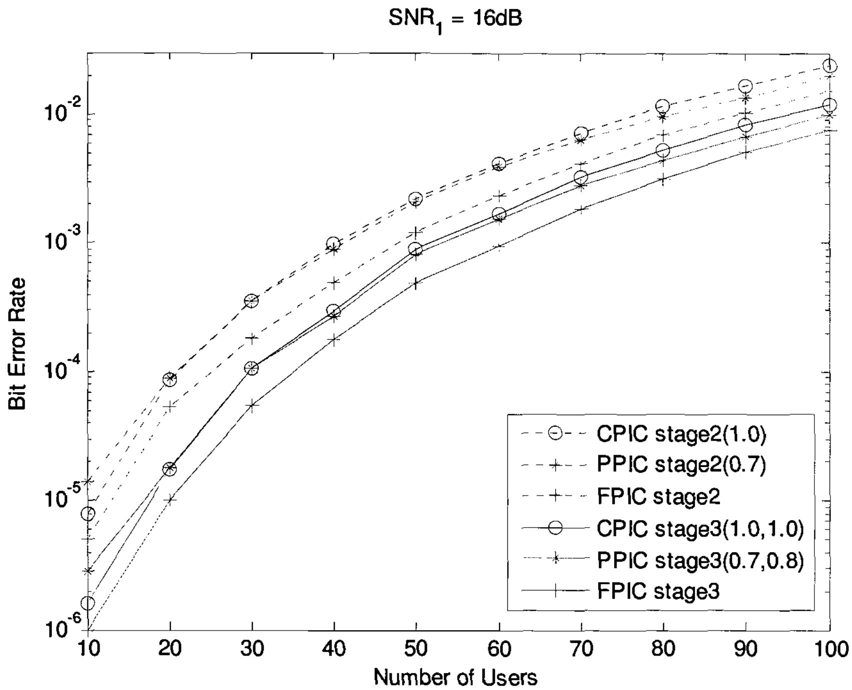

Figure 4.7: BER of the detectors against N_u with SNR_1 =16dB

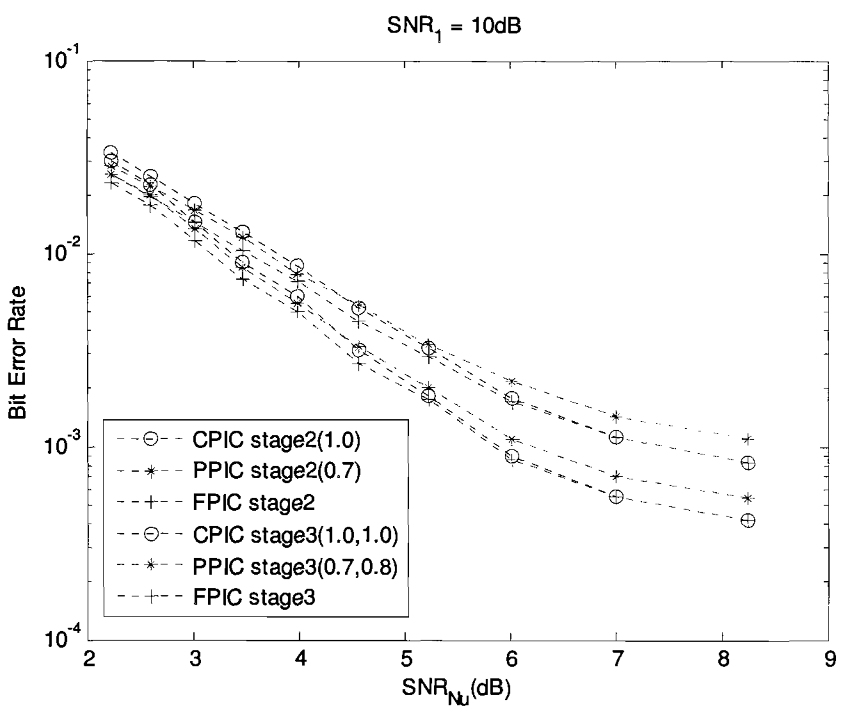

Figure 4.8: BER of the detectors against SNR_{Nu} with SNR_1 =10dB

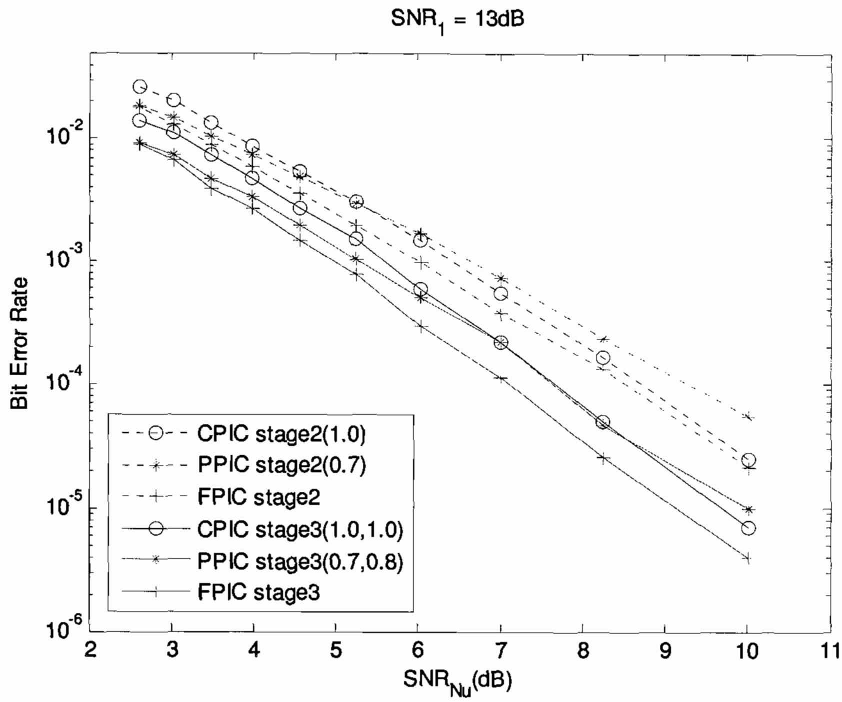

Figure 4.9: BER of the detectors against SNR_{Nu} with SNR_1 =13dB

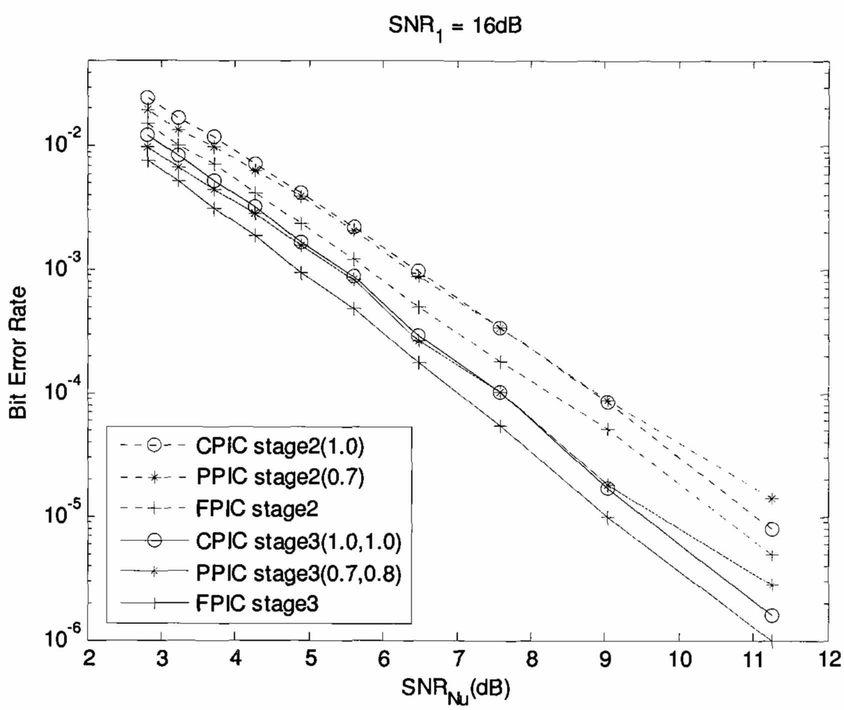

Figure 4.10: BER of the detectors against SNR_{Nu} with SNR_1 =16dB

Chapter 5

Discussion and Conclusion

In this thesis, several fuzzy detection schemes for handling Multi-Access Interference (MAI) in UWB-IR communications have been analyzed and presented. These fuzzy detection schemes include Fuzzy Integration (FI) detection scheme, fuzzy detection scheme using Fuzzy Inference System (FIS), and the Fuzzy multistage Parallel Interference Cancellation (FPIC) detection scheme.

The fuzzy integration detection scheme in Time Hopping UWB-IR communications for handling MAI has been presented in chapter 2. The FI detector suppresses the MAI by the fuzzification of individual correlator outputs of over-sampling pulses before carrying out the integration process. In order to keep the advantage of simplicity of the conventional UWB detector, the FI detector uses only a single membership function to carry out the fuzzification. This adopted membership function is a piecewise linear function, and performs as a clipping-like process to the MAI, preventing the domination of any inferior samples in the decision process. Result has indicated that, the fuzzy integration detection scheme could improve the detection performance of the multi-access UWB system, and a gain of 3.4dB in signal-to-noise ratio has been obtained.

When the number of operating users within the network is small, the FI detector can only perform more or less the same, or even worse as compared to the conventional detector. The simplicity of the FI detector using a single membership function is a traded-off to the system performance when the number of users is small. In order to overcome the drawback of the FI detector in this aspect, an improved fuzzy integration detection scheme using Fuzzy Inference System (FIS) is presented in chapter 3. The FIS detector selects the appropriate thresholds of the FI detector according to the operation conditions, and results illustrated that a further improvement has been obtained. The merit of the FIS detector is that, it would simply be reduced to the conventional detector when the number of users is small. Therefore FIS performs better than the FI detector when the system load is light. Results illustrated that the FIS detector in different loading situations is more robust as compared to the FI detector.

In chapter 4, a fuzzy multistage parallel interference cancellation scheme is presented. Various PIC detection schemes including Conventional Parallel Interference

Cancellation (CPIC), Partial Parallel Interference Cancellation (PPIC) and the presented Fuzzy Parallel Interference Cancellation (FPIC) scheme are presented. Results illustrated that, the FPIC always performs better than the CPIC and PPIC scheme along a large range of number of users. The FPIC is especially superior to the conventional PIC when the number of users is large, while the FPIC is especially superior when the number of users is low. The FPIC detector shows a more robust performance in the multi-access system.

To conclude this thesis, several fuzzy detection schemes in the time hopping UWB-IR systems haven been investigated. The algorithms of the fuzzy detection schemes have been presented and the performances of these fuzzy detectors have been demonstrated.

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