Research on MAC Protocols for UWB Ad-hoc Networks

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Abstract

This research focuses on solving issues for Impulse Radio Ultra Wideband (IR-UWB) communication systems. Since the IR-UWB systems use short pulse waves of less than 1 nano second, they can achieve very high data rate. The short pulse waves also make possible to detect distance between nodes accurately. The UWB systems can be employed for indoor positioning applications and have been investigated for short-range wireless communications and ad-hoc networks. This is because of the limited transmission power of UWB. The communication range of UWB is actually too small to cover a whole house. Even in an indoor environment, it should be considered communications between people in long distance. It is not possible to communicate with someone longer than 10m away using UWB. The other radio systems or cable transmissions have to be used in conjunction with the UWB system. However, if the other radio systems are used with UWB, the transmission data rate is too limited to support digital household electric appliances.

The limited communication range of UWB renders multihop transmission essential for applications requiring extended ranges such as full building coverage. Ad-hoc networks usually use multihop transmission. Ad-hoc networks do not require base stations unlike conventional radio systems. Each node should have a routing function and it is essential to use multihop transmission. Since each node has a network control function, even if one of the nodes is out of order, the influence to the whole network is quite limited. The ad-hoc networks are excellent in respect of cost and robustness. It attracts large attention from researchers in the military and the commercial fields. However, since its topology always changes, it is hard to control the network.

In this thesis, the main issue is to consider and solve the various problems to realize UWB ad-hoc networks with high data rate and high quality communications. This thesis introduces and evaluates the following issues.

- Various routing schemes for ad-hoc networks have been proposed such as Ad-hoc on demand distance vector (AODV), Optimized Link State Routing (OLSR) and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF). However, these routing schemes do not employ the information about the location of the nodes and are not designed for the UWB ad-hoc networks. The routing schemes based on signal-to-noise ratio have been proposed by Advanced Telecommunications Research institute international (ATR). It requires array antennas to determine the route of the packets. Nevertheless, it is difficult to implement the array antennas in the small nodes. Location based routing schemes have also been proposed. These schemes do not employ spread spectrum communications and the location information is only used by limiting the range for forwarding a packet. Those routing schemes are not suitable for UWB ad-hoc networks.

- In radio communication systems, Medium Access Control (MAC) protocol has the important role to establish the communication links efficiently. In general, Carrier Sense Multiple Access (CSMA) protocols have been used. CSMA is the protocol that checks whether the other nodes are transmitting carrier signals before packet transmission. In the conventional CSMA schemes, the communication channel is used to sense the existence of the carrier signal. However, when UWB or Code Division Multiple Access (CDMA) is employed, the power level of the pulse is too low to detect the carrier signal. Therefore, the optimal MAC protocols are needed for UWB ad-hoc networks.

- In a conventional retransmission scheme like Automatic Repeat Request (ARQ), an ACKnowledge (ACK) packet is used for the confirmation of successful data reception. Once a packet has been received successfully, an ACK packet is returned to the sender. In the case of erroneous reception, a Negative-ACKnowledge (NACK) packet is returned to the sender, requesting retransmission of the lost packet. As the number of hops increases, more ACK / NACK packets are required in the system, which results in the total interference.

- The aim of acquisition is to find the phase of the sequence at the initial stage of signal reception. Many kinds of acquisition schemes have been proposed. They are mainly classified into two kinds. One is based on a matched filter and the other is based on a correlator. In the acquisition scheme based on a matched filter, the hardware is more complex and expensive. On the other hands, schemes based on a correlator are simpler in terms of the hardware. Therefore, this scheme is less expensive and suitable for UWB. The serial search scheme is known to be the simplest one among the schemes based on a correlator. This scheme requires long time to achieve the acquisition.

The 1st chapter introduces the background and the motivation of this research. In addition, the issues of the conventional protocols are introduced in the case where those protocols are employed in UWB ad-hoc networks.

The 2nd chapter investigates a routing protocol to improve throughput in UWB ad-hoc networks regardless of the power of the received signal and interference. The novel routing scheme for a UWB ad-hoc network utilizes the positioning capability of the UWB systems. Based on the location information, the spreading factor (SF) has been increased in proportion to the square of the transmission distance in order to keep the received signal-to-noise ratio per bit (E_b/N_0) constant. In addition, the Packet-Forwarding (PF) zone has been defined in order to restrict the transmission distance. If the transmission distance is longer than the radius of PF zone, a packet is relayed by a intermidiate node by multi-hop transmission. The route of the packets is specified based on the location information. We evaluate the performance of this system through simulations. As the results, our proposed routing scheme shows better performance than the conventional routing scheme.

The system in the 2nd chapter employs pure ALOHA in MAC protocol. Pure ALOHA is a very simple algorithm. However, its throughput is quit low. The 3rd chapter investigates a code sense scheme to improve throughput in UWB ad-hoc networks regardless of the power of the received signal and interference. This is the scheme to sense the carrier signal of the other node by using the correlation value of the spreading codes. Nodes in network can therefore identify whether the special node is transmitting or receiving a packet or not. Code sense method can sense the received signal whose power level is too low for the conventional CSMA to detect the carrier signal. We evaluate the performance of code sense through computer simulations. As the results, it is proved that code sense scheme can become a novel MAC protocol for UWB ad-hoc networks and the concept of code sense scheme is very useful.

The 4th chapter investigates retransmission protocols to compensate the packet loss. Because the packet loss increases rapidly as more hops are required even if code sense scheme is employed. Therefore, retransmission is necessary in order to compensate for the packet loss. We propose a novel retransmission scheme encompassing code sense scheme. Our proposed retransmission scheme does not use an ACK or a NACK packet for the notification to the sender. It is expected that reduction of the number of ACK / NACK packets shall improve the total network throughput. We evaluate the performance of this system under several conditions through simulations. The results show that the retransmission with code sense scheme is more efficient for compensation and reduction of packet collision in UWB ad-hoc networks.

The 5th chapter investigates the acquisition scheme optimized for IR-UWB systems. The performance of the above-mentioned code sense scheme depends on the performance of the acquisition of spreading sequence. In order to realize a simple and high-speed acquisition scheme, a two stage acquisition scheme has been proposed. This scheme has the timing detection stage and the phase synchronization stage. In the timing detection stage, the timing of the pulse signal is detected. Based on the pulse timing information, the phase of the sequence is acquired in the second stage. The two stage acquisition with the squared circuit is evaluated under several environments through computer simulations. The results show that the two stage acquisition can shorten the mean acquisition time and improve the probability of success acquisition as compared to the conventional acquisition scheme.

Finally, the 6th chapter summarizes the results of each chapter and concludes this thesis.

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Chapter 1

General Introduction

In this chapter, at first, we present a background of spread spectrum communication systems and UWB systems. We explain how different between UWB systems and the conventional wireless systems are. Also, we introduce ad-hoc networks technologies. The purpose of this chapter is to present the motivation of this thesis. This thesis consists in six chapters. This chapter also explains the relationship among each chapter and the historical background of each chapter.

1.1 Spread Spectrum Communication System

1.1.1 Characteristices of Spread Spectrum Communication

In general of radio communications, signals are transmitted by using a narrow frequency band. On the other hands, there are the radio communication schemes to transmit a signal whose power density is quite low like noise power density by multiplying a wide frequency band signal. They are called Spread Spectrum (SS) communications [1], [2]. In SS, a narrow band signal is spread and transmitted. Spread spectrum signal has high robustness to noise and frequency fading as compared to the narrowband signals. The features of SS are as follows.

- It is impossible to demodulate a signal without knowing the spreading code of a sender. Therefore, SS is excellent for secret communications.
- The signal is hidden over noise because of the power of the spread signal being lower than that of noise. Therefore, the anonymity communication is possible.
- SS communication has the robustness for jamming signal such as interference and noise.

However, there are the following issues.

- The synchronization for the spread sequence is difficult.
- It is difficult to sense the illegal signal.

- It is assumed that a receiver and two transmitters exist. If both transmitters transmit simultaneously and at equal powers then the receiver will receive more power from the nearer transmitter. This makes the farther transmitter more difficult to understand. This effectively jams the communication channel. This is commonly solved by dynamic output power adjustment of the transmitters. That is the closer transmitters use less power so that the Signal-to-Noise Ratio (SNR) for all transmitters at the receiver is roughly the same.

In Direct Sequence Spread Spectrum (DS/SS), the pulse signal that is the modulated information signal is spread by the pulse sequence. Fig. 1.1 shows the look of the DS/SS modulation. In a receiver side, the received signal is demodulated with the same pulse sequence of the sender at the same phase. At this time, the despread signal is recovered to the original narrowband signal at the receiver. This process is called "despread". The noise in cannel and circuit components is added to the received signal at the first time in here. Therefore, SNR can be improved for getting the gain in the despread process.

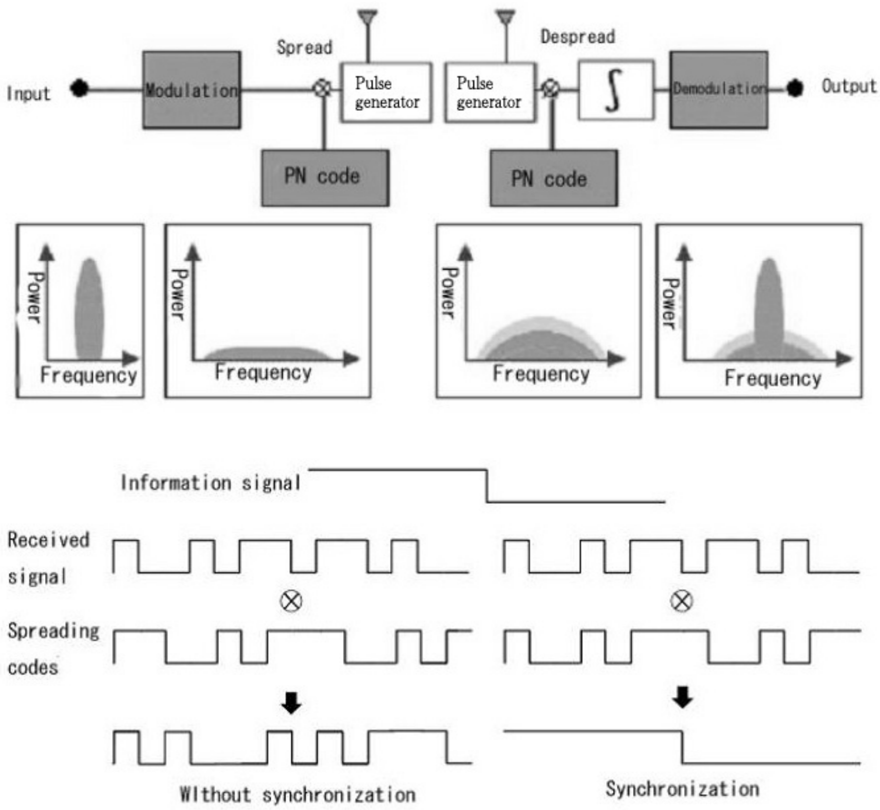

Figure 1.1: Block diagram of direct sequence spread spectrum and the look of processing of changing the information signal.

1.1.2 Process Gain

In spread spectrum, the data is modulated by a spreading signal which uses more bandwidth than the data signal. Since multiplication in the time domain corresponds to convolution in the frequency domain, a narrow band signal multiplied by a wide band signal ends up being wide band. One way of doing this is to use a binary waveform as a spreading function, at a higher rate than the data signal.

Here the three signals corresponds to $x(t)$, $c(t)$ and $m(t)$ discussed above. The first two signals are multiplied together to give the third waveform.

Bits of the spreading signal are called chips. T_b represents the period of one data bit and T_c represents the period of one chip. The chip rate, $\frac{1}{T_c}$, is often used to characterize a spread spectrum transmission system.

The Processing Gain or sometimes called the Spreading Factor (SF) is defined as the ratio of the information bit duration over the chip duration.

$$PG = SF = \frac{T_b}{T_c}. \tag{1.1}$$

Hence, it represents the number of chips contained in one data bit. SF is also called as Process Gain (PG). Higher PG means more spreading. High PG also means that more codes can be allocated on the same frequency channel [3].

1.1.3 Pseudo-Noise Sequences

Spread spectrum is used to avoid jamming or narrow band interference. The signal overcoming narrow band interference, the spreading function needs to behave like noise. Random binary sequences are such functions and have the following important properties [4].

1. Balanced: they have an equal number of 1's and 0's

2. Single Peak auto-correlation function

In fact, the autocorrelation function of a random binary sequence is a triangular waveform as in Fig. 1.2, where T_C is the period of one chip.

Hence the spectral density of such a waveform is a sinc function squared, with first zeros at $\frac{1}{T_C}$

Pseudo Random Sequence Noise (PN) sequences are periodic sequences that have a noise like behavior. They are generated using shift registers, modulo-2 adders (XOR gates) and feedback loops. The Fig. 1.3 illustrates them.

The maximum length of a PN sequence is determined by the length of the register and the configuration of the feedback network. An N bits register can take up to $2N$ different combinations of zeros and ones. Since the feedback network performs linear operations, if all the inputs are zero, the output of the feedback network will also be zero. Therefore, the all zero combination will always give zero output for all subsequent clock cycles, so we do not include it in the sequence. Thus, the maximum length of any PN sequence is $2N - 1$ and sequences of that length are called Maximum-Length Sequences or m-sequences. They are useful because longer sequences have better properties. Therefore, PN sequences are periodic noise like binary functions generated by a network of feedback loops, modulo-2 adders and flip-flops. Maximum length PN functions have a period of $2N - 1$.

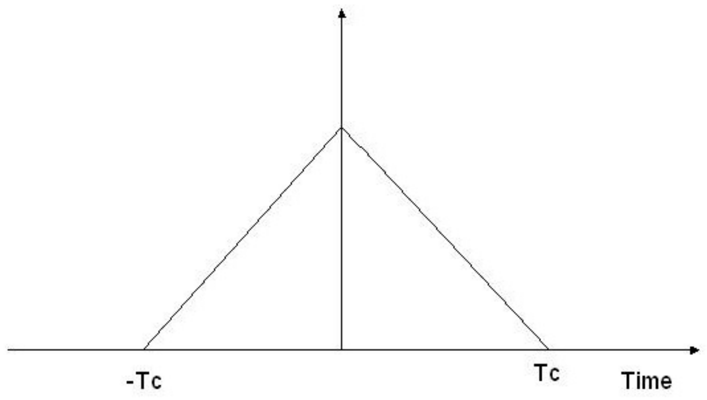

Figure 1.2: Auto correlation function.

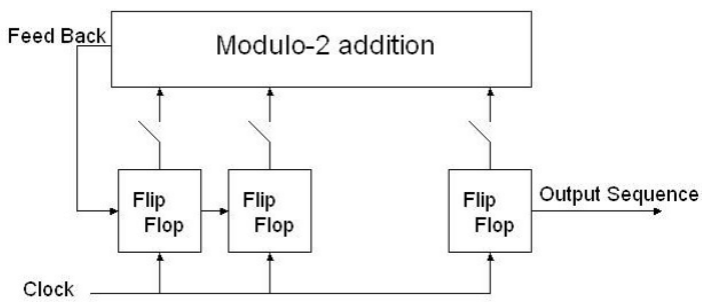

Figure 1.3: Diagram of shift register.

1.1.4 Synchronization Scheme

1.1.4.1 Acquisition and Tracking

Synchronization is to make the phase of the received signal in agreement with the phase of the template signal. In spread spectrum communication systems, if the template signal generated by receiver synchronizes to the received signal, the received signal can be demodulated. That is why the timing of the synchronization cannot be acquired with the schemes of the narrowband radio systems since the SNR at the receiver is quite low. Therefore, a receiver generates the template signal and make its phase in agreement with that of the received signal.

Synchronization consists in two stages, which are the acquisition and the tracking. The acquisition of spreading sequence is required at the receiver side. The aim of acquisition is to find the phase of the sequence at the initial stage of signal reception. Tracking is to keep synchronization state after the acquisition [5]. In this thesis, we focus on investigating of only acquisition stage.

1.1.4.2 Sliding Acquisition Scheme

The acquisition scheme based on the sliding correlation systems has been investigated for the long time [6], [7], [8], [9], [10], [11]. This scheme changes the phase of the code sequence generated in the receiver and searches the peak of autocorrelation value between the received and the template signal as shown in Fig. 1.4. The correlation value between the received and the template signal is compared to the threshold value. If the correlation value is lower than the threshold, the phase of the template signal is sifted by the step size. This process continues until the correlation value exceeds the threshold for the search time. The sliding schemes have to search the all phase of the code sequence by finding out the phase whose correlation value is over the threshold value. According to the initial phase, there is the case that the sliding acquisition schemes take the long time to finish the acquisition [5].

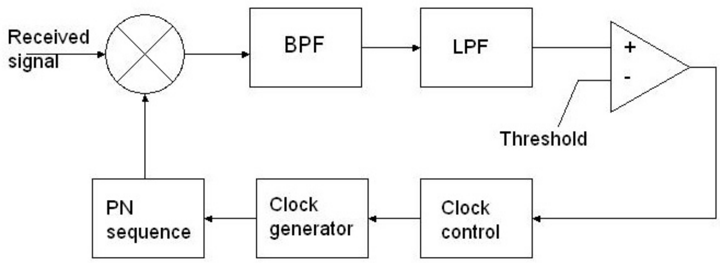

Figure 1.4: Block diagram of sliding acquisition scheme.

1.1.4.3 Matched filter Acquisition Scheme

The acquisition scheme based on the matched filter correlation systems can search the values of auto correlation at each chip when the received signal is received [12], [13]. Fig. 1.5 shows the block diagram of the matched-filter. This scheme need the duration of the code sequence length to search the acquisition point. Therefore, the duration of this scheme is shorter than that of the sliding acquisition schemes. However, this scheme is not robust to the noise and interference. This is because of treating the received signal as it is. Besides, this scheme requires a large amount of hardware complexity as compared to the sliding acquisition schemes. Therefore, we employ the sliding acquisition schemes to our proposed system.

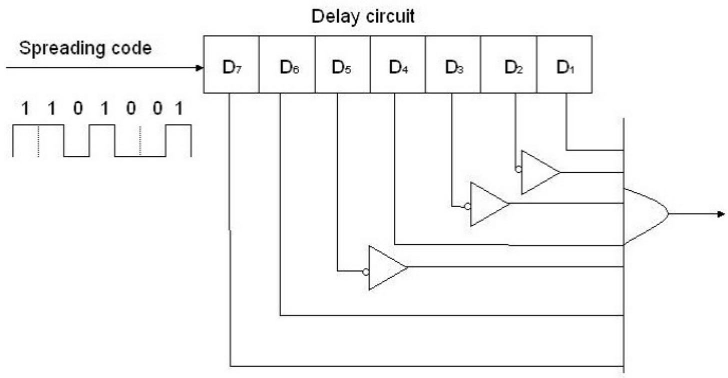

Figure 1.5: Block diagram of matched filter acquisition scheme.

1.2 Ultra Wideband System

1.2.1 Features of Ultra Wideband Systems

UWB radio has received much attention for features of UWB such as high speed, high precise positioning capability, and low power consumption since the Federal Communication Commission (FCC) has approved it for the commercial use in Feb. 2002 [14], [15], [16], [17], [18]. As an example, although UWB systems can achieve 100 or more than times data rate of Bluetooth (50 - 480 Mbps), the power consumption of UWB is the same as that of Bluetooth (100 - 200 mW). On the other hand, IEEE802.11a/g systems can achieve the maximum bit rate of 56Mbps. It is difficult for them to make power consumption less than 1 [W]. Moreover, the battery life is very important for mobile terminals. UWB systems are very useful with respect to the battery life. In near future, it is expected that UWB systems will be used for digital household electric appliances and peripheral equipments of PCs such as wireless digital video and wireless USB. In wireless USB, transmission speed is up to more than 480 Mbps. In wireless video transmission, transmission speed without compression is required more than 30 Mbps in order to realize the transmission of HDTV video. Moreover, transmission speed of MPEG2 requires about 20 Mbps and transmission speed of high quality 5.1-surround-sound requires about 27 Mbps. UWB systems can achieve such a high data rate transmission easily [19].

The following features are expected to the UWB communication systems [16], [20].

1. Shanon's channel capacity, C b/s, is given by the following equation.

$$C = Blog_2 1 + \frac{P}{BN_0}, \tag{1.2}$$

   where B is the frequency bandwidth, P W is the signal power, and N_0 W/Hz is the spectral density of the noise. This equation shows that the channel capacity increases in proportion to the frequency bandwidth. With UWB, very high speed wireless communications with the order of Gbps may be possible as the bandwidth B is quite large.

2. Since the UWB signal occupies very large bandwidth, power spectrum density can be stay in a low level. Therefore, the interference to the existing wireless systems are limited. Conversely, since the spectrum of the UWB signal is very wide, it is robust to the interference from the other radio systems.

3. Since the peak of the autocorrelation function is sharp, UWB signal is excellent in terms of multipath resolution. Therefore, precise positioning can be achieved.

4. Impulse Radio UWB which transmits pulse waveform does not employ a carrier signal. Therefore, radio frequency circuits such as Voltage Controlled Oscilators (VCOs) or mixers in the conventional wireless systems are not required. Since most of all the circuits can be constructed with digital technology, all the elements can be integrated in one chip. Thus, the reduction in power consumption and cost is expected.

Table 1.1: Comparison of UWB bit rate with other wired and wireless standards.

Speed (Mbit/second)	Standard
480	UWB, USB 2.0
200	UWB (4m minimum), 1394a (4.5m)
110	UWB (10m minimum)
90	Fast Ethernet
54	802.11a
20	802.11g
11	802.11b
10	Ethernet
1	Bluetooth

Table 1.2: Power consumption of UWB and other mobile communication chipsets.

Application chipset	Power consumption [mW]
802.11a	1500 – 2000
400 Mbps 1394 LSI	700
Mobile telephone RISC 32-bit MPU	200
Digital camera 12-bit A/D converter	150
UWB	100
Mobile telephone TFT color display panel	75
MPEG-4 decoder LSI	50
Mobile telephone voice codec LSI	19

One of the advantages of UWB transmission for communications is its high data rate. Table 1.1 shows the comparison of UWB bit rate with other wired and wireless standards. The most important advantage of UWB technology is the low system complexity and low cost. UWB systems can be made nearly "all-digital", with minimal RF or microwave electronics. The less number of circuit components leads to the reduction of cost. The smaller chip sizes invariably also lead to low-cost systems. The simplest UWB transmitter could be assumed to be a pulse generator, a timing circuit, and an antenna. To take one early example, it has been reported that the XtremeSPectrum chipset is priced at $19.59 for $100000 units [21].

With proper engineering design the resultant power consumption of ultra wideband can be quite low. As with any technology, power consumption is expected to decrease as more efficient circuits are designed and more signal processing is done on smaller chips at lower operating voltages. The current target for power consumption of UWB chipsets is less than 100 mW. Table 1.2 shows some figures for power consumption of current chipsets.

1.2.2 History of Ultra Wideband Systems

In the US the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) worked for over three and a half years to address all interference concerns. Final rules in this proceeding were issued on February 14, 2002 [14], [22].

The FCC developed a robust and extensive record on those interference concerns. NTIA participated throughout the proceeding and submitted interference studies on GPS and other government spectrum operations.

The rules issued by the FCC, now supported by recent test data, reach a well-balanced approach to UWB that will protect existing spectrum users, while allowing consumers to benefit from this remarkable new technology. UWB will deliver jobs, innovation, investment and economic growth at this most important time for our country.

Both NTIA and the FCC have concluded that UWB is a safe technology. The emission mask contained in the final Report and Order protects incumbent and government spectrum users, including those in the PCS and GPS bands. Sound technical analysis has repeatedly proven that this spectral mask provides all the needed protection to allow UWB devices to operate safely.

As part of these tests, the FCC and NTIA tested the DS-UWB standard method extensively, which provided the basis for the February 2002 rules.

The FCC and NTIA are currently testing the multi-band, frequency-hopping UWB specification as it was not tested by either body, and current FCC rules indicate that such frequency-hopping systems must be tested with the frequency hopping turned off. That method would require multi-band OFDM systems to operate at lower power levels, which would result in decreased range for these systems.

The FCC's prime directive is to ensure no interference, particularly to licensed spectrum users. The FCC always tends to err on the side of caution in implementing this objective, and the current Report and Order reflects a difficult balancing effort by the FCC (in conjunction with NTIA and other federal agencies) to ensure full protection of existing users while enabling market entry of an important new technology.

The delicate final balance of UWB rules was a result of intense negotiations and engineering on the part of the FCC and government users, which entailed over 1100 submissions to the docket, three and a half years, and several companies who did not survive until the final rules. This balancing act now serves as a template for federal spectrum reform, particularly in the unlicensed areas - not just for the United States, but also for other parts of the world like Europe and Japan, who are watching the US closely. We cannot afford to place this unprecedented agreement in jeopardy, especially for a standard that may cause increased interference. Therefore, the UWB Forum is support of the Common Signaling Mode (CSM) to ensure co-existence mechanisms and inter-communication is built into devices from the beginning.

1.2.3 Regularization of Ultra Wideband Systems

In 1962, U.S.Army carried out a nuclear experiments at Jonston lagoon island which is 1300 km southwest of Hawaii islands. The nuclear bomb was explored at the altitude of 400 km. Due to the electro-magnetic pulses (EMP) generated by the explosion, the streetlights went out, the telephone system went down, and the broad casting was interrupted. U.S.Army had realized the power of the EMP and started two researches. One was the robust distributed network that is nowadays called the Internet. The other was the EMP itself which was the original of UWB [15].

As the beginning of the research, UWB was employed for radar systems. An example of the UWB pulse waveform is shown in Fig. 1.6. Since the pulse duration is quite short such as 100 psec, it is possible to improve the resolution of the radar. It may be able to locate the objects with the order of *cm*. Since mid 90s, UWB had been also investigated for communication systems. In 1998, the companies such as U.S.Radar, Time Domain, and Zircon applied the commercial use of the UWB to Federal Communication Committees (FCC) [14]. In 2000, FCC proposed the revision of Part 15 rule (Notice of Proposed Rule Making) and approved the commercial use of UWB systems in 2002 [22]. Following the FCC's decision, the regulatory issues of UWB has been discussed by European Conference of Postal and Telecommunications Administrations (CEPT) in Europe, and by Ministry of Public Management, Home Affairs, Posts and Telecommunications in Japan [23], [24].

UWB systems is defined as follows.

1. The spectrum of the UWB siganl satisfies the following equation.

$$\eta = 2 \cdot \frac{f_H - f_L}{f_H + f_L} > 0.2, \tag{1.3}$$

   where f_H and f_L are given in Fig. 1.7. Or

2. η is more than 500 [MHz].

By FCC, the bandwidth assigned for UWB systems is about 7 GHz from 3.1 GHz to 10.6 GHz. UWB systems occupy the same frequency band that has been assigned for the existing radio communication systems (ex. 802.11a, Satellite, etc.). Therefore, the transmission power is regulated less than -41.3 dBm/MHz as much lower than the conventional wireless systems as shown in Fig. 1.8. However, the assignments of frequency bands for the radio systems are different among each country. For this, each country has a right to make regulations of UWB. In Japan, the UWB spectrum mask is different from FCC's mask. The transmitted power between 4.8 GHz and 7.25 GHz is limited less than -70.0 dBm/MHz in order to avoid interfering to other radio systems that uses 5 GHz frequency band as shown in Fig. 1.9.

Now, UWB systems have been discussed in two organizations according to the use of UWB systems [25]. One is IEEE802.15.3a for high-speed UWB systems and the other is IEEE802.15.4a for low-speed UWB systems. Fig. 1.10 shows the relationship of IEEE802 organizations.

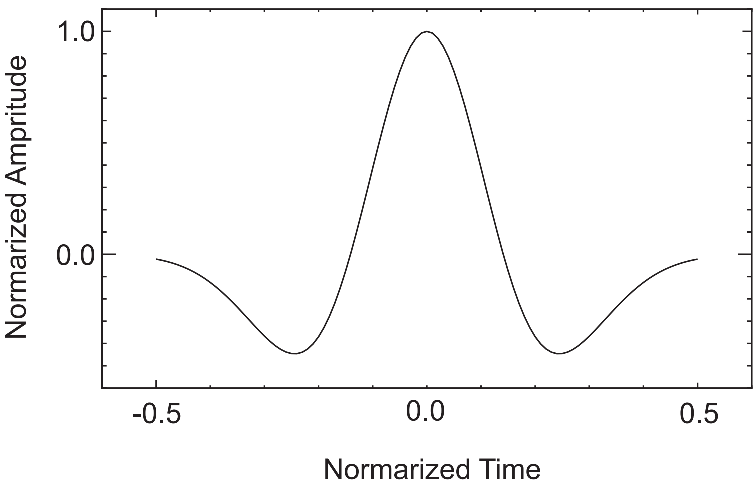

Figure 1.6: UWB Pulse Wave

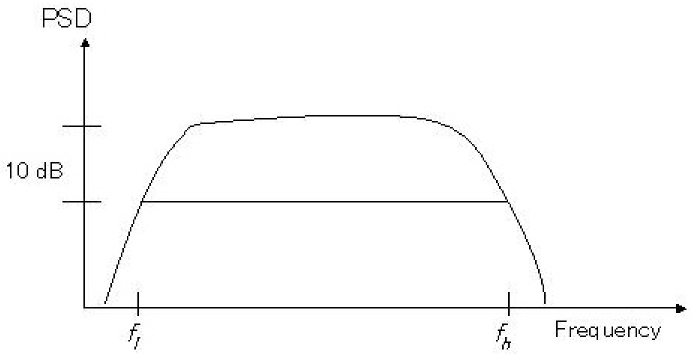

Figure 1.7: UWB definition by FCC

1.2.4 Introduction of IEEE802.15.3a

As for standardization, UWB systems have been under discussion in Institute of Electrical and Electronics Engineers (IEEE) in U.S.A., European Telecommunications Standards Institute (ETSI) in Europe, and in Multimedia Mobile Access Communication Forum (MMACF) in Japan. Among them, TG3a of IEEE802.15 is the most advanced in terms of the standardization of UWB systems [26]. IEEE802.15 TG3a is the task group that discusses the standard of high-speed wireless personal area network (WPAN) [27], [22]. The applications of this WPAN are such as the connections between digital audio-visual electronics devices or the connections between PC and its peripheral equipments. The technical requirements of the UWB systems proposed by TG3a is shown in Table 1.3. For example, in order to transmit the video data in video cameras without compression, at least the data rate of 30 Mbps is required. Therefore, WLAN systems such as IEEE802.11a/b/g can not be employed as the maximum data rate of those systems are at most 20 Mbps in actual as shown in Table 1.4.

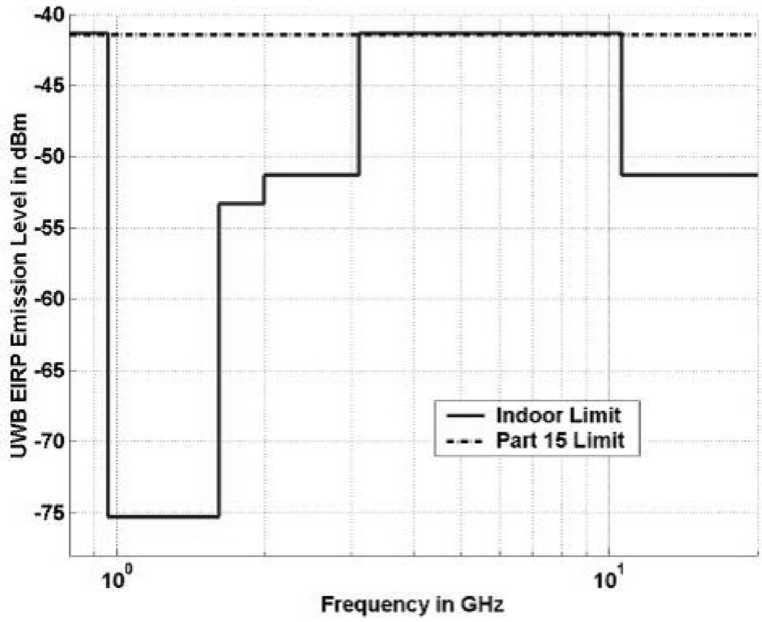

Figure 1.8: UWB spectrum mask defined by FCC

The IEEE 802.15.3a most commendable achievement was the consolidation of 23 UWB PHY specifications into two proposals using Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) UWB supported by the WiMedia Alliance [28], and Direct Sequence - UWB (DS-UWB) supported by the UWB Forum [29].

Table 1.3: Specification of UWB system proposed by TG3a.

Bit rate	110[Mbps]@10[m], 200[Mbps]@4[m]
Shared Pico Net	4
Shared with the others	Bluetooth, 802.11, ISM
MAC Protocol	802.15.3
Power consumption	100[mW]@110[Mbps], 250[mW]@200[Mbps]

Table 1.4: Comparison of wireless LAN.

	Bandwidth	Data rate	Features
2.4G WLAN	20 [MHz]	11 [Mbps]	The effective data rate < 20 [Mbps]
5G WLAN	20 [MHz]	54 [Mbps]	
UWB	7 [GHz]	1 [Gbps]	high speed, short range

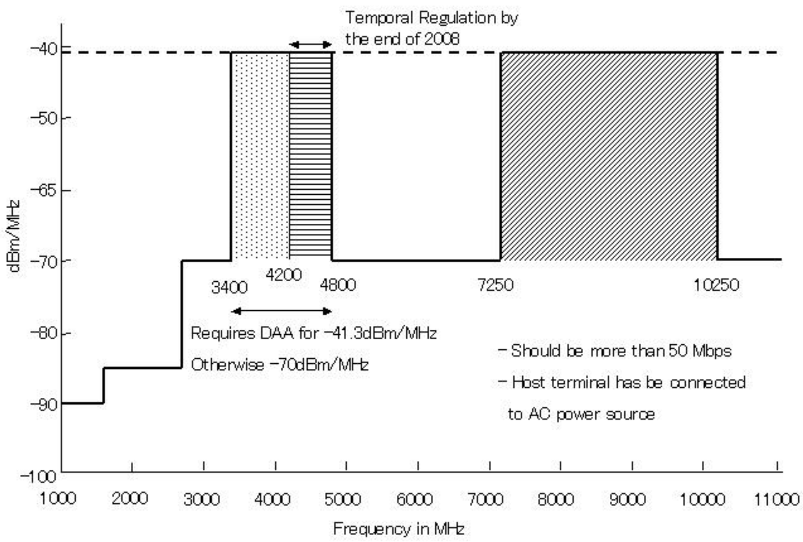

Figure 1.9: UWB spectrum mask in Japan

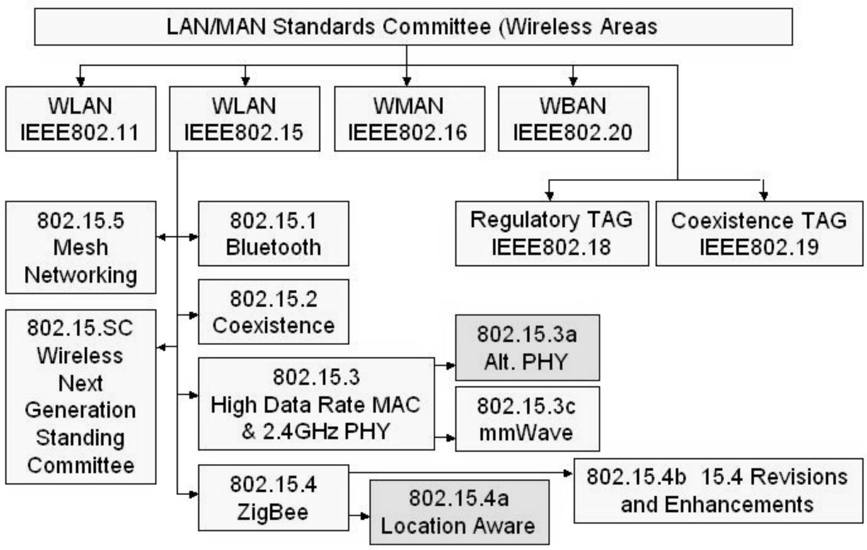

Figure 1.10: The IEEE802 organizations

1.2.5 Introduction of IEEE802.15.4a

The IEEE 802.15 Low Rate Alternative PHY Task Group (TG4a) for Wireless Personal Area Networks (WPANs) has defined a project for an amendment to 802.15.4 for an alternative PHY.

The principle interest is in providing communications and high precision ranging / location capability (1 meter accuracy and better), high aggregate throughput, and ultra low power; as well as adding scalability to data rates, longer range, and lower power consumption and cost. These additional capabilities over the existing 802.15.4 standard are expected to enable significant new applications and market opportunities.

802.15.4a became an official Task Group in March 2004 with its committee work tracing back to November 2002. The committee is actively drafting an alternate PHY specification for the applications identified in accordance with the project timeline. The first edition of the 802.15.4 standard was released in May 2003.

In March 2005, the TG4a selected the baseline specification without enacting our down-selection procedures. The baseline is two optional PHYs consisting of a UWB Impulse Radio (operating in unlicensed UWB spectrum) and a Chirp Spread Spectrum (operating in unlicensed 2.4GHz spectrum). The UWB Impulse Radio will be able to deliver communications and high precision ranging.

Table 1.5: 802.15.4 PHY Specs / Values.

-	Standard	Typical	Units
Xmit PO	-3	0	dBm
Sens.	-85/-92	-95/-97	dBm
Channels	1, 10, 16	-	-
Data rate	250/40/20	250/40/20	kb/s
Battery life	-	.5 - 2	years
Location Awareness	no	no	-

1.2.6 Channel Model of Ultra Wideband Systems

In IEEE802.15.3a and 4a, the UWB channels are modeled as follows.

The UWB channel impulse response in complex baseband is expressed as [30], [31]:

$$h(t) = \sum_{l=1}^{L} a_{k,l} \exp(\jmath\phi_{k,l})\delta(t - d_l - \tau_{k,l}), \tag{1.4}$$

which comes from the Saleh-Valenzuela mode, where $a_{k,l}$ is the tap weight of the k-th component of the l-th multipath cluster, d_l is the delay of the l-th cluster, $\tau_{k,l}$ is the delay of the k-th component relative to the l-th cluster delay d_l, and $\delta(\cdot)$ is the δ-function. The phase ϕ is uniformly distributed in $[0, 2\pi)$. The number of multipath clusters, L, is modeled as a random variable with the Poisson distribution

$$p_L(L) = \frac{\bar{L}^L \exp(\bar{L})}{L!}, \tag{1.5}$$

where $\bar{L}$ is the mean of L. Set $\tau_{1,l} = 0$. The distribution of cluster arrival times is given as a Poisson process

$$p(T_l, |T_{l-1}) = \Lambda_l \exp[-\lambda_l(T_l - T_{l-1})], l > 1, \tag{1.6}$$

where Λ_l is the cluster arrival rate, independent of l. The ray arrival time is approximated by the mixture of two Poisson processes as

$$\begin{aligned} p(T_{k,l}, |T_{k-1,l}) &= \beta\lambda_1 \exp[-\lambda_1(T_{k,l} - T_{k-1,l})] \\ &-(1-\beta)\lambda_2 \exp[-\lambda_2(\tau_{k,l} - \tau_{k-1,l})], k > 1, \end{aligned} \tag{1.7}$$

where β is the mixture ratio, and λ_1 and λ_2 are the ray arrival rates. The mean power of multi-paths within each cluster follows the exponential decay, i.e.,

$$E[|a_{k,l}|^2] \propto \Omega_l \exp(-\frac{\tau_{k,l}}{\zeta_l}),, \tag{1.8}$$

where Ω_l is the integrated energy of the l-th cluster, and ζ_l is the intra-cluster decay time constant.

In IEEE802.15 TG3a, four kinds of environments have been defined for evaluating the performance of UWB systems, based on actual measurement [32], [33]. Each channel model is given in Table 1.6. CM1 is a line-of-sight (LOS) channel within a distance between 0 m and 4 m. CM2 is a non-line-of-sight (NLOS) channel within a distance between 0 m and 4 m. CM3 is a NLOS channel within a distance between 4 m and 10 m. CM4 is an extreme NLOS channel. There are 100 path models for each channel models.

Table 1.6: Parameters for channel models in TG3a.

	Number of Channels	Mean Excess Delay (nsec)	RMS Delay (nsec)
CM1	100	4.9	5
CM2	100	9.4	8
CM3	100	13.8	14
CM4	100	26.8	26

On the other hands, channel models of IEEE802.15.4a is defined in [34]. In IEEE802.15.4a, four kinds of environments (Residential, Office, and Industry, Outdoor) have been assumed and each model is distinguished between the Line-Of-Sight (LOS) and the Non LOS (NLOS) case. Each channel model is given in Table 1.7.

1.2.7 Modultaion Schemes of Ultra Wideband Systems

1.2.7.1 Direct Sequence Ultra Wideband Systems (DS-UWB)

Impulse Radio Ultra Wide Band (IR-UWB) uses the impulse sequence whose width is less than 1 nano second without modulating the information signal by the carrier signal [35], [36]. Pulse

Table 1.7: Channel model in IEEE802.15.4a.

Channel Model	Environment
CM1	Residential LOS
CM2	Residential NLOS
CM3	Office LOS
CM4	Office NLOS
CM5	Outdoor LOS
CM6	Outdoor NLOS
CM7	Industrial LOS
CM8	Industrial NLOS
CM9	Open Outdoor Environment NLOS

shaping systems employing UWB pulses yield robust performance in high multipath environments, since, by resolving these extremely short pulses, it is possible to mitigate the harmful effects of multipath fading [37]. Another advantage of pulse shaping in UWB communications is the possibility of proposing an algorithm to mitigate narrow band interference induced by other concurrent communication services using the same transmission band [38]. In general, Direct Sequence Spread Spectrum (DS-SS) is used. Motorola and Freescale support DS-UWB [39], [29]. Originally, IR-UWB was considered for the standard modulation scheme in 2002. That is why IR-UWB can realize the low power consumption and the low cost.

1.2.7.2 Multi-band Orthogonal Frequency Division Multiplexing (MB-OFDM) - Ultra Wideband Systems

MB-OFDM is the combination of OFDM and frequency hopping. MB-OFDM is supported by WiMedia [28]. WiMedia UWB is the basis for the industry ’s first UWB standards. The WiMedia Ultra-Wideband (UWB) Common Radio Platform incorporates medium access control (MAC) layer and physical (PHY) layer specifications based on Multi-band Orthogonal Frequency Division Multiplexing (MB-OFDM) [40], [41]. The solution enables short-range multimedia file transfers at data rates of 480 Mbit/s and beyond with low power consumption, and operates in the 3.1 to 10.6 GHz UWB spectrum. WiMedia UWB is optimized for the personal computer (PC), consumer electronics (CE), mobile device and automotive market segments.

The UWB system provides a wireless PAN with data payload communication capabilities of 53.3, 55, 80, 106.67, 110, 160, 200, 320, and 480 Mb/s.

The WiMedia UWB platform is also optimized for complementary wireless personal area network (WPAN) technologies such as Bluetooth 3.0, Certified Wireless USB, the 1394 Trade Group ’s “ Wireless FireWire ” Protocol Adaptation Layer (PAL) (Non-IP Peer to Peer architecture) and Wireless TCP/IP - UPnP (WiNet) [28]. Different wireless protocols can operate within the same wireless personal area network without interference. In addition to these, many other industry protocols can reside on top of the WiMedia UWB platform. Those include Ethernet, DVI and HDMI. Presently, the WiMedia PHY specification has an over-the-air uncoded capability of more than 480 Mbit/s; the specification is highly scalable and will ultimately support wireless DVI and HDMI, operating at Gbit/s data rates.

The proposed UWB system employs orthogonal frequency division multiplexing (OFDM) using a total of 122 modulated and pilot subcarriers out of a total of 128 subcarriers. The proposed UWB system also utilizes a time-frequency code (TFC) to interleave coded data over upto three frequency bands (called a band group). UWB frequency band is divided into 528 MHz 14 subbands. For such band groups with three bands each and one band group with two bands are defined, along with four 3-band TFCs and two 2-band TFCs. Together, these band groups and the TFCs provide the capability to define eighteen separate logical channels or independent piconets. Devices operating in band group #1 (the three lowest frequency bands) are denoted Mode 1 devices, and it shall be mandatory for all devices to support Mode 1 operation, with support for the other band groups being optional and added in the future.

1.3 Ad-hoc Network

1.3.1 Introduction of Ad-hoc Networks

Ad-hoc networks are not necessary to have base stations unlike conventional radio systems [42]. Therefore, each node has to have a routing function and it is essential to use multi-hop transmission. Since each node has a network control function, even if one of the nodes is out of order, the influence to the whole network is quite limited. Therefore, the ad-hoc networks are excellent in respect of the cost and the robustness. Several experiences with natural disasters such as tsunami and construction accidents have focused on the need to facilitate access to distributed knowledge and data critical to effective emergency response and recovery. Therefore, It attracts large attention from researchers in the military and the commercial fields. However, since its topology always changes, it is hard to control the network.

Developments in wireless ad-hoc networks that communicate effectively in short distances are being investigated. Desirable features for ad-hoc networks include high precision location estimation abilities, extremely low power consumption, low production cost, autonomous operation and adaptation to the environment. These features make UWB radio as an attractive transmission medium for wireless ad-hoc networks.

1.3.2 Routing Protocols

Since the topology of ad-hoc network always changes, it is hard to control the network. For this, the conventional static routing protocol cannot be used in ad-hoc network. The dynamic routing protocol has been used and investigated [43]. The advantage of dynamic routing protocol is to save the management since the routing information is renewed dynamically by routing protocol. The dynamic renewal of routing information enables routing protocol to select the adaptive route of a delivery and to break the routing information that could not have been already used as soon as possible. However, if the wrong information was broadcasted, a communication cannot be used in large area. Moreover, if the loop of the delivery route (infinite problem) is occurred, the load of CPU and the traffic of network is increased rapidly and then network would be down. Recently, as the investigation of ad-hoc network goes ahead, positioning information has been considered to the dynamic routing protocol. Thus, the use of UWB has attracted large attention. In UWB ad-hoc network, the investigation is mainly about medium-access control (MAC) - scheduling, routing protocols and power control. The MAC layer controls routing of a delivery, power control and scheduling policies. Routing protocols have been introduced. Many routing protocols can be divided into the three types [43].

1. Reactive routing system

2. Proactive routing system

3. Hybrid routing system

In reactive routing system, there are Dynamic Source Routing Protocol (DSR) [44] and Ad-hoc On-demand Distance Vector (AODV) [45]. DSR is the scheme that all routing information is included in a packet. AODV is the scheme that each node has routing table. AODV performs higher than DSR in environment the number of nodes and traffic is large. On the other hand, there are Optimized Link State Routing (OLSR) [46] and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [47] in proactive routing system. OLSR is efficiency flooding scheme and TBRPF exchanges topology information mutually by the neighbor node. In the routing system that uses both reactive system and proactive system, there is Zone Routing Protocol (ZRP) [48]. ZRP uses proactive system to the node that exists in zone and uses reactive system to the other node. However, these routing schemes do not employ the location information of the nodes and use the flooding scheme. The flooding scheme is the simple mechanism and high reliance for delivery of data. However, the flooding scheme is not good scheme to mobile node because this is bad efficiency to bandwidth. The routing schemes based on signal-to-noise ratio have also been proposed by ATR [49], [50]. ATR system changes a route according to communication condition such as SINR. Location based routing schemes have also been proposed [51]. These schemes do not employ spread spectrum communications and limiting the range for forwarding a packet only uses the location information. Location based routing systems can relay the packet to the desired region and save the network resources. Therefore, Location based routing systems with GPS has been proposed. However, the size of GPS is too large to use GPS on the small modules of mobile devices. Besides, GPS cannot be used in indoor environment. Now, the use of UWB has been expected instead of GPS. That is why the time resolution of UWB is so high that the location estimation capability of UWB is very high. Therefore, the investigation of the routing protocol for UWB is mainly about location based routing system [52], [53]. Also, there is a minimum energy and loss route (MELR) [54]. The power consumption of UWB system is very low. If location capacity of UWB is used in MAC layer, the power consumption of it can be reduced efficiently. This investigation focuses on maximizing the capacity of the system and considering the shortest route and high rates, route loss and energy.

1.3.3 Medium Access Control Protocols

1.3.3.1 Aloha Protocols

In radio communication systems, Medium Access Control (MAC) protocol is the protocols that one node gets the right of using the radio signal in the multiple environment. MAC protocol has the important role to establish the communication links efficiently. MAC protocols have been investigated in Hawaii University since 1968. The Algorithms of many MAC protocols is based on ALOHA system of Hawaii University. ALOHA system is the system that any nodes can transmit a signal whenever they want to do it [55], [56], [57]. This system is called contention scheme. ALOHA systems have two types, pure ALOHA and slotted ALOHA. On the other hands, there are schemes that a node that has a right to transmit a signal can transmit a signal

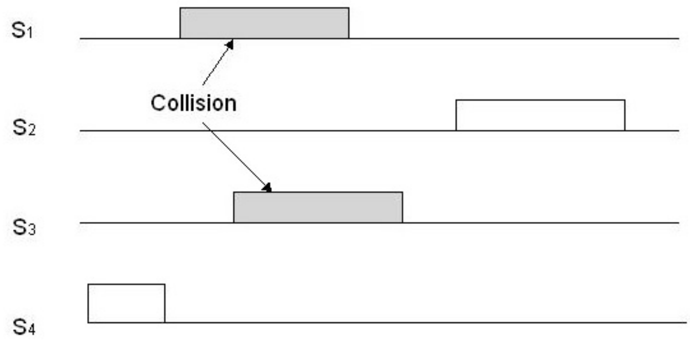

Figure 1.11: Pure ALOHA.

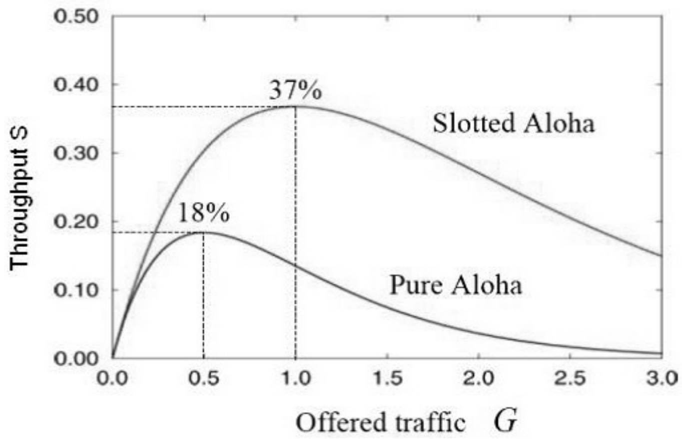

Figure 1.12: Throughput of Pure ALOHA.

without competition. This scheme is called polling system.

There are mainly ALOHA and Carrier Sense Multiple Access (CSMA) in a typical method.

Pure ALOHA is the protocol that each node can start transmission at free as shown in Fig. 1.11. In this protocol, if the collision has not been occurred, the transmission is success and a receiver can receive the signal. This protocol is a very simple. However, its throughput is less than 18 % as shown in Fig. 1.12. Slotted ALOHA is the improvement of pure ALOHA. Its throughput is less 36 %.

1.3.3.2 Carrie Sense Mulptiple Access Protocols

CSMA is the protocol which checks whether the other nodes are transmitting carrier signals before packet transmission [58], [59], [60], [61]. If a node can sense the channel being busy before transmission, the transmission is carried out for a random delay. This can reduce the probability

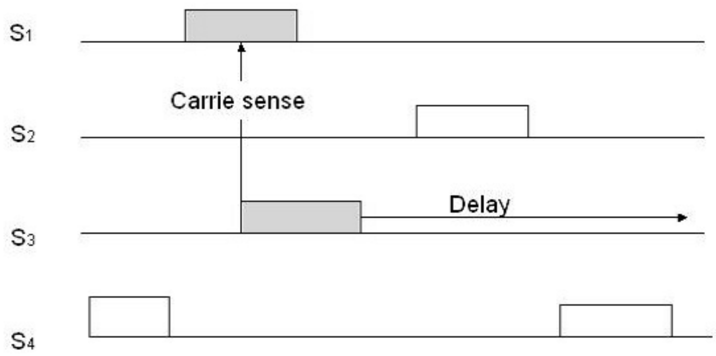

Figure 1.13: Carrier Sense Multiple Access (CSMA).

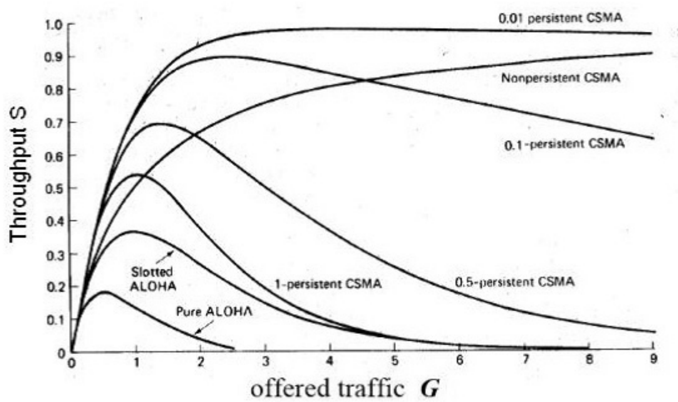

Figure 1.14: Throughput of CSMA.

of packet collisions. Fig. 1.13 shows the data transmission of CSMA. The performance of CSMA is better than that of pure ALOHA as shown in Fig. 1.14. CSMA is now used in many radio systems and selected to the standard MAC protocol of IEEE802.11a/b/g. the multichannel CSMA schemes have been considered [62], [63], [64]. One of the problems of CSMA protocols is that it is not possible to sense the channel while sending a packet, therefore CSMA is not possible. Another problem is the hidden terminal problem. The hidden terminal is as follows. A node X is located in range of the receiver R but is not located in range of the sender S. Therefore, X cannot know that S is transmitting to R. For the hidden terminal problem, Request to Send (RTS) / Clear to Send (CTS) is used with CSMA. In RTS/CTS, a sender and a receiver exchange a RTS packet and a CTS packet.

1.3.4 Retransmission Protocols

The retransmission function is very important for compensating for the lost packet and improving the throughput. Automatic Repeat Request (ARQ) protocol is usually used for retransmission [65], [66], [67]. In ARQ protocol, an ACK packet is used for the confirmation of successful transmission and retransmission. When a packet has been received successfully, the receiver returns an ACKnowledge (ACK) packet to the sender. If on the other hand a packet is lost, the receiver returns a Negative-AcKnowledge (NACK) packet to the sender requesting retransmission of the packet. There are four main ARQ protocols, namely, Stop-and-wait (SAW), Go-and-N (GBN), Selective-repeat (SR), and Hybrid ARQ [68], [69]. In SAW ARQ, the sender transmits a Protocol Data Unit (PDU) and waits for a response. The receiver returns an ACK PDU or a NACK PDU according to whether a data PDU is received correctly or not. In GBN ARQ, the sender continuously transmits PDUs without waiting for a positive or negative acknowledgement. In case a NACK is received, the sender will retransmit all the PDUs with serial numbers greater or equal to the one that was unsuccessfully received. SR ARQ is similar to GBN ARQ, the difference being that in SR ARQ only the erroneous PDUs are retransmitted. Fig. 1.15 shows examples of SAW ARQ and GBN ARQ. Hybrid ARQ is employed in High Speed Downlink Packet Access (HSDPA) [70], [71], [72]. In Hybrid ARQ, an error correcting code such as Forward Error Correction (FEC) is employed to the ARQ protocol. Since FEC can repair a number of errors without retransmission, it reduces the required number of retransmissions. On the other hand, echo detection scheme has been proposed in [73]. Echo detection is premised on the use of Time Division Multiple Access (TDMA). This scheme checks in the time-slot used by a relay node for the confirmation of successful transmission. If the sender can sense the power of the signal of the relay node in that slot, the sender regards the transmission successful. The TDMA-based echo detection cannot be applied because the transmitted power of DS-UWB is too low that the node cannot sense the signal whose power is less than the noise level. It is thus clear that echo detection cannot be used in a DS-UWB system.

For an example, the detail of the ARQ protocol with FEC is explained. This system uses an ACK packet and a NACK packet as shown Fig. 1.16. Suppose that node S is a source node and node A is a relaying node. When node A receives a packet from node S successfully, it returns an ACK and transmits the data packet to B. If B doesn't receive successfully the transmitted packet, it sends a NACK to A, requesting retransmission. Even if A receive neither an ACK nor a NACK packet from B, A transmits the data packet again. This procedure is repeated until the packet is successfully received by node B and, finally, the destination node, C.

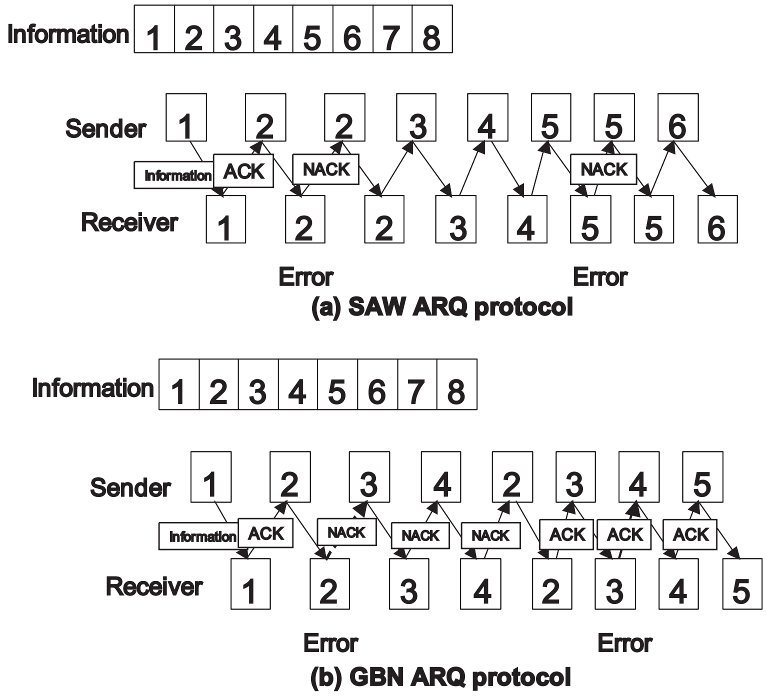

Figure 1.15: The transmission with SAQ ARQ and GBN ARQ.

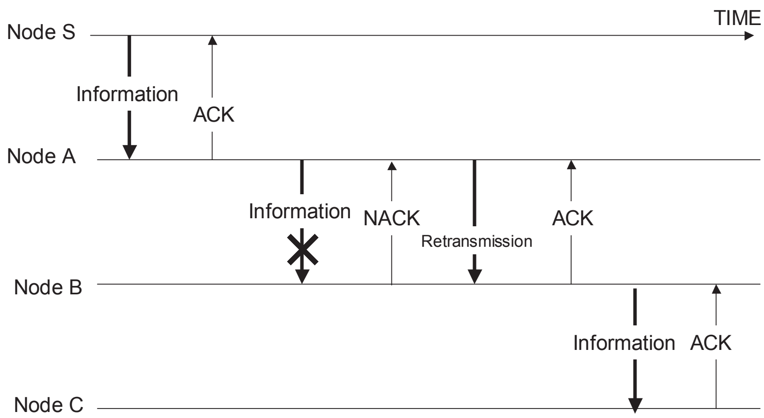

Figure 1.16: Multihop transmission with Hybrid ARQ system.

1.4 Motivation of the Research

1.4.1 Realization of UWB Ad-hoc Networks

‘ Ubiquitous computing ’ is the ability to access a computer at any time of day, wherever one is . There are numerous issues that need to be addressed in order to realize it; battery life and transmission data rate are just two examples. There is considerable amount of research in the field of ubiquitous wireless modules that are currently undertaken, although the size, data rate, and communication range do not yet meet the required specifications. Nevertheless, ubiquitous computing will become reality in the near future once these issues have been resolved.

Ultra Wide Band (UWB) radio has received large media attention since it was approved by Federal Communication Commission (FCC) for commercial use in February, 2002 [16], [35]. Since UWB systems use short pulse waves of less than 1 [ns], high data rate communication can be achieved in addition to precise positioning capability and low power consumption. While the transmission data rate of UWB systems can achieve more than 100 times that of Bluetooth (50 - 480 Mbps), the power consumption of UWB is the roughly equivalent to that of Bluetooth (100 - 200 mW). The maximum transmission data rate of IEEE802.11a/g systems is about 56 Mbps although the actual transmission rate is less than 20 Mbps. In addition, construction of low power devices (less than 1 W) poses considerable obstacles. In terms of battery life,

- UWB is very useful for ubiquitous computing in comparison to the existing radio systems.

UWB systems have been investigated for very short-range wireless communications in the indoor environment. This explains the limited transmission power of the UWB.

- The communication range of UWB is actually too small to cover a whole house as shown in Fig. 1.17.

Even in an indoor environment, it should be considered long distance communications. It is not possible to communicate with someone greater than 10 m away by using UWB. As one-way, the other radio systems or cable transmissions have to be used in conjunction with the UWB systems. On the other hands, if the other radio systems are used with UWB, the transmission data rate is too limited to support digital household electric appliances. Thus, our research employs ad-hoc networks to extend the communication range of UWB.

Therefore, this research aims to propose and investigate the MAC protocols for UWB ad-hoc networks to cover an indoor environment perfectly, even if it is used in a large building such as a hotel for example.

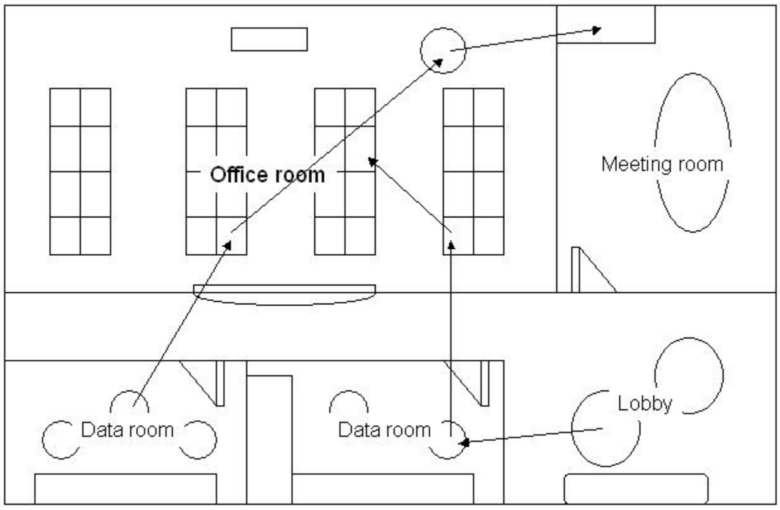

Figure 1.17: Communication range of UWB systems.

1.4.2 Packet Routing Scheme for UWB Ad-hoc Networks

At first, we have considered about the low transmission power of UWB systems. We have applied variable spreading factor DS-SS systems to UWB systems for solving the power problem of UWB systems. Variable spreading factor is used to change the transmission data rate in general. We have used it to keep the power of the received signal. For this, spreading factor is changed according to the distance between the nodes. In addition, we have considered using ad-hoc networks for multihop transmission.

For ad-hoc networks, many routing schemes have been proposed such as AODV [45], OLSR [46] and TBRPF [47]. They do not employ the location information of the nodes and use the flooding scheme. The flooding scheme is the simple mechanism and high reliance for delivery of data, although the flooding scheme is not good scheme to mobile node because this is bad efficiency to bandwidth. Besides, they do not employ spread spectrum communications and limiting the range for forwarding a packet only uses the location information. The routing schemes based on signal-to-noise ratio have been proposed by ATR [49], [50]. It requires array antennas to determine the route of the packets. Neverthless, it is difficult to implement the array antennas in the small nodes. Location based routing schemes have also been proposed [52], [53]. They do not employ spread spectrum communications and the location information is only used by limiting the range for forwarding a packet. Moreover, they never consider about the features and the weakness of UWB systems.

Our proposed routing scheme employs UWB's features such as high location estimation to control the maximum transmission distance. As mentioned above, the spreading factor has to increase in proportion to the distance. As it increases, the data rate decreases rapidly if the transmission distance is large. In addition, longer packet length cause more interference to the other packets. we have proposed the routing scheme with making distance between hops shorten. Our proposal chooses the intermidiate node only by the relative distance between the nodes, even if the source node does not know the direction of the destination node. This can also solve the infinite loop problem.

We proposed this routing scheme in 2003 [74]. At that time, UWB systems have been mainly considered for high data rate communication systems with pulse shape waves whose width is less than 1 [nano] second. UWB systems have been investigated in many field and many research centers. Almost researches are about the signal processing. There are a few papers about UWB ad-hoc networks. Moreover, they have not considered about the low transmission power of UWB systems and DS-CDMA systems. In additions, they have not investigated the performance between singlehop and multihop transmission. Therefore, our proposed scheme has an emphasis impression to the UWB communities at that time.

The relationship among the proposed scheme and the previous works are illustrated in Fig. 1.18.

1.4.3 Code Sense Scheme for DS-UWB Ad-hoc Networks

MAC protocols are very important to establish the communications and improve the throughput of networks. That is because packet loss is usually happened so many times in communications.

Conventional CSMA schemes sense the power of the carrier signal for checking the existence of the carrier signal. In CSMA schemes, there are one channel CSMA and multichannel CSMA schemes. Multichannel CSMA schemes make the communication channel divided and one of them is used for CSMA schemes [62], [63], [64]. However, when UWB or CDMA is employed, the power level of the received signal is too low to detect the carrier signal. Moreover, CDMA systems can make two or more signals shared in the same time slot. If the conventional CSMA schemes are employed in DS-UWB systems, the large frequency bandwidth of UWB systems should be divided for sensing the carrier signal. This means that the features of UWB systems are lost.

At first, we consider that the power of UWB systems is very low. It is very difficult for the conventional CSMA protocols to detect the existence of UWB signal. IR-UWB systems use DS-SS modulation scheme in general. In DS-SS, the bandwidth of the modulated signal is much wider than that of the original signal. The correlation value of DS-SS signals is good. The bandwidth of UWB signals is very large as compared to the existing narrowband wireless DS-SS systems. That means that the correlation value of UWB can be better than that of the conventional DS-SS systems. A novel CSMA scheme for UWB ad-hoc network employs the correlation of the spreading code and detects the existence of UWB signal (code sense) [75]. We show the performance of this proposed scheme through computer simulation. There was no paper about MAC protocols optimized for UWB ad-hoc networks before we proposed this

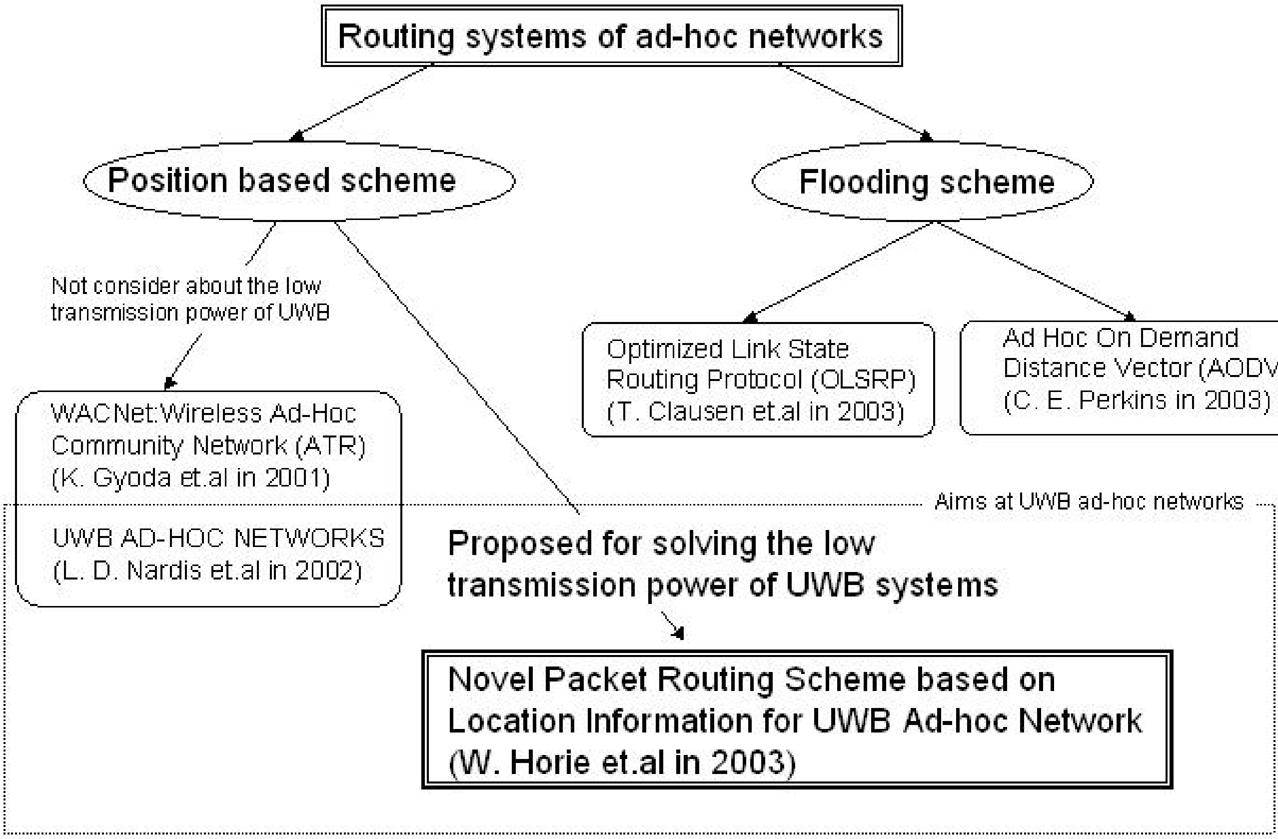

Figure 1.18: Relationship of the research about the Packet Routing Scheme.

scheme in 2004. I think that our proposed scheme was the first paper about MAC protocols for UWB systems in the world. This scheme has been actually referred from many papers about MAC protocols for UWB systems.

The relationship among the proposed scheme and the previous works are illustrated in Fig. 1.19.

1.4.4 Retransmission Scheme for DS-UWB Ad-hoc Networks

In Automatic Repeat Request (ARQ) protocols [65], [66], [67], an ACK packet is used for the confirmation of successful transmission and retransmission. When a packet has been received successfully, the receiver returns an ACK packet to the sender. If on the other hand a packet is lost, the receiver returns a NACK packet to the sender requesting retransmission of the packet. An ACK packet interferes with other nodes. In ARQ protocols, there are mainly the following types such as Stop-and-wait (SAW) ARQ, Go-and-N (GBN) ARQ, Selective-repeat (SR) ARQ,

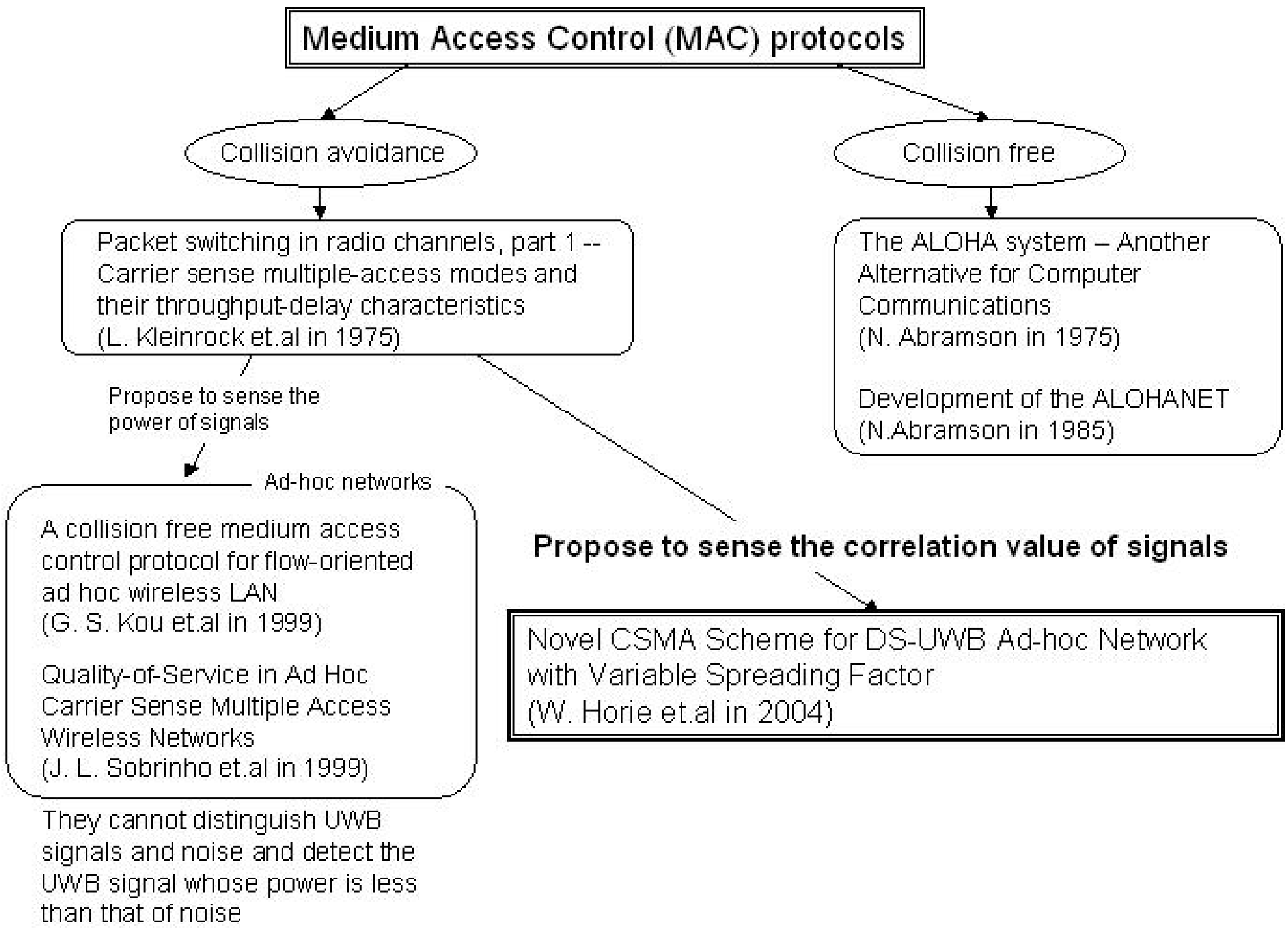

Figure 1.19: Relationship of the research about Medium Access Control (MAC) protocols.

and Hybrid ARQ. All ARQ protocols use an ACK packet for confirmation. Those protocols are improved to reduce the number of ACK packets used in transmission.

In multihop transmission, the required number ACK packets are higher than in the case of singlehop transmission, thus increasing the amount of interference. By decreasing the required number of ACK packets, the throughput in network can be improved. In this view, echo detection scheme has been proposed in [73]. Echo detection is premised on use of Time Division Multiple Access (TDMA). This scheme checks in the time-slot used by a relay node for the confirmation of successful transmission. If power of a signal can be sensed at that slot, the sender regards transmission successfully. However, the received power of a carrier signal in DS-UWB is too low for echo detection to distinguish between noise and signal. Echo detection cannot be used in UWB ad-hoc networks.

We have propose code sense scheme for DS-UWB system and applied it to retransmission [76], [77]. Code sense scheme uses the specific combinations of the spreading codes and doesn ’ t need to use an ACK packet. These spreading codes are assigned to each node based on a node 's ID and the other nodes can sense if the target node is receiving a packet or not. Only if the target node is the intermediate node, code sense is used. If the target node were the destination node, it uses an ACK packet. This proposal has been assumed to be used after communication links are established. Of course, an ACK packet is required in the initial stage to establish the link between nodes.

The relationship among the proposed scheme and the previous works are illustrated in Fig. 1.20.

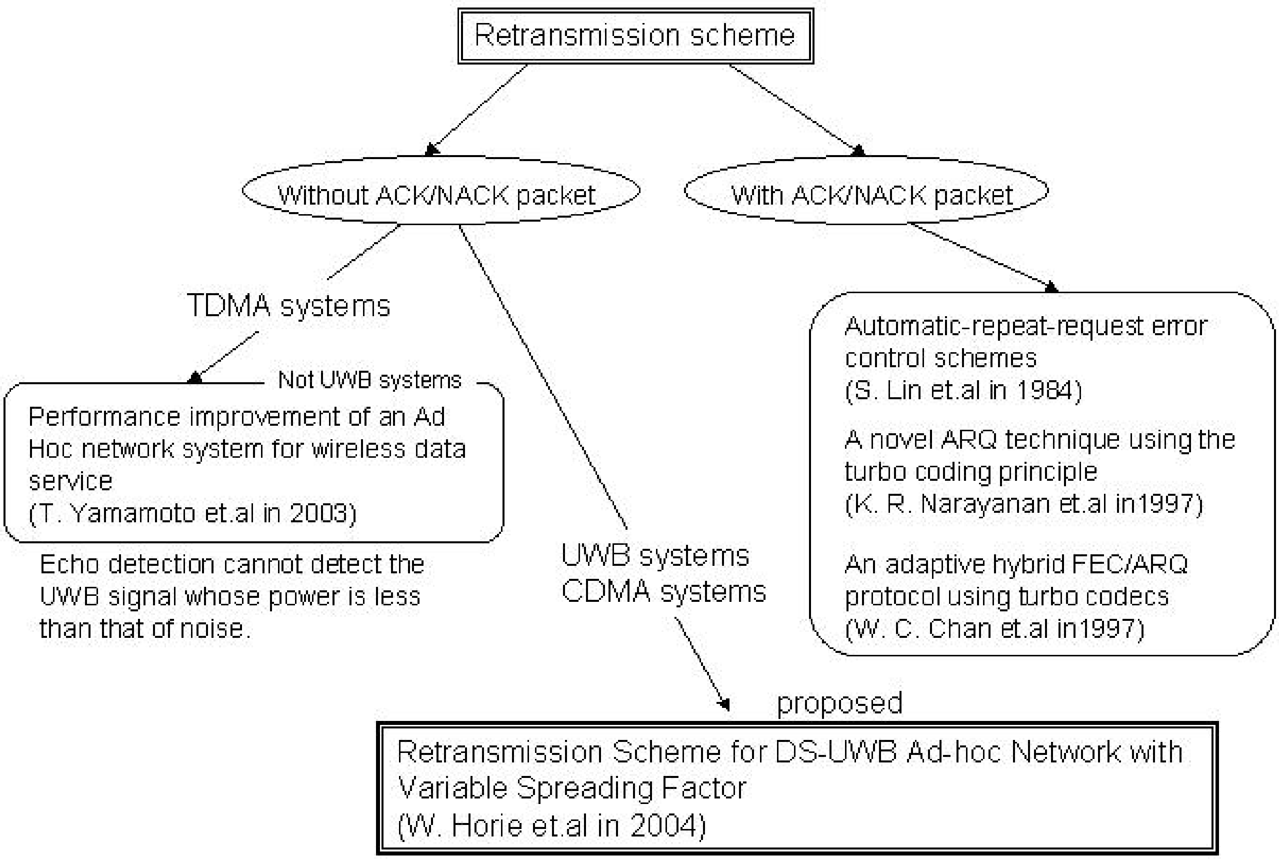

Figure 1.20: Relationship of the research about retransmission scheme.

1.4.5 Two Stage Acquisition Scheme with Squared Circuit for Impulsed-Based UWB Systems

Acquisition is very important role in order to get the good condition for the correlation. The aim of acquisition is to find the phase of the sequence at the initial stage of signal reception [5]. Acquisition is one of the key issues in recent wireless communication research. Many kinds of acquisition schemes have been proposed. They are mainly classified into two kinds [1]. One is based on a matched filter and the other is based on a correlator. In the acquisition scheme based on a matched filter, the hardware is more complex and expensive. On the other hands, schemes based on a correlator are simpler in terms of the hardware. These schemes require long time to achieve the acquisition in general. The above-mentioned schemes are not suitable for UWB communication systems as it is.

In order to realize a simple and high-speed acquisition scheme, a two stage acquisition scheme has been proposed. This is based on a correlator. The aim of this scheme is to reduce the acquisition time with the equivalent complexity compared to the conventional correlator search schemes. Other correlator search schemes focus on investigating the step size, detection threshold on narrowband radio systems. They search all cells by completing the acquisition. Our proposal is optimized to IR-UWB systems and other impulse radio systems. Impulse signals exist at one cell in each frame. In the proposed scheme, the search algorithm has two stages. The first stage is the timing detection stage and the second stage is the sequence acquisition stage. In the first stage, the receiver detects the timing of the pulse signals. In the second stage, based on the timing information of the pulse signals, the receiver finds the phase of the sequence. Our proposal does not need to search the cells in which the pulse signal does not exist in the second stage. If this scheme is used in the conventional narrowband radio systems and MB-OA systems, the advantages of this scheme is lost. In that case, the performance of this scheme has not been different from the conventional acquisition scheme.

All papers about acquisition employ the rectangle shape as the pulse shape [78], [79], [80], [81], [82]. The rectangle shape wave has been usually employed since the equation of the rectangle shape wave is very easy. However, the rectangle shape wave never exists in actual environment. In order to evaluate our proposal in actual environment - pulse shape and channel model, we consider Gaussian wave pulse as the UWB pulse shape.

The first proposal has been presented in 2004 [83]. That has not included the squared circuit. In 2005, we have proposed a two stage acquisition scheme with squared circuit scheme [84], [85]. Besides, we have to change the assumed environment. At first, IR-UWB systems have been considered to be the standard model in IEEE802.15.3a that investigates the high-speed communication systems. The first proposal has been assumed to be used in IEEE802.15.3a model. Now, IR-UWB systems have changed IEEE802.15.3a to IEEE802.15.4a that investigates the low-speed communication systems. Therefore, this thesis has investigated and evaluated our proposed acquisition scheme in IEEE802.15.4a channel models.

The relationship among the proposed scheme and the previous works are illustrated in Fig. 1.21.

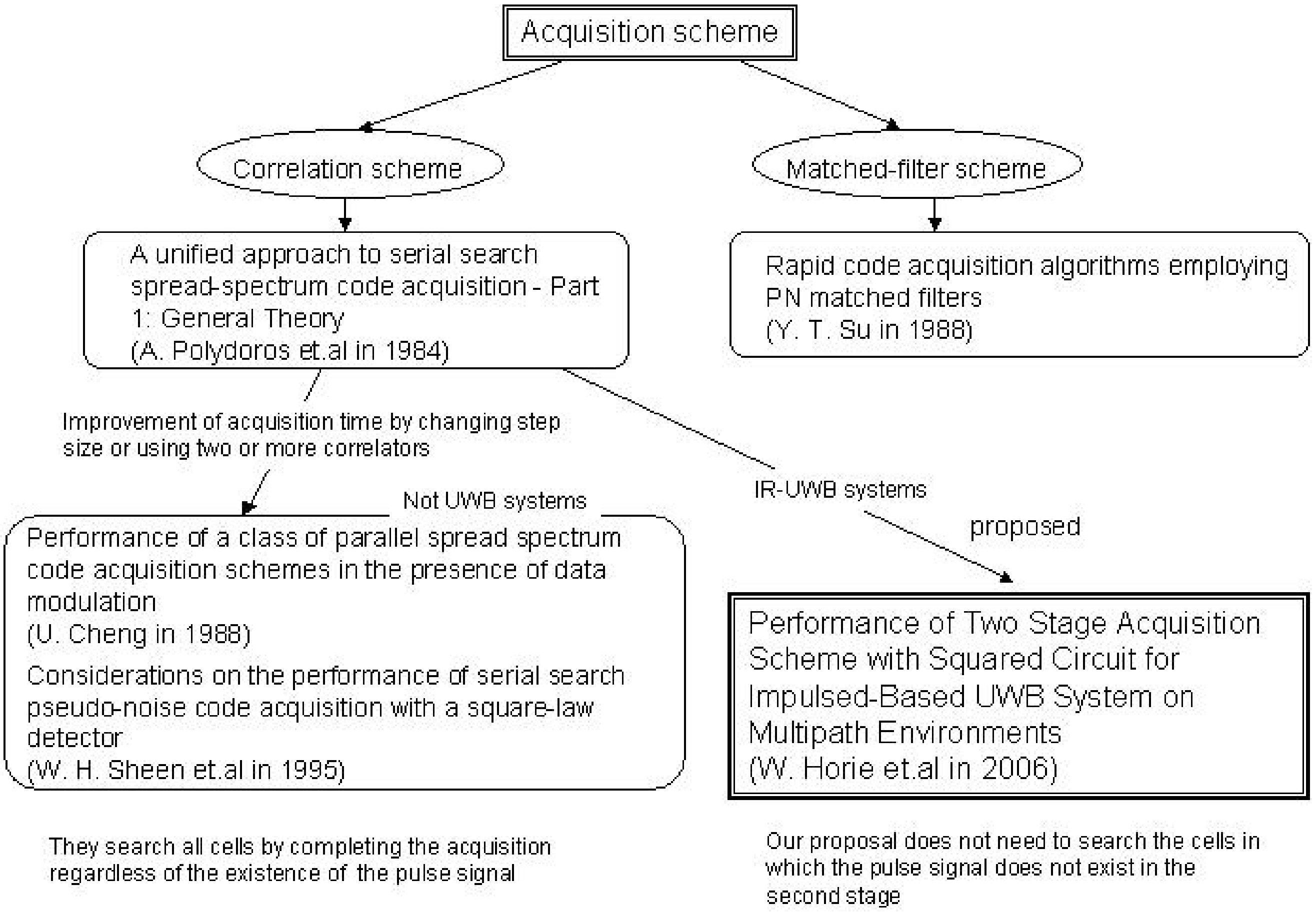

Figure 1.21: Relationship of the research about acquisition scheme.

1.5 Thesis Outline

This thesis consists of six chapters. The 1st chapter introduces the background and the motivation of this research.

The 2nd chapter presents a routing protocol to improve throughput in UWB ad-hoc networks regardless of the power of the received signal and interference.

The 3rd chapter presents the investigation of Code Sense scheme. This scheme is to sense the carrier signal of the other node by using the correlation value of the spreading codes. Code sense method can sense the received signal whose power level is too low for the conventional CSMA to detect the carrier signal.

The 4th chapter presents a novel retransmission protocols encompassing Code Sense scheme in order to compensate the packet loss.

The 5th chapter presents the investigation of the novel acquisition scheme optimized for UWB ad-hoc networks.

Finally, the 6th chapter summarizes the results of each chapter and concludes this thesis.

The outline of this thesis is depicted graphically in Fig. 1.22.

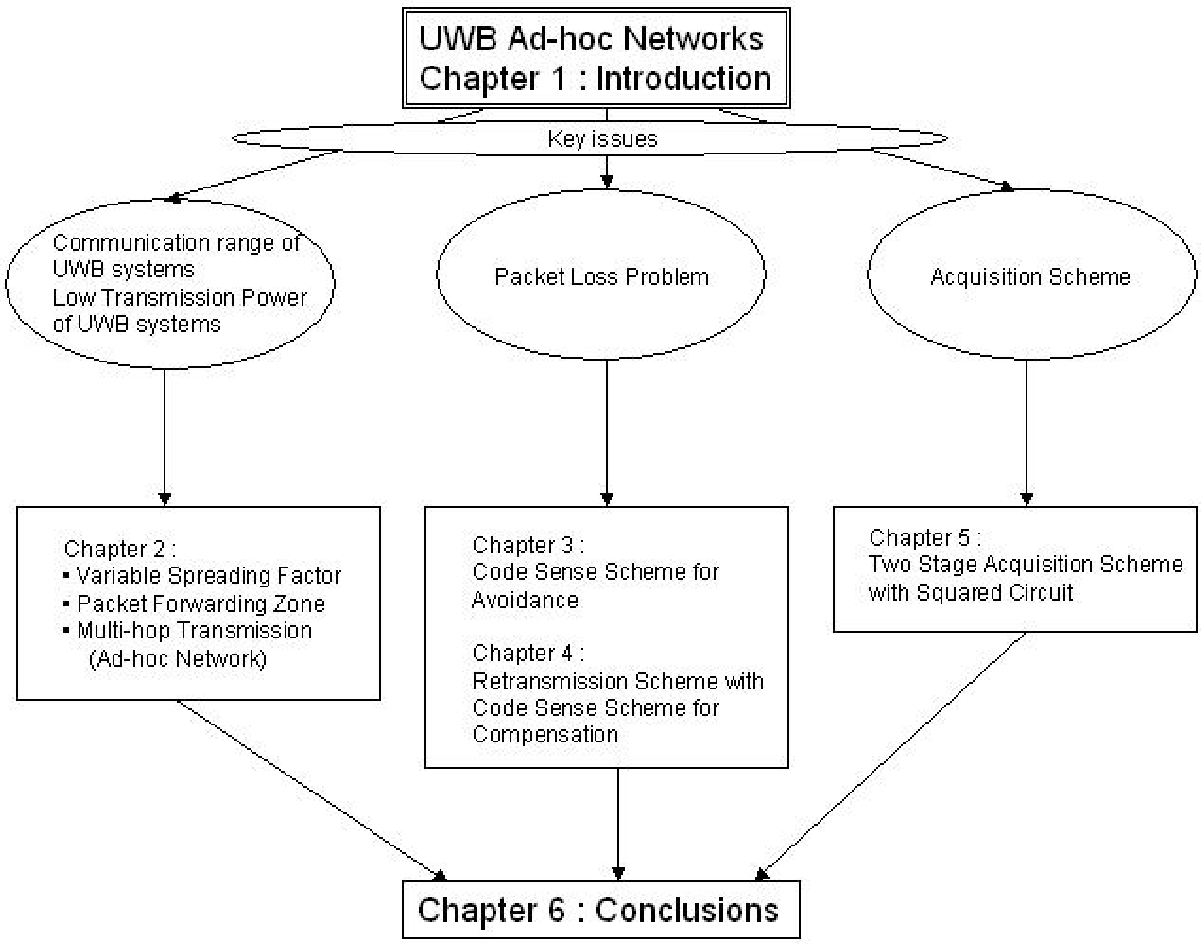

Figure 1.22: Outline of this thesis

Chapter 2

Packet Routing Scheme based on Location Information for UWB Ad-hoc Network

In this chapter, a novel packet routing scheme for UWB ad-hoc network is proposed and evaluated. UWB is a kind of spread spectrum communication and it is possible to detect the distance between the nodes. The novel routing scheme proposed in this chapter employs UWB's features and controls spreading factor according to the distance between the nodes. With controlling the maximum transmission distance and adopting multi-hop transmission, the throughput performance can be improved as compared to single-hop transmission.

2.1 Introduction

Ad-hoc networks are not necessary to have base stations unlike conventional radio systems [42]. Therefore, each node has to have a routing function and it is essential to use multi-hop transmission. Since each node has a network control function, even if one of the nodes is out of order, the influence to the whole network is quite limited. Therefore, the ad-hoc networks are excellent in respect of the cost and the robustness. It attracts large attention from researchers in the military and the commercial fields. However, since its topology always changes, it is hard to control the network. In order to solve this problem, various routing schemes have been proposed such as AODV [45], OLSR [46] and TBRPF [47]. However, these routing schemes do not employ the information about the location of the nodes and are not designed for the CDMA systems with the variable spreading factor. The routing schemes based on signal-to-noise ratio have been proposed by ATR [49], [50]. It requires array antennas to determine the route of the packets. Nevertheless, it is difficult to implement the array antennas in the small nodes. Location based routing schemes have also been proposed [52], [53]. These schemes do not employ spread spectrum communications and the location information is only used by limiting the range for forwarding a packet.

In this chapter, the novel routing scheme for a UWB ad-hoc network is proposed. The proposed scheme utilizes the positioning capability of the UWB systems. Based on the location information, the spreading factor is determined, and by adopting the variable spreading factor, the received signal-to-noise ratio per bit (E_b/N_0) is kept constant. In addition, multi-hop transmission is investigated. The route of the packets is specified based on the location information.

2.2 System Model

2.2.1 Signal - to - Interference and Noise Ratio (SINR)

The UWB system assumed in this thesis employs spread spectrum modulation for multiple access. Due to the multiple access condition, the signals from the other nodes will give interferences to the desired signal. It is assumed that the communication channel in this thesis is an Additive White Gaussian Noise (AWGN) channel, and the number of the nodes is N. When node i has transmitted a packet to node j, the interference from the other nodes

$$N_i \sum_{k=1,k\neq i}^{N} P_k g_{kj}. \tag{2.1}$$

The power of the received signal is

$$(N_i m_p)^2 g_{ij}. \tag{2.2}$$

where P_k is the signal power which node k transmits, and g_{kj} is the propagation loss from node k to node j and N_k is the spreading factor of node k. m_p is the correlation outputs for 1 pulse wave. Therefore, when the noise power is set to σ_{rec}, Signal-to-Interference and Noise Ratio (SINR) per 1 bit is expressed as follows [86]:

$$SINR = \frac{(N_i m_p)^2 g_{ij}}{N_i \sum_{k=1,k\neq i}^{N} P_k g_{kj} + \sigma_{rec}}. \tag{2.3}$$

2.2.2 The Location Estimation Method

The positioning capability of UWB is employed in order to estimate the transmission distance. UWB systems have been studied as positioning systems in some research [87], [88], [89], [90], [91], [92]. For example, peer-to-peer ranging technique is presented based on time-of-arrival (TOA) information in [88]. Two nodes exchange a data packet and an ACK packet with this technique. Based on the total elapsed time of the packet exchange, the relative distance between the nodes can be estimated with a high-precision timer. The range of location estimation error of UWB is within 5cm. This is more precise than the one of Global Positioning System (GPS) which varies from 10m to 30m.

Moreover, in the positioning system, there are many techniques to know the position of the target node from UWB signals. The angle of arrival(AOA), the signal strength(SS), or time delay information can be used to estimate the position of the node.

1. **AOA** The AOA technique uses the angles information from reference nodes, which is done by means of antenna arrays. The AOA measurement is not suited to UWB positioning for the following reasons. First, the cost of system with antenna array is high. Next, because of its large bandwidth, UWB have the large number of pass in indoor environment. So accurate angle estimation is very difficult.

2. **SS** SS-based positioning is achieved by measuring the strength of received signal. To estimate the distance of node from SS-based measurement, the characteristics of the channel must be known. Therefore, SS-based positioning is very sensitive to the estimation of those parameters.

3. **Time-based** Time-based measurement is carried out by estimating the time of arrival or the time difference of arrival. Unlike SS-based measurement, time-based measurement can be improved by increasing the SNR or the effective bandwidth.

2.2.3 Variable Spreading Factor (SF) based on Distance

The power of the UWB systems is quite limited. In this paper, in order to keep E_b/N_0 constant at the receiving node, variable SF is assumed. There are many researches on the propagation of the UWB signals [30]. Here, for simplicity, it is assumed that the signal power decreases in proportion to the square of the distance. The propagation loss $PL(d)$ of a signal is expressed as follows

$$PL(d) \simeq PL_0 + 20 \cdot \log_{10} d, \tag{2.4}$$

where d is the distance of the nodes and PL_0 is the propagation loss at $d = 1$ [m] [93]. Therefore, the proposed system increases the SF in proportion to the square of the distance.

In FCC, the bandwidth for the communication at the UWB system is specified as about 7 GHz from 3.1 GHz to 10.6 GHz. Therefore, in this paper, the chip rate is set to 5 Gchip/sec and the SF for 10 m is set to 50 in order to achieve the bit rate of 100 Mbps.

2.3 Network Model

2.3.1 Single-Hop (SH) Transmission

Single-Hop transmission does not need a relay node because the source node transmits the packet directly to the destination node. Three types of the Single-Hop transmission are investigated. The first one is the conventional ALOHA type which does not employ DS/SS modulation [55]. The second one transmits the packets with DS/SS modulation with fixed SF (FSF). The last one employs DS/SS with variable SF (VSF).

2.3.2 Multi-Hop (MH) Transmission

In order to keep E_b/N_0 constant as mentioned above, the SF has to increase in proportion to the square of the distance. However, as it increases, the data rate decreases rapidly if the transmission distance is large. In addition, longer packet length causes more interference to the other packets. Therefore, Multi-Hop transmission with short distance between hops is investigated. In the proposed scheme the distance for each hop is restricted. In order to control the transmission distance, a packet forwarding zone is defined.

2.4 Proposed Routing Scheme

2.4.1 Algorithm of Routing Scheme

Suppose that node S is a source node and node D is a destination node, node N_i are the nodes in the S's PF zone. The proposed routing scheme is described as follows.

1. Node S investigates whether node D is in S's own PF Zone.
   (a) If node D is in S's PF Zone, node S directly transmits a packet to node D.
   (b) If not, node S searches nodes in S's PF Zone as the candidate nodes, $\{N_i\}$, for packet relay.
2. Node S checks node N_i, and compares the distance $L_{S->D}$, which is between node S and node D, to the distance $L_{N_i->D}$, which is between N_i and node D.
   (a) If $L_{S->D} > L_{N_i->D}$, the candidate node N_i will be chosen as a relay node, and node S will transmit the packet for node D to N_i.
   (b) If $L_{S->D} < L_{N_i->D}$, node S repeats the search until it finds $L_{S->D} > L_{N_i->D}$, as long as $i \geq k$.

The node which has received a packet as the relay node from node S then repeats the above-mentioned process as a source node. An example of the packet transmission is shown in Fig. 2.1. The flow chart of the proposed routing scheme is shown in Fig. 2.2.

Since the intermediate node is chosen only by the relative distance between the nodes, even if the source node does not know the direction of the destination node, this proposed scheme can solve the infinite loop problem.

2.4.2 Packet Forwarding (PF) Zone

As shown in Fig.2.3, the PF Zone is defined as the circle of radius R centering on the source node. The source node can directly communicate with the node which is located within this circle. That is, node S can directly transmit a packet to node B located in the inside of its PF Zone. However, node S cannot directly transmit a packet to node A located outside of S's PF Zone. In this case, a packet has to be relayed by the other node which locates in S's PF Zone.

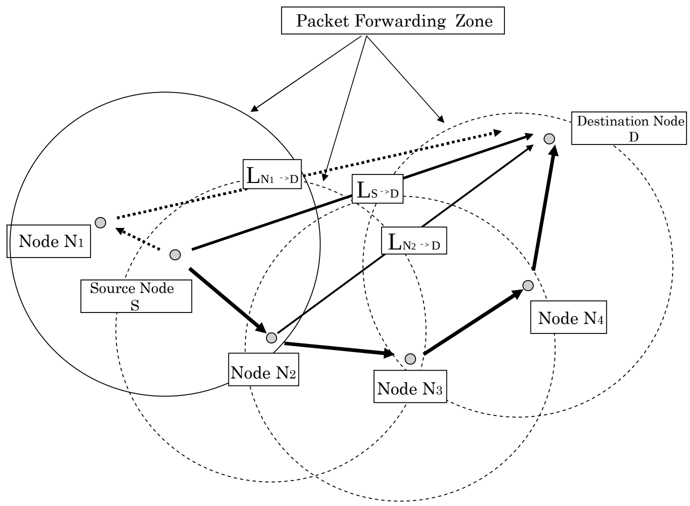

Figure 2.1: Packet Routing Scheme.

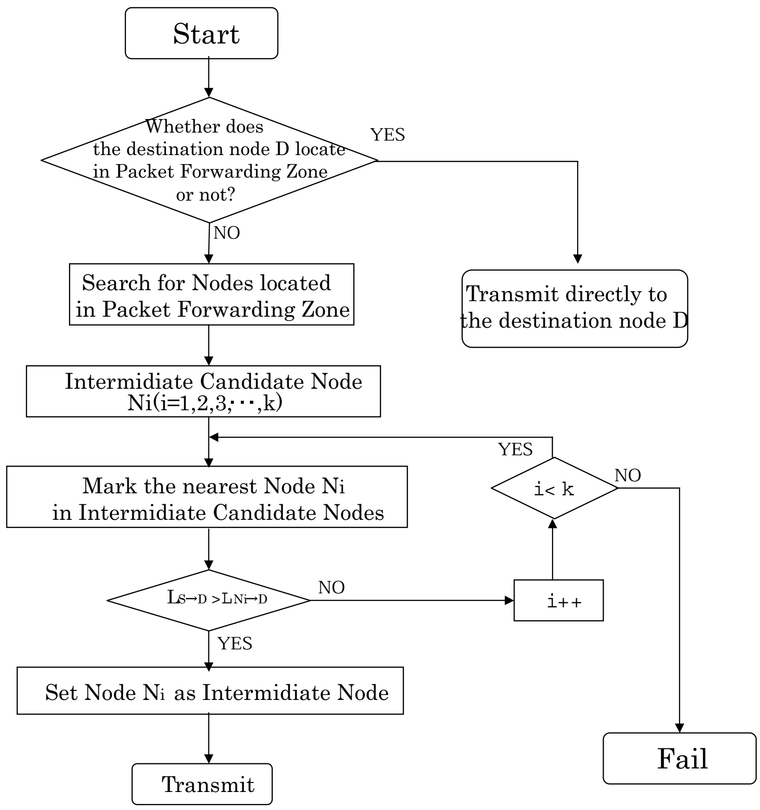

Figure 2.2: Packet Routing Algorithm.

2.5 Simulation Results

2.5.1 Effective data rate (EDR)

Effective data rate (EDR) is defined in order to evaluate the proposed system. EDR expresses the expected amount of data that reaches the destination. It is given by multiplying the data

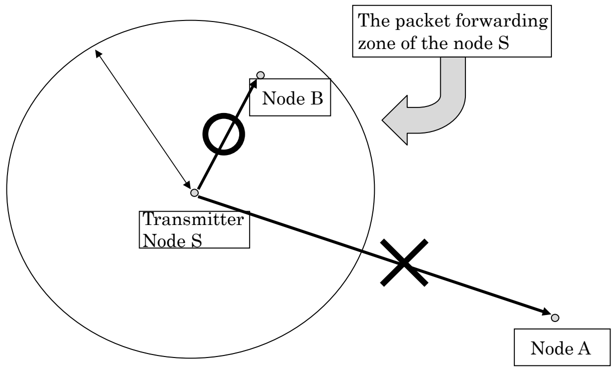

Figure 2.3: Packet Forwarding Zone.

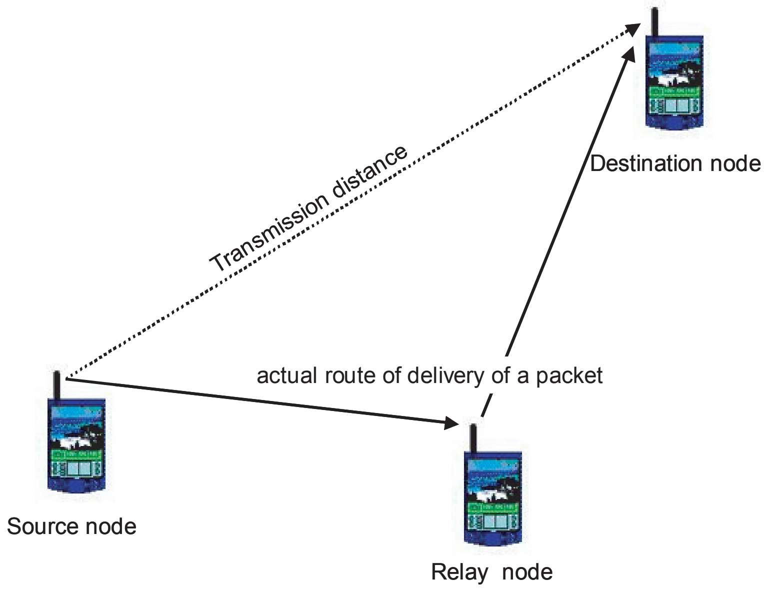

Figure 2.4: Transmission distance and actual route.

rate to the success probability of a transmission. The transmission distance is d [m] while the transmission period of one packet together with the propagation delay is t sec. The number of packets generated by the source node is S_S. The number of packets that reach the destination node is S_d. The packet length is L Mbyte. The EDR Mbps at the distance of d m is given as follows.

$$EDR = L \times 8 \times \frac{1}{t} \times \frac{S_d}{S_S}. \tag{2.5}$$

The data rate varies depending on the transmission distance in VSF/DS-UWB system. In this paper, we refer to the transmission distance as the distance between the source and destination nodes, if direct communication was possible, as shown in Fig. 2.4.

2.5.2 Simulation Conditions

The simulation conditions are shown in Table 2.1. The nodes are located at random in the area of 60 [m] $\times$60 [m]. The transmission channel is assumed as AWGN. There is no obstacle between nodes. Each packet occurs according to the Poisson distribution, and is transmitted to the destination node which is chosen at random. The transmission power of each node is kept constant. Success or failure of a packet transmission is specified by the following rules.

1. When two or more packets are arrived simultaneously, both of the packets are discarded.
2. If SINR is less than 8 [dB], a bit error occurs. The packet is discarded if the number of errors is more than 5.

According to [94], when FEC is used, it is possible to achieve $BER < 10^{-6}$ if $SINR \geq 8$ [dB]. Therefore, the threshold is set as $SINR \geq 8$ [dB].

In addition, retransmission is not considered in the case of the packet loss due to the collision, interference, and relay node absence, etc. Moreover, each node on the network is fixed.

Table 2.1: Simulation conditions

Modulation	DS-CDMA
Control System	Pure ALOHA
Channel Model	AWGN
Number of Nodes	$30, 100$
Spreading Factor	SH ($SF = 50, 900, VSF$) MH ($SF = VSF$)
Radius of PF Zone	$R = 10, 15, 20, 25$ [m]
Packet Length	64 Byte
E_b/N_0	10 [dB] @ 10 [m]
Threshold	$SINR < 8$ [dB]

2.5.3 Numerical Results

Fig. 2.5 shows effective data rate [Mbps] of the FSF and VSF Single-Hop transmission vs. the distance between the source and destination nodes. The $SF = 50, 900$. Node is the numbers of the nodes. As for Single-Hop transmission without use of the DS/SS modulation, almost all the packets have been lost by the interference or the collision. Thus, these results are not shown in Fig.2.5. In the FSF Single-Hop transmission, all the packets are lost at $45 - 50$ [m] when $SF = 900$ and about 15 [m] when $SF = 50$. Since transmitted signal power and the SF are fixed, the SINR becomes less than 8 [dB] due to the attenuation and the interference from the other signals when the distance is large. In any distance between the source and destination node, the effective data rate of the FSF Single-Hop transmission is lower than the one of the

VSF Single-Hop transmission. This is because the SF in the VSF Single-Hop transmission is optimized to the transmission distance, as compared to the FSF Single-Hop transmission.

Figs. 2.6 and 2.7 have shown the effective data rate [Mbps] of the VSF Single-Hop transmission and the proposed Multi-Hop transmission when the number of nodes is 30 or 100. In the figures, R is the radius of the PF Zone in Fig.2.3. In Figs. 2.6 and 2.7, it is clear that the difference of the effective data rate between the VSF Single-Hop transmission and the proposed Multi-Hop transmission. The effective data rate with the VSF Single-Hop transmission drops rapidly when the number of nodes or the distance increase. On the other hand, the one with the proposed Multi-Hop transmission remains relatively higher as the distance or the number of the nodes increases. Especially, in the proposed Multi-Hop transmission at $R = 10$ and $R = 15$, the effective data rate improves remarkably when the number of the nodes increases. This is because the difference of the main cause of the packet loss for those transmission scheme. In the proposed Multi-Hop transmission, the relay failure is the main cause of the packet loss. As the number of the nodes increases, the probability that the relay node is busy reduces. Therefore, the effective data rate with 100 nodes shows better than the one with 30 nodes. As the distance increases, the effective data rate decreases in spite of the number of the nodes. It is simply because the probability of the packet loss at the relay node increases as the number of hop increases.

On the other hand, in the VSF Single-Hop transmission, the interference is the main cause of the packet loss. If the number of the nodes under communication increases, the amount of the interference becomes significant. Therefore, when the number of the nodes increases, the packet loss increases, and the effective data rate is deteriorated. On the other hand, in the proposed Multi-Hop transmission, there is less probability of the packet loss due to the interference. The reason is that the average packet length is shorter than the one with the VSF Single-Hop transmission. This is due to the restriction of the transmission distance with the PF zone. The shorter packet length also makes longer idle time for the nodes. Therefore, it introduces less packet collision.

As a result, the proposed Multi-Hop transmission with the variable spreading factor and the PF zone can realize higher throughput for all transmission distance.

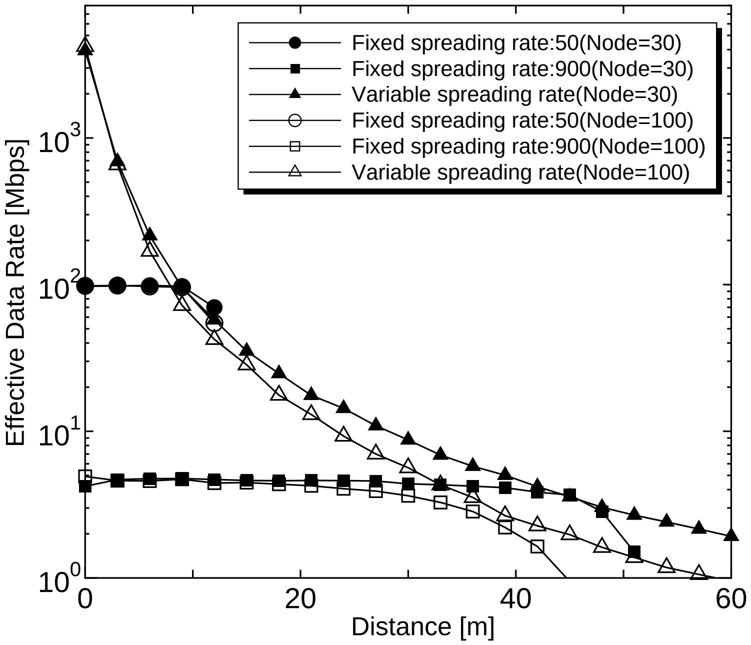

Figure 2.5: Effective data rate vs. distance in Single-Hop transmission schemes.

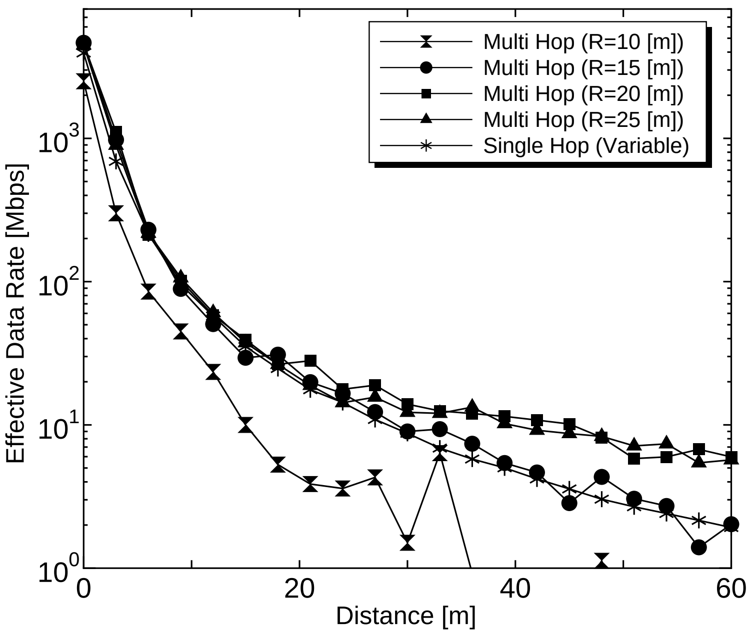

Figure 2.6: Effective data rate vs. distance in Variable Single-Hop transmission and Multi-Hop transmission schemes (The number of terminals is 30).

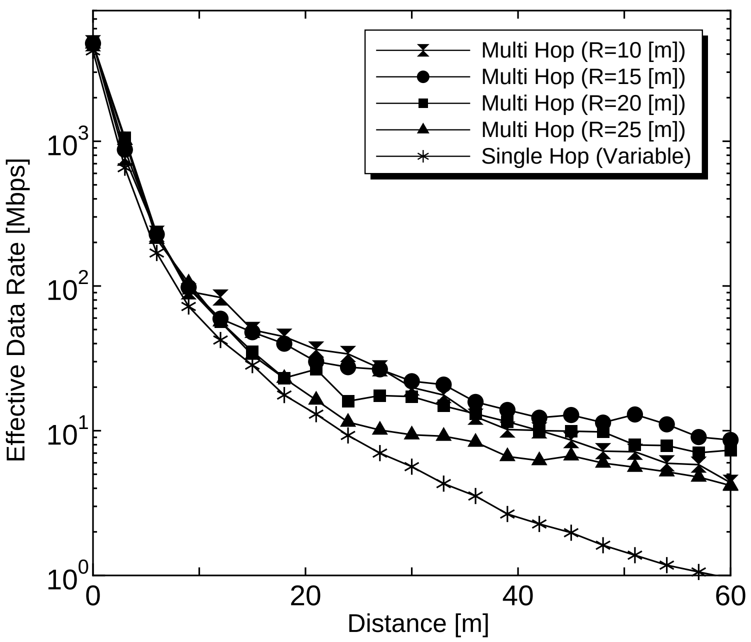

Figure 2.7: Effective data rate vs. distance in Variable Single-Hop transmission and Multi-Hop transmission schemes (The number of terminals is 100).

2.6 Conclusions

In this chapter, the novel routing schemes for the UWB ad-hoc network have been proposed and evaluated. In the proposed scheme, variable spreading factor in proportion to the distance between nodes and packet forwarding zone have been implemented. This proposed scheme has improved the effective data rates compared to the conventional system. At the same time, it has been shown that multi-hop transmission is very effective if the number of the node is large enough.

Chapter 3

Code Sense Scheme for DS-UWB Ad-hoc Network with Variable Spreading Factor

In this chapter, a novel Carrier Sense Multiple Access (CSMA) scheme for UWB ad-hoc network is proposed and evaluated.

UWB is a kind of spread spectrum communication. UWB systems can detect the distance between the nodes acculately. With this positioning capability of the UWB systems, DS-SS UWB (DS-UWB) scheme with variable spreading factor is used as mentioned in Section 2. In Section 2, pure ALOHA system has been employed as MAC protocol. As a results, many packet collisions has occured. This chapter investigates another MAC protocol for UWB ad-hoc networks mentioned in Section 2 and proposes a novel CSMA scheme that employs the correlation of the spreading code.

3.1 Introduction

For UWB ad-hoc networks, the DS-CDMA scheme with variable spreading factor (VSF/DS-UWB) has been proposed in [74], and in that paper Pure ALOHA is employed. In the proposed scheme, in order to keep the received signal-to-noise ratio per bit (E_b/N_0) constant, the spreading factor is increased in proportion to the square of the transmission distance. In addition, the distance for each hop is restricted and multihop transmission is employed. As compared to the conventional schemes, the proposed scheme can realize higher throughput for all the transmission distance. However, since the number of hops increases as the transmission distance becomes long, the packet loss increases rapidly. Therefore, a new MAC (Medium Access Control) protocol for the UWB ad-hoc network is required.

In radio communication systems, MAC protocol has the important role to establish the communication links efficiently. Many MAC protocols has been proposed. CSMA is the protocol which checks whether the other nodes are transmitting carrier signals before packet transmission [58]. In the conventional CSMA schemes, the communication channel is used to sense the existence of the carrier signal. However, when UWB or CDMA is employed, the power level of the received signal is too low to detect the carrier signal. On the other hand, the multichannel CSMA schemes have been considered [62], [63], [64]. However, in these schemes, if the multichannel CSMA is employed, it is required to assign the special band for carrier sense. The features of UWB systems are spoiled by dividing one communication channel to multiple channels.

In this chapter, a new CSMA scheme for UWB systems is proposed. This scheme uses the specific combinations of the spreading codes for carrier sense. These spreading codes are pre-assigned to each node and the other nodes can sense if the target node is receiving a packet or not.

3.2 System Model

3.2.1 Modulation and Demodulation Scheme

In this thesis, binary sequence keying modulation is employed and the following algorithm is proposed.

1. Each node is assigned three kinds of the spreading code m_0, m_1, M.
2. According to the information bit, m_0 or m_1 is selected as binary sequence keying modulation.
3. Each chip of the code M is spread with m_0 or m_1.
4. The spreading code M is used only for the carrier sense.

The block diagram of the modulation scheme is shown in Fig. 3.1. Fig. 3.2-(a) shows an example of the transmission signal when the spreading factor is minimum and Fig. 3.2-(b) is the one when the spreading factor is the 4 times of Fig. 3.2-(a). For example, node j has the spreading code m_{0j}, m_{1j}, M_j. The length of the spreading codes m_{0j}, m_{1j} are L. Suppose that node k transmits a packet S_k to node j. A packet S_k consists of the sequence of M_j code and is spread with the spreading code m_{0j} when the information bit is 0 or the spreading code m_{1j} when the information bit is 1. After node j receives the signal S_k, the siganl S_k is correlated with m_{0j} and m_{1j}. Therefore,

$$R_{0j}(N) = \sum_{n=0}^{L-1} S_k(NT_L + nT_c)m_{0j}(nT_c), \tag{3.1}$$

$$R_{1j}(N) = \sum_{n=0}^{L-1} S_k(NT_L + nT_c)m_{1j}(nT_c), \tag{3.2}$$

where R_{0j} and R_{1j} are the outputs of the N-th matched filter for the codes m_{0j} and m_{1j}, T_c is the duration of the spreading code m_{0j} and m_{1j}, and T_L is the duration of the spreading code

M. The outputs of the matched filters are combined as

$$E_0 = \sum_{N=0}^{SF/L-1} |R_{0j}(N)|, \tag{3.3}$$

$$E_1 = \sum_{N=0}^{SF/L-1} |R_{1j}(N)|, \tag{3.4}$$

where SF is the spreading factor. From Eqs. (3.3) and (3.4), the data information is demodulated as follows.

1. if $E_0 > E_1$, the data is demodulated to 0.

2. if $E_0 < E_1$, the data is demodulated to 1.

The block diagram of the demodulation scheme is shown in Fig. 3.3.

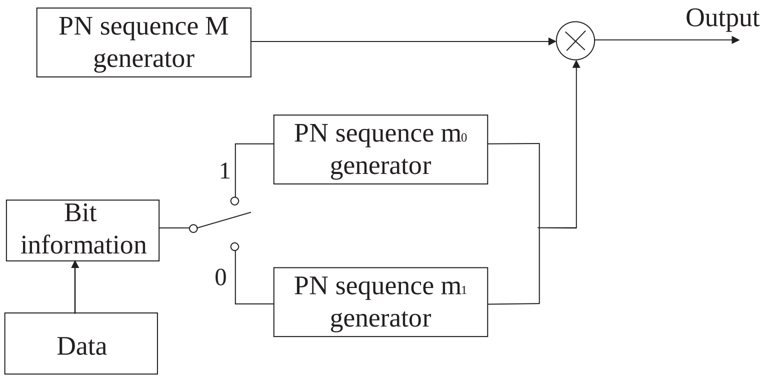

Figure 3.1: Block diagram of the modulation scheme.

3.2.2 Code-Sense Multiple Access

CSMA has been investigated in so many researches [58], [61]. In general, CSMA checks the condition of the communication channel before the transmission of the packet. However, when DS-UWB systems are employed, the transmission power is very low. In addition, the interference from the other nodes is very low because of CDMA. Therefore, it is difficult to detect the carrier signal. On the other hand, there is multichannel CSMA. In multichannel CSMA, one communication band is divided into the two or more communication channels. However, the transmission power of UWB systems is limited, it is hard to sense the carrier signal. Therefore, in this thesis, the novel CSMA scheme has been proposed for DS-UWB ad-hoc networks. This scheme senses the carrier signal by the correlation value of the spreading codes, and detects if the target node can receive a packet or not.

For example, node i senses the carrier signal in order to decide if node i should transmit a packet to node j. If node i can detect the packet transmission to node j, it does not transmit

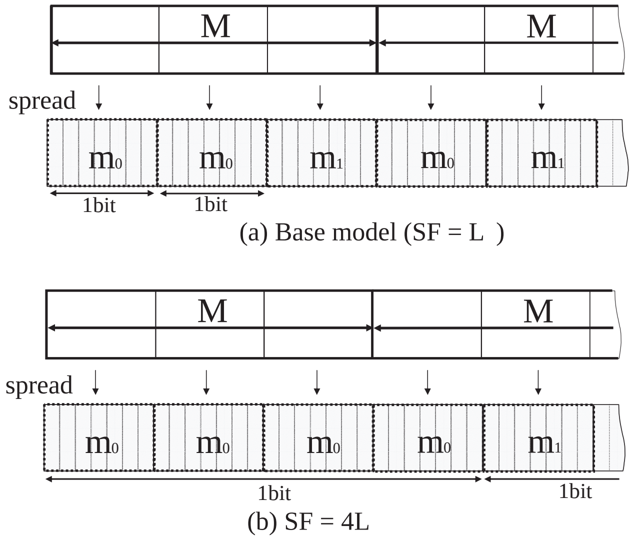

Figure 3.2: Look of a packet.

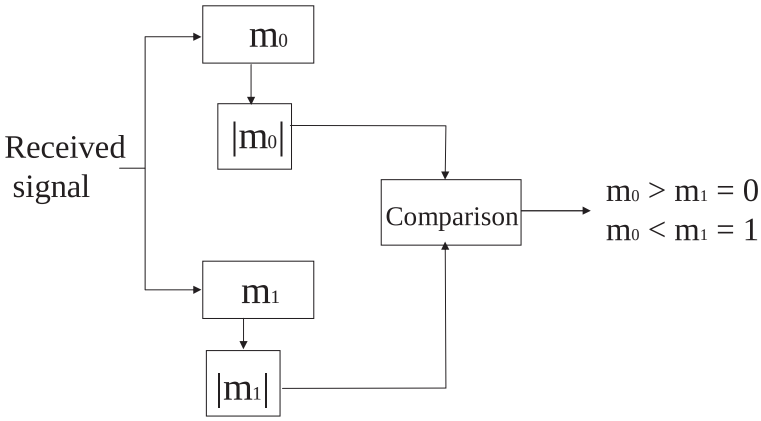

Figure 3.3: Block diagram of the demodulation scheme.

a packet to node j as shown in Fig.3.4. As mentioned in Sec. 4.2.1, node j is assigned three kinds of the spreading code m_{0j}, m_{1j}, M_j. Fig.3.5 shows the block diagram of the carrier sense scheme of the proposed CSMA and Fig.3.6 is the block diagram of the comparator.

1. The transmitted signal to node j is correlated with m_{0j} and m_{1j}, and the amplitude of the outputs are compared in the comparator.

2. The larger output is selected and multiplied to the corresponding chip of the code M_j.

3. The despread signals are summed together, if the sum exceeds the threshold, node i judges that node j is receiving a packet.

In this scheme, as the transmission distance increases, the signal power per inner code, m_0 or

m_1, decreases compared to E_b. However, in this system, the packet-forwarding zone is defined. Therefore, since the length of the total spreading factor is limited, the reduction of the signal power per inner code is also limited. The success probability of carrier sense is improved.

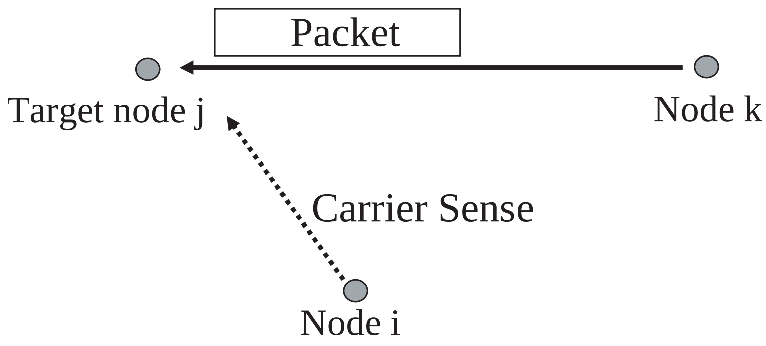

Figure 3.4: The proposed CSMA scheme.

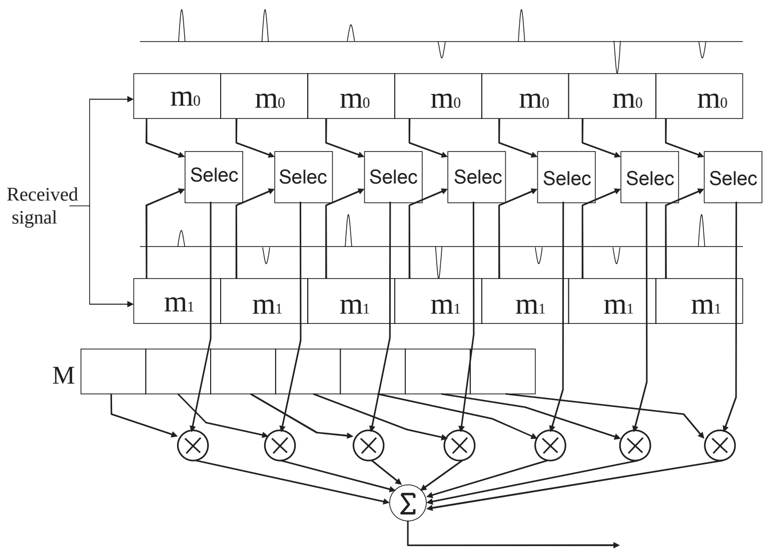

Figure 3.5: Block diagram of the carrier sense scheme of the the proposed CSMA scheme.

3.3 Simulation Results

3.3.1 Simulation Conditions

The simulation conditions are shown in Table 3.1. The nodes are located at random in the space of 30 [m] ×30 [m] ×30 [m]. The channel is assumed as AWGN channel. There is no obstacle between nodes. Each packet occurs according to the Poisson distribution, and is transmitted to the destination node which is chosen at random according to the routing scheme proposed in [74]. The configuration of the network is more than $10,000$ times. The transmission power of

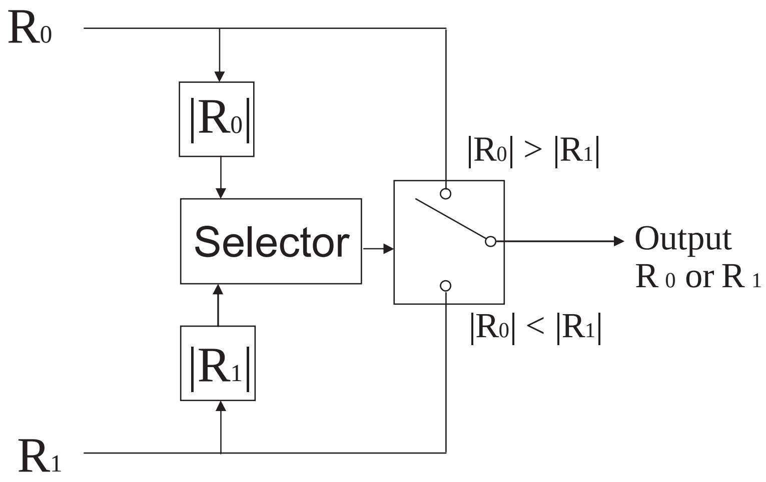

Figure 3.6: Block diagram of the comparator.

each node is kept constant. In this simulation, each node has three spreading codes and those codes are phase shifted versions of the same M sequence or its flipped one with the length of 7. The time of carrier sense is set to the duration of 98 chips. Success or failure of the packet transmission is specified by the following rules.

1. When two or more packets are arrived simultaneously, both of the packets are discarded.

2. If SINR is less than 8 dB, a bit error occurs.

3. The packet is discarded if the number of errors are more than 5 bit in one packet.

In order to evaluate the performance of MAC layers of the conventional and proposed schemes, the same modulation and demodulation technique is employed in the both systems. According to [94], when FEC is used, it is possible to achieve BER$< 10^{-6}$ if $SINR \geq 8$ dB. Therefore, the threshold is set as $SINR = 8$ dB.

In addition, retransmission is not considered in the case of packet loss due to the collision, interference, or relay node absence, etc. Moreover, each node on the network is fixed. The traffic is defined as the number of packets generated in the period of one packet length for the transmission distance of 15 m (the radius of the packet forwarding zone). The chip rate is set to 5 Gchip/sec and the spreading factor (SF) for 10 m is set to 50 in order to achieve the bit rate of 100 Mbps as shown in Fig. 3.7.

3.3.2 Numerical Results

Table 3.2 shows the success probability of the carrier sense. The success probability in Table 3.2 means the probability that the node could successfully sense the carrier signal of the target node. False alarm implies the probability that the node transmits a packet by mistake when the target node is receiving another packet. False detection expresses the probability that the

Table 3.1: Simulation conditions

Modulation	DS-CDMA
Control System	Pure ALOHA Proposed CSMA
Channel Model	AWGN
Traffic	0.25, 0.5, 0.75, 1.0, 1.5, 2.0
Number of Nodes	28
Spreading Factor	$SF = Variable$
Radius of PF Zone	$R = 15$ [m]
Packet Length	64 Byte
E_b/N_0	10 [dB] @ 10 [m]
Threshold in CSMA	$SINR = 8$ [dB]
Threshold in Pure ALOHA	$SINR = 5$ [dB]

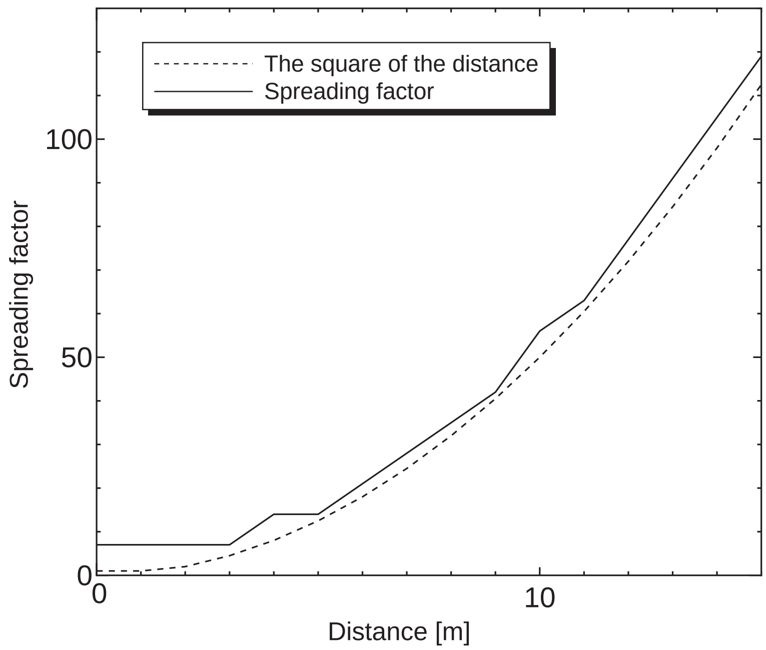

Figure 3.7: The spreading factor vs. the transmission distance.

node does not transmits a packet by mistake when the target node is not busy, or the target node is transmitting a packet or sensing carrier signals. Fig. 3.8 shows the probabilities of success packets and collision packets in Pure ALOHA and CSMA vs. the traffic of the network. As the traffic of the network increases, the accuracy of carrier sense decreases a little. However the accuracy of carrier sense is kept more than 90 [%] in all the traffic conditions in Table 3.2. Therefore, although transmission delay is produced due to carrier sense in CSMA, the probability of success packet in CSMA has become higher than the one in Pure ALOHA. Even though the accuracy of carrier sense is more than 90 [%], packet collision can not be avoided.

The reason is that the proposed scheme bases on non-persistent CSMA.

Fig. 3.9 shows the effective data rates and data rates of the multi-hop transmission of Pure ALOHA and CSMA vs. the transmission distance between a source node and a destination node when the traffic of the network is 1.0. Effective data rate means the expected value of the amount of data that reach to the destination. It is given by multiplying data rate to the probability of a success transmission. The data rate varies depending on the transmission distance. In the case of multihop transmission, the average data rate over the hops from the source node to the destination node is calculated. From Figs. 3.8 and 3.9, the effective data rate of CSMA is much lower than the data rate although the probability of a success transmission in CSMA is high. This is because many packets in CSMA survive during the multihop transmission, although almost all the packets in the Pure ALOHA are dropped within a couple of hops. In CSMA, the high probability of a success transmission increases the load of the network. On the other hand, in Pure ALOHA and CSMA, the effective data rate for the short distance transmission is lower than one for the middle distance transmission. This is because the signals are not robust for the interference due to the low spreading factor.

Fig. 3.10 shows the effective data rates [Mbps] of the multi-hop transmission of Pure ALOHA and CSMA vs. traffic when the distance between the source and destination nodes is 10 [m]. Fig. 3.11 shows the effective data rates [Mbps] of the multi-hop transmission of Pure ALOHA and CSMA vs. traffic when the distance between the source and destination nodes is 20 [m]. When the traffic is low, the effective data rate of Pure ALOHA is much better than the one of CSMA for the short distance transmission. However, as the transmission distance increases, the effective data rate of Pure ALOHA rapidly decreases. On the other hand, in spite of the transmission distance, the effective data rate of CSMA is kept constant. In addition, the effective data rate of CSMA increases as the traffic of the network increases while the effective data rate of Pure ALOHA decreases.

Table 3.2: Accuracy result of carrier-sense [%]

Traffic	Success probability	False alarm	False detection	etc
0.25	98.7214	0.1410	0.2341	0.9035
0.5	97.5119	0.2677	0.4823	1.7382
0.75	96.7315	0.3254	0.6836	2.2596
1.0	95.1548	0.5463	0.8499	3.4489
1.5	93.5148	0.6428	1.2985	4.5439
2.0	91.1799	0.9301	1.5779	6.3120

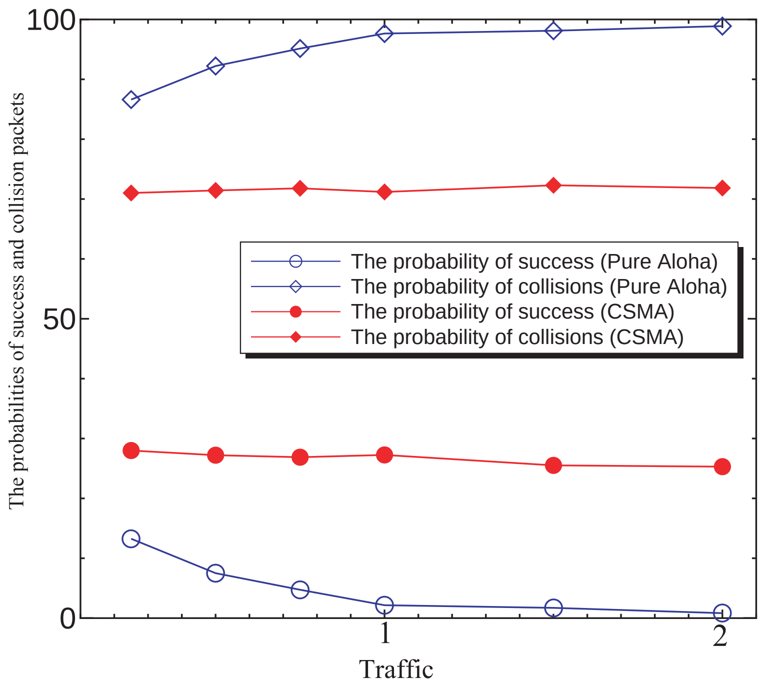

Figure 3.8: Probability of a success and a collision in Pure ALOHA and CSMA vs. the traffic of a network.

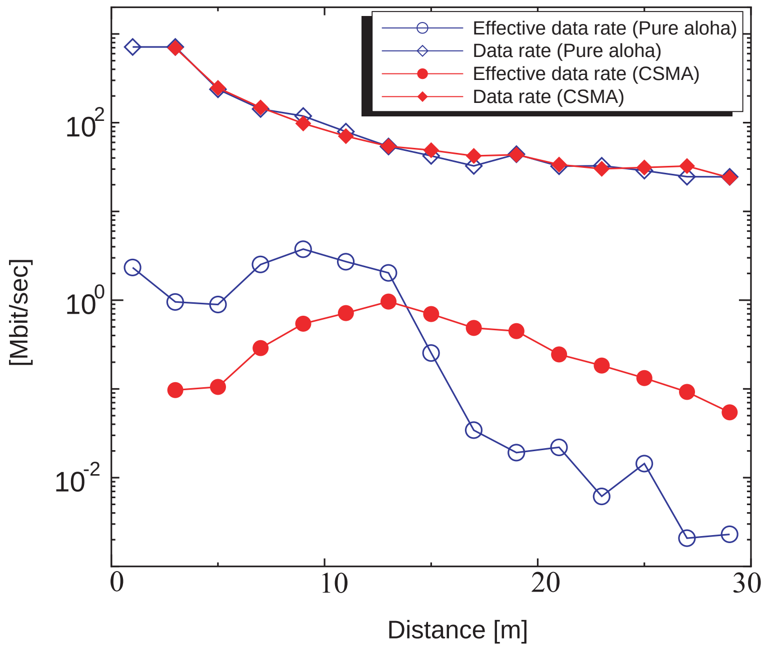

Figure 3.9: Effective data rate and the data rate vs. the transmission distance between a source node and a destination node in Multi-Hop transmission of Pure ALOHA and CSMA (The traffic is 1.0).

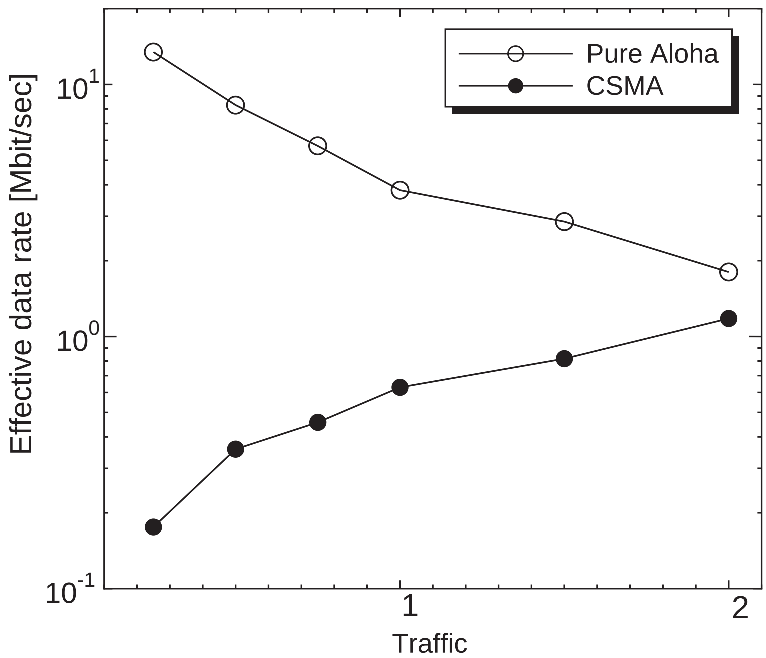

Figure 3.10: Effective data rate vs. traffic in Multi-Hop transmission of Pure ALOHA and CSMA (The distance between the nodes is 10 [m]).

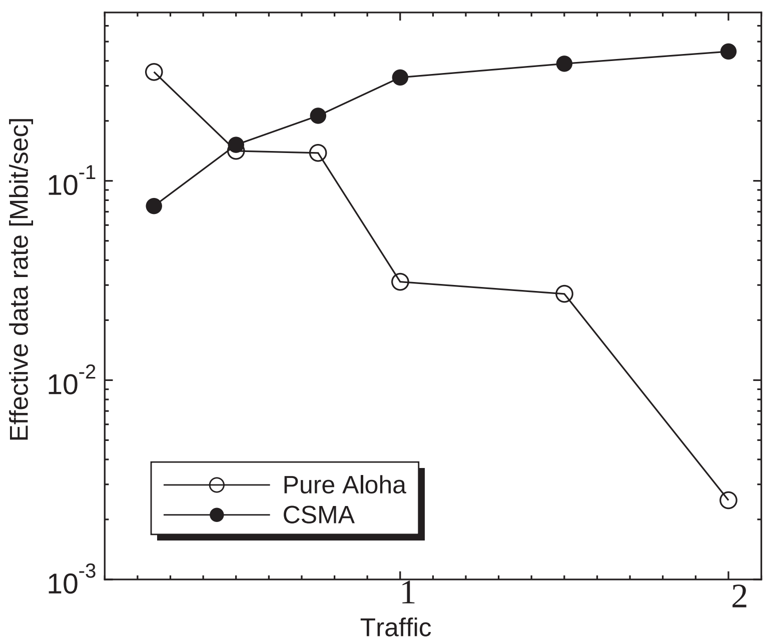

Figure 3.11: Effective data rate vs. traffic in Multi-Hop transmission of Pure ALOHA and CSMA (The distance between the nodes is 20 [m]).

3.4 Conclusions

The novel CSMA scheme for DS-UWB ad-hoc network has been proposed. This proposal utilizes the correaltion value between the signal and the sequence code of the relay node. This chapter has shown that our proposal can avoid packet collisions and better data rate performance compared to Pure ALOHA. This means that our proposal can solve the problem of the low transmission power of UWB systems and develop the novel MAC protocol for UWB systems. However, this scheme assumes that each node knows the sequence code of other nodes. This has the security problem which does not exist in DS-SS systems. Therefore, we have to consider this problem in future work. In addition, since the assumed condition is heavy traffic mode, we have to investigate the performance of this proposal in the actual environment.

Chapter 4

Retransmission Scheme for DS-UWB Ad-hoc Network with Variable Spreading Factor

In this chapter, we propose a novel retransmission scheme by using Code sense scheme. DS-UWB ad-hoc network with variable spreading code has been proposed to extend the communication range and to keep high transmission data rate. However, the increase in the number of hops leads to increased packet loss rate. An ARQ system, requiring an ACK packet being sent in confirmation of correct data reception is employed to compensate for the packet loss and improve the network throughput. The ACK packets though are themselves a source of interference. A novel retransmission scheme encompassing code sense is proposed to reduce the amount of ACK packets generated. We assume that this scheme would be used after the links between the sender and the receiver has been estimated. This scheme has not been assumed to be used in the initial stage. Code sense uses the correlation value of spreading codes between packets for the confirmation of successful transmission and retransmission. The performance in this system is shown through simulations.

4.1 Introduction

The limited communication range of UWB renders Multi-hop transmission essential for applications requiring extended range such as full building coverage. For this, the Direct Sequence Code Division Multiple Access (DS-CDMA) UWB system with variable spreading factor (VSF/DS-UWB) has been proposed in [74]. In [74], pure ALOHA has been employed in the Medium Access Control (MAC) protocol. In this system, the spreading factor (SF) has been increased in proportion to the square of the transmission distance in order to keep the received signal-to-noise ratio per bit (E_b/N_0) constant. In addition, the Packet-Forwarding (PF) zone has been defined in order to restrict the transmission distance. If the transmission distance is longer than the radius of PF zone, a packet is transmitted by multi-hop transmission. Compared to the single-hop transmission system or the DS-UWB system without variable spreading factor, the VSF/DS-UWB system can realize higher throughput for all transmission distances.

However, as more hops are required, the packet loss increases rapidly. For this, retransmission is necessary in order to compensate for the packet loss. In a conventional retransmission scheme like Automatic Repeat Request (ARQ) [65], [66], [67]. An ACKnowledge (ACK) packet is used for the confirmation of successful data reception. Once a packet has been received successfully, an ACK packet is returned to the sender. In the case of erroneous reception, a Negative-ACKnowledge (NACK) packet is returned to the sender, requesting retransmission of the lost packet. As the number of hops increases, more ACK / NACK packets are required in the system, increasing the total interference. It is therefore expected that a decrease in the number of ACK / NACK packets shall improve the total network throughput.

In this chapter, a novel retransmission scheme encompassing code sense is proposed. This scheme uses the specific combinations of the spreading codes for code sense. These spreading codes are assigned to each node based on the node's ID. The behavior of the nodes upon reception defers based on their position in the multihop path. If the target node is the *destination* node, ARQ procedure is followed, and the receiver returns an ACK or a NACK to the previous node upon successful or erroneous reception respectively. In any other case, where the receiver is an intermediate node, code sense procedure is employed. We evaluate the performance of this system under several conditions through simulations.

4.2 System Model

4.2.1 Network Model

According to the high precision positioning capability of UWB, each node knows the location information (relative distance) of all the other nodes in the network. We employ the network model from [74]. Each node has a PF zone which is defined as the disk of radius R [m] centered on it. A node can directly communicate with destination nodes located within its PF zone. If the destination node lies beyond the boundary of the source's PF zone, multihop transmission is required as shown in fig. 4.1. In this example, node S cannot directly communicate with node D since the latter is located outside the PF zone of the former node. Instead, S will transmit the required data to node A, which in turn, will relay the packet to node B, so that the destination node D is finally reached. A relay node is selected according to the relative distance between nodes as shown in fig. 4.2. Node S searches among its neighbor nodes and determines the one to be used for relaying based on the relative distance from the destination node D. If $L_{S-D} > L_{N_1-D} > L_{N_2-D}$, the candidate node N_1 is chosen as a relay node, and node S transmits the packet for node D to N_1. In addition, S has to wait to transmit the next packet for node D until N_1 finishes to receive the previous packet from S.

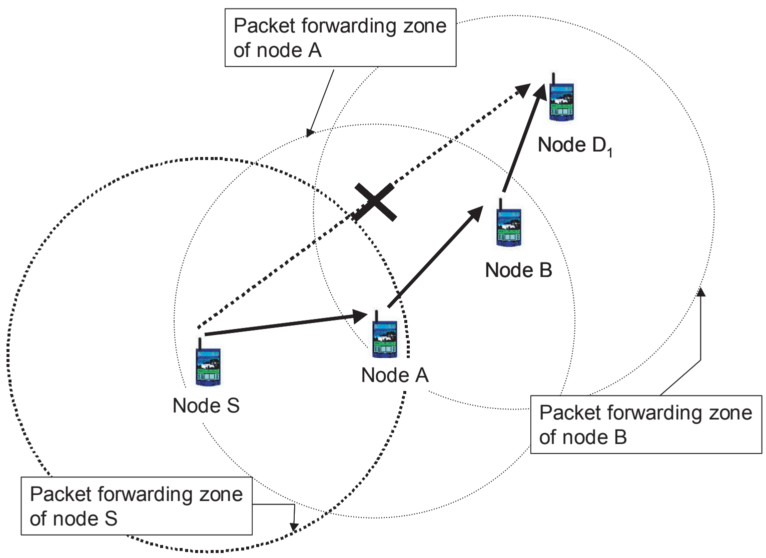

Figure 4.1: An example of packet-forwarding zone and multihop transmission.

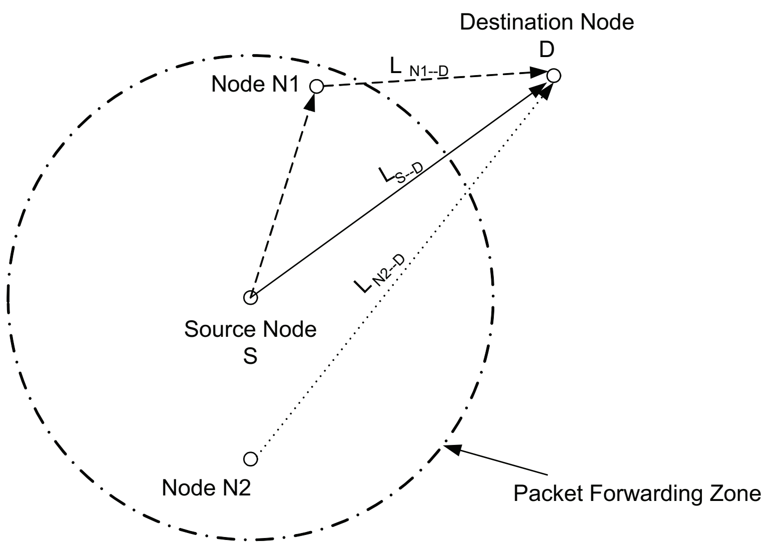

Figure 4.2: The relative distance routing scheme.

4.2.2 Variable Spreading Factor

Since the power of UWB is limited, power control cannot be employed. In order to maintain the received E_b/N_0, the method of changing the SF in proportion to the transmission distance has been proposed in [74]. Since the signal power decreases in proportion to the square of the distance, the SF is increased according to the square of the transmission distance. In FCC, the bandwidth for the communication at UWB is specified as about 7 GHz from 3.1 GHz to 10.6 GHz. Therefore, the pulse occupies the whole bandwidth between 3.1 GHz and 10.6 GHz. The chip rate is set to 5 GChip/sec and the SF for 10 m is set to 56 in order to achieve the bit rate of 100 Mbps. Fig. 4.3 shows the propagation loss and the SF vs. the transmission distance.

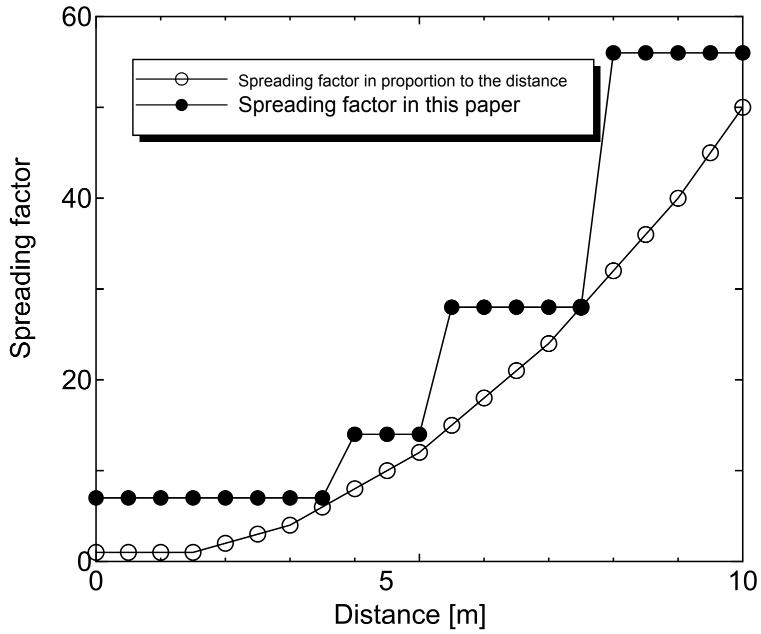

Figure 4.3: Spreading factor vs. the transmission distance.

4.3 Proposed Scheme

An ACK packet interferes with other nodes as shown in Fig. 4.4. In multihop transmission, the required number of ACK packets is higher than in the case of singlehop transmission, thus extensively affecting the system performance by increasing the amount of interference. By decreasing the required number of ACK packets, the amount of interference and collisions can be reduced. In this chapter, the code sense scheme proposed in [75] is applied for retransmission instead of an ACK packet. According to this scheme, the transmitter senses the carrier signal of the intermediate node by using the correlation value of the spreading codes. Nodes can therefore identify whether the next node is relaying a packet or not. The time of code sense depends on the spreading factor since code sense doesn't checks the whole but the head of the packet relayed by the next node. Therefore, the longer the packet size is, the longer the time of code sense isn't.

The retransmission scheme with code sense is used as shown in Fig. 4.5.

Any node, j, is assigned two kinds of spreading codes m_j and M_j. Code M_j is a hadamard code and m_j is an m-sequence whith length 7. Fig. 4.6 shows the block diagram of the code sense scheme.

1. Node i calculates the SF of the target signal according to the distance between node k and node j.
2. Next, node i detects the spreading codes m_j and M_j by the ID of node j.
3. The transmitted signal to node k is correlated with m_j.

4. The output is multiplied to the corresponding chip of the code M_j.

5. The despread signals are summed together.

6. If the sum > a detection threshold, node i judges that node j is relaying a packet.

7. If the sum < the threshold, node i retransmits a packet to node j.

However, this code sense scheme is used only if the next node k is the intermediate node. If the next node k were the destination node, k uses the ACK packet like the ARQ protocol as shown in Fig. 4.7.

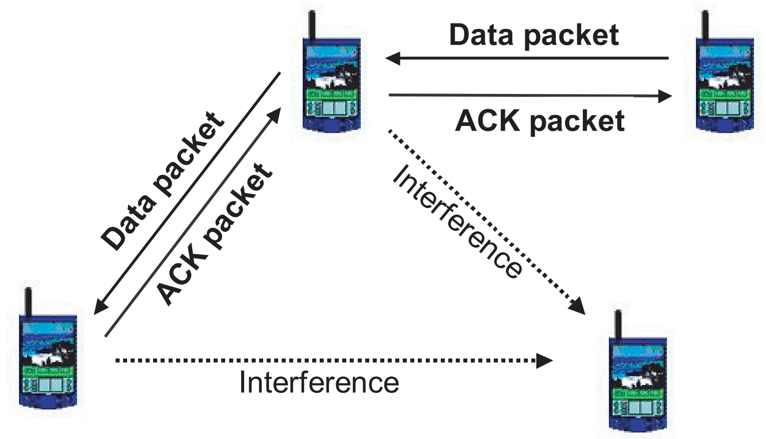

Figure 4.4: Look of the interference of ARQ system to the other nodes.

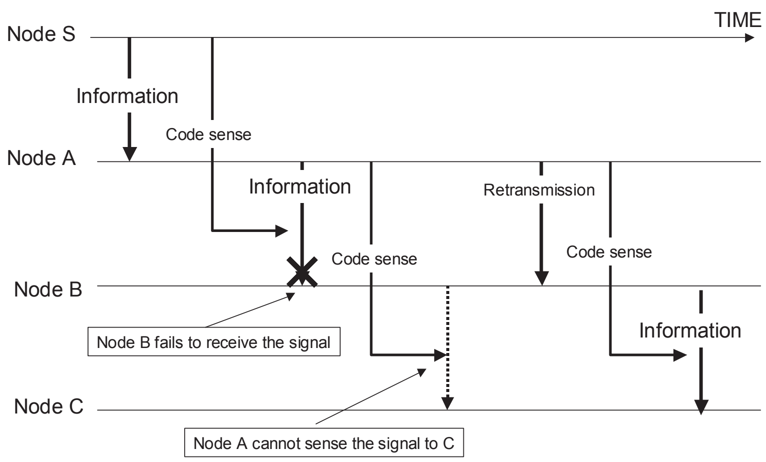

Figure 4.5: Multihop transmission with code sense system.

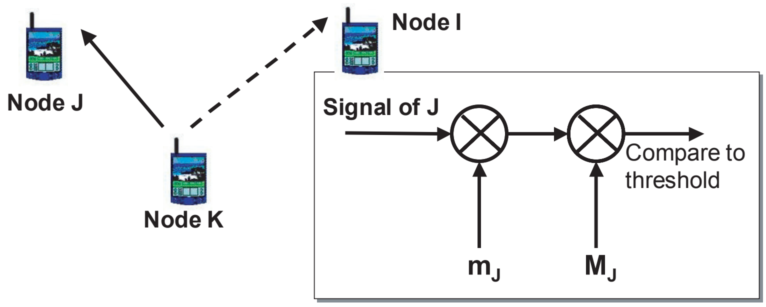

Figure 4.6: Block diagram of the code sense scheme.

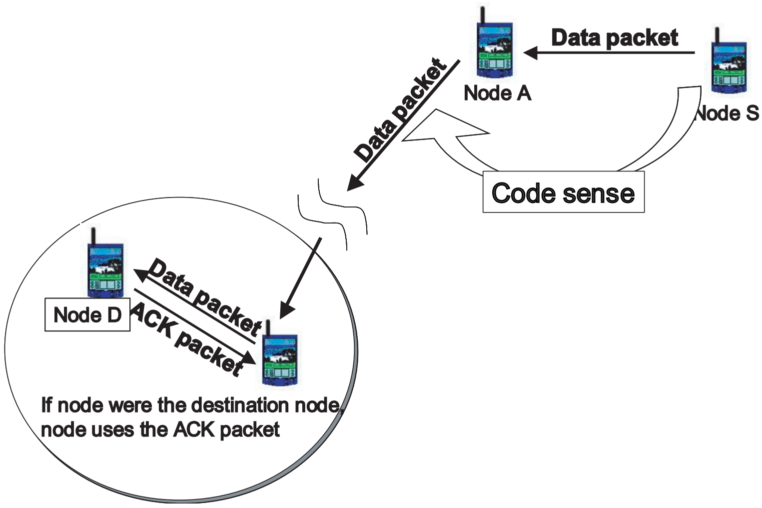

Figure 4.7: Multihop transmission with code sense system when the next node were the destination node.

4.4 Simulation Results

4.4.1 Traffic

The traffic volume is normalised to the transmission time. This means that *Traffic* of value 1 is defined when the network generates 1 packet in the period required to transmit one packet to a node at the maximum transmission distance without the packet getting lost. In our simulations, the maximum transmission distance is 30 [m] and traffic values of 1, 2, 3 and 4 are used.

4.4.2 Detection Threshold of Code Sense

The transmission power of each node is kept constant. It is defined as 1.00. Since the propagation loss increases in proportion to the square of the distance, the received power per pulse is 0.01 at the distance of 10 [m] which is the radius of the packet-forwarding zone. At that distance, the spreading factor used is 56. Therefore, The maximum received power per bit is 0.56. Our system uses a variable spreading factor in proportion to the distance. The targeted received power per bit is equal to 0.56 at any distance within the PF zone. This value is normalized to 1.00. However, the received power is also affected by the interference level. In this thesis, 0.5, 0.75, 1.00, 1.25 is used in the simulation in order to evaluate the relation between traffic and a detection threshold of code sense.

4.4.3 Simulation Conditions

The simulation parameters are summarised in Table 4.1. The nodes are uniformly and randomly distributed over a square area of 30 [m] by 30 [m] as shown in Fig. 4.8. The following assumptions have been made:

1. There is no obstacle between the nodes.
2. The transmission power of each node is kept constant.
3. Each node on the network is fixed.
4. Each node cannot send and receive a packet at the same time.

Each packet is transmitted to the destination node which is chosen at random according to the routing scheme proposed in [74]. The configuration of the topology of the network is simulated more than $10,000$ times and the number of generated packets is $10,000$ in each topology of the network. In this simulation, each node has two spreading codes. The first code is based on the phase shifted versions of the same M-sequence and its flipped one with the length of 7. The other is the Hadamard code with length based on the distance between the sender and the receiver. Success or failure of the packet transmission is specified by the following rules:

1. When two or more packets arrive simultaneously, both of the packets are discarded. This is because low cost and low power UWB devices are assumed here and only one spreading code can be demodulated at a time.
2. If Signal-to-Interference-plus-Noise-Ratio (SINR) is less than 8 [dB], a bit error occurs.
3. The packet is discarded if the number of errors are more than 5 bits in one packet.

According to [94], when FEC is used, it is possible to achieve Bit Error Rate (BER) $< 10^{-6}$ if SINR ≥ 8 [dB]. Therefore, the threshold is set as SINR $= 8$ [dB]. Location estimate error is generated within 50 [cm].

In this chapter, the following channel models are used.

- Additive White Gaussian Noise (AWGN) and Multiple Access Interference (MAI)

The noise power is defined according to [93]. Therefore, Signal to Noise Ratio (SNR) per 1 bit is defined as 10 [dB] at 10 [m].

Table 4.1: Network conditions.

Modulation	DS-CDMA
Control System	Pure ALOHA
Channel Model	AWGN + MAI
Number of Nodes	30
Radius of PF Zone	$R = 10$ [m]
Packet Length	64 [Byte]
ACK Packet	8 [Byte]
E_b/N_0	10 [dB] @ 10 [m]
Threshold	$SINR = 8$ [dB]
Traffic	1, 2, 3, 4
Number of Retransmission	4 per hop
Threshold in CS	0.5, 0.75, 1.0, 1.25

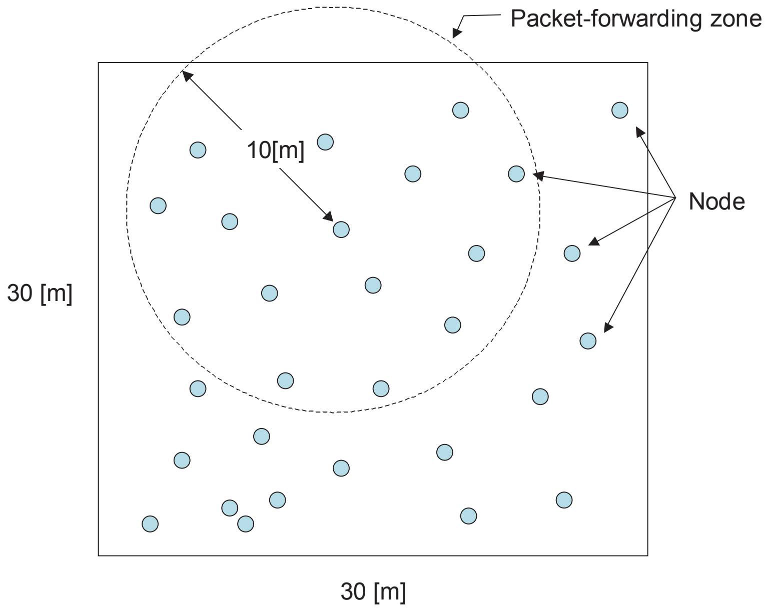

Figure 4.8: Example of the nodes in network in this simulation.

4.4.4 Numerical Results

In our simulations, a source node picks randomly its destination node, at any distance. Depending on the *transmission distance* between the source and the destination, singlehop or multihop transmission is employed. Once the simulation is finished, the results are categorised according to the transmission distance of each packet transmission.

Fig. 4.9 shows the average number of hops of multi-hop transmission vs. the distance between the source and destination nodes when the number of nodes is 30.

Figs. 4.10 - 4.12 show the probability of a successful transmission with ARQ and code sense systems vs. the traffic when the transmission distance between the source and destination nodes is 10 [m], 20 [m], and 30 [m]. The probability of a successful transmission with code sense is about 20 % better than the one of the ARQ system regardless of a detection threshold of code sense. When the transmission distance is less than 10 [m], singlehop transmission is used in both systems as shown in Fig. 4.9. This means that both systems use an ACK packet for retransmission at this distance. However, in the case of code sense, the reduced number of ACK packets in the system leads to a reduced total interference, compared to the ARQ system, thus resulting to higher performance. The probability of a successful transmission with ARQ system has been kept constant regardless of the traffic. On the other hand, in code sense scheme for transmission distance of 30 [m], we see that the probability of successful transmission varies with different threshold values and offered traffic. When traffic is 1, 2 and 3, threshold 0.75 of code sense scheme shows the best performance. When traffic is 4, threshold 0.5 of code sense scheme shows the best performance. These results show that the effect of traffic is little in ARQ system, while in code sense it is possible to select an optimal threshold corresponding to the present system traffic load.

Figs. 4.13 - 4.15 show the EDR with ARQ and code sense systems vs. the traffic when the transmission distance between the source and destination nodes is 10 [m], 20 [m], and 30 [m]. It is clear that code sense outperforms ARQ for large traffic volume. When the traffic has value of 3 and 4, the EDR with code sense is about 20 Mbps more than that with ARQ at the distance of 10 [m]. The variation of the EDR in ARQ coincides with the variation of the probability of a successful transmission. This is not the case with code sense. Interestingly, we notice that the improvement with code sense is less than what is expected from the probability of a successful transmission. The reason is that the average transmission time includes the retransmission time. Retransmission with code sense works better than that of ARQ, however, the better retransmission works, the larger the transmission time is.

Figs. 4.16 - 4.18 and Figs. 4.19 - 4.21 show the probability of a successful transmission and the EDR respectively with ARQ and code sense systems vs. the traffic when the transmission distance between the source and destination nodes is 10 [m], 20 [m], and 30 [m]. In Figs. 4.16 - 4.21, we are also considering the location estimation error. In code sense scheme, a transmitting node has to estimate the spreading factor and the spreading code at next hop with the positioning information. The validity of this estimation is greatly affected by the location estimation error. In the presented figures we see that code sense is subjected by the effect of location estimation error more than ARQ. However, even if location estimation error occurs, the probability of a successful transmission with code sense is better than that of ARQ.

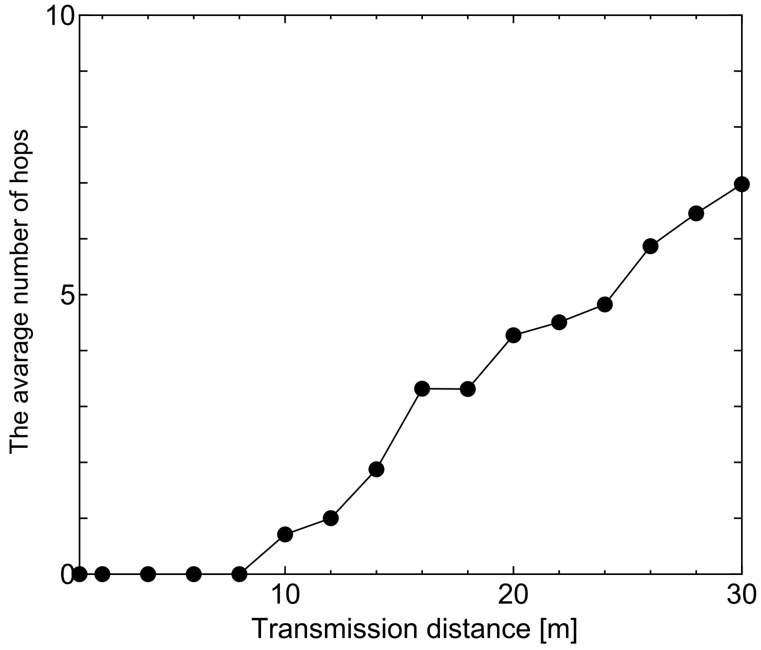

Figure 4.9: Average number of hops of multi-hop transmission vs. the distance between the source and destination nodes when the number of nodes is 30.

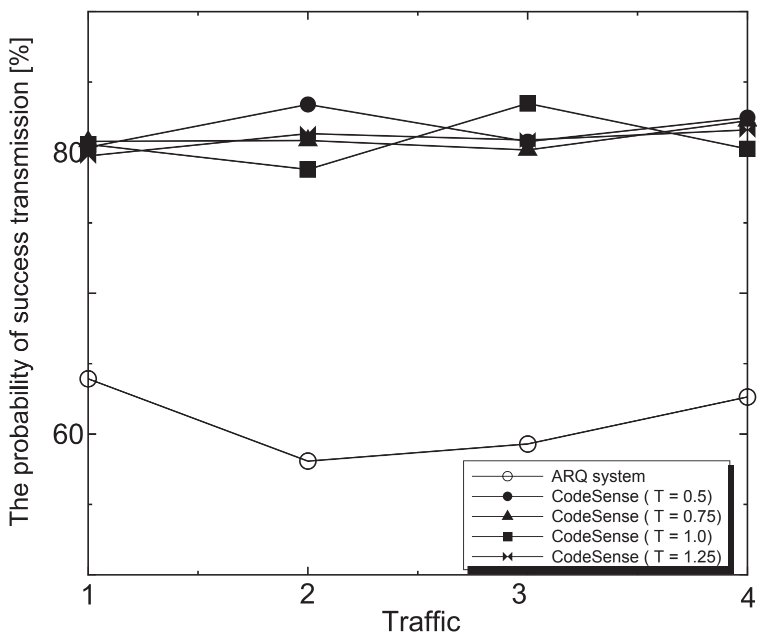

Figure 4.10: Probability of a successful transmission with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 10 [m] (Without location estimation error).

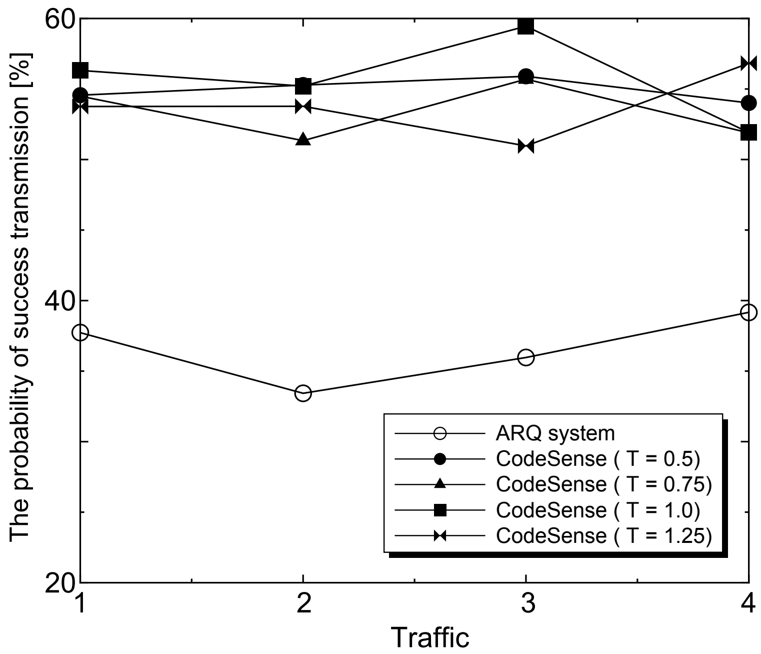

Figure 4.11: Probability of a successful transmission with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 20 [m] (Without location estimation error).

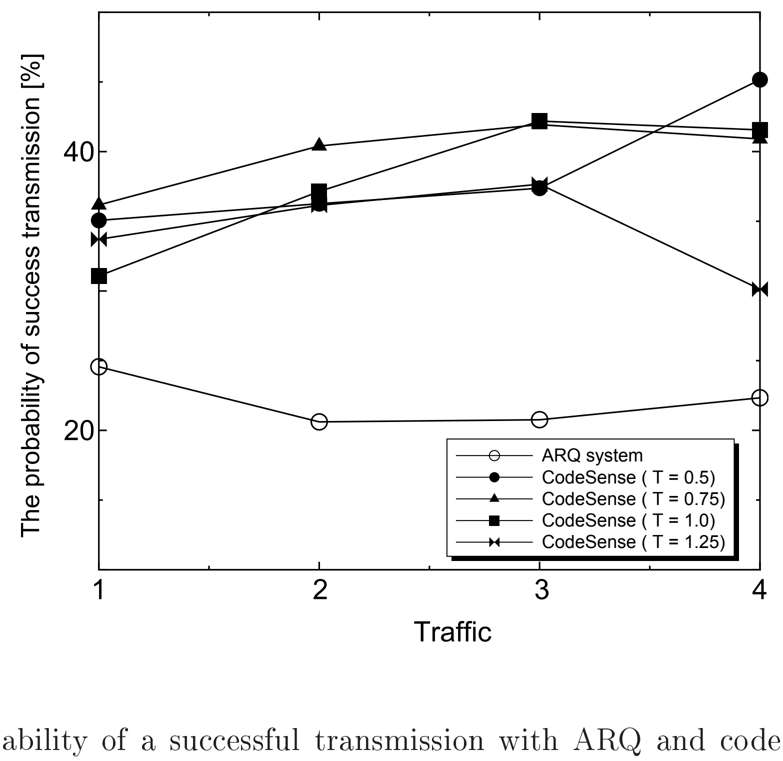

Figure 4.12: Probability of a successful transmission with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 30 [m] (Without location estimation error).

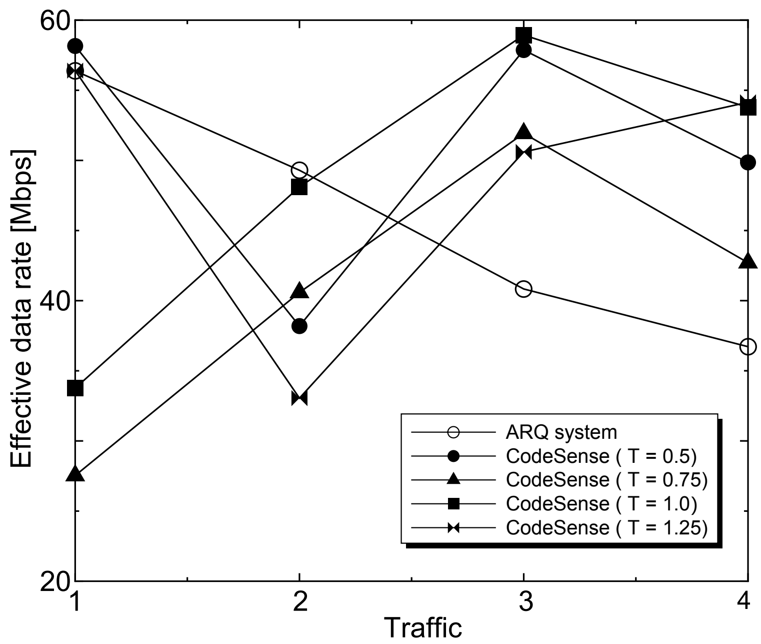

Figure 4.13: The effective data rate with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 10 [m] (Without location estimation error).

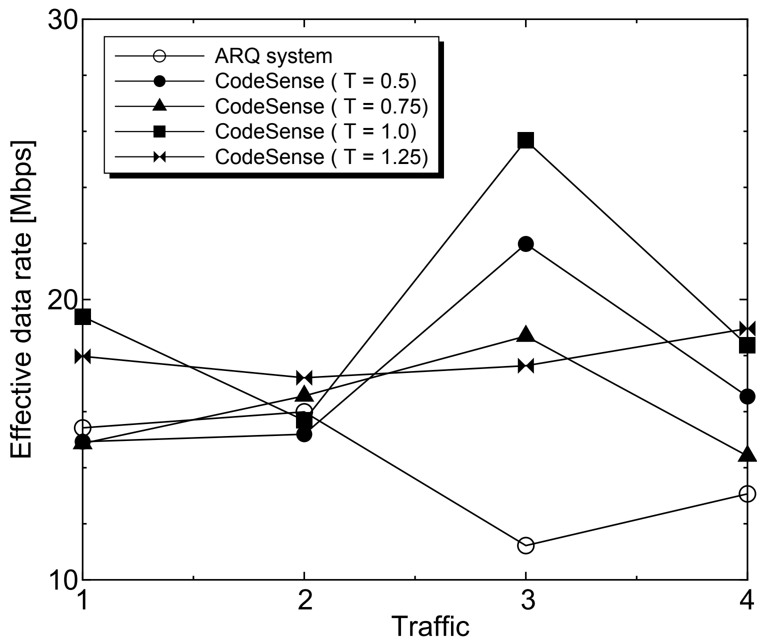

Figure 4.14: The effective data rate with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 20 [m] (Without location estimation error).

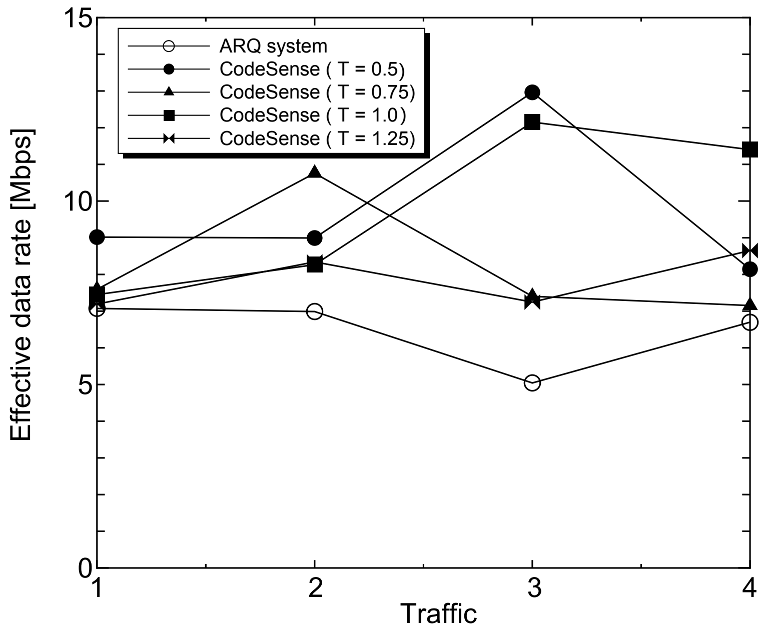

Figure 4.15: The effective data rate with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 30 [m] (Without location estimation error).

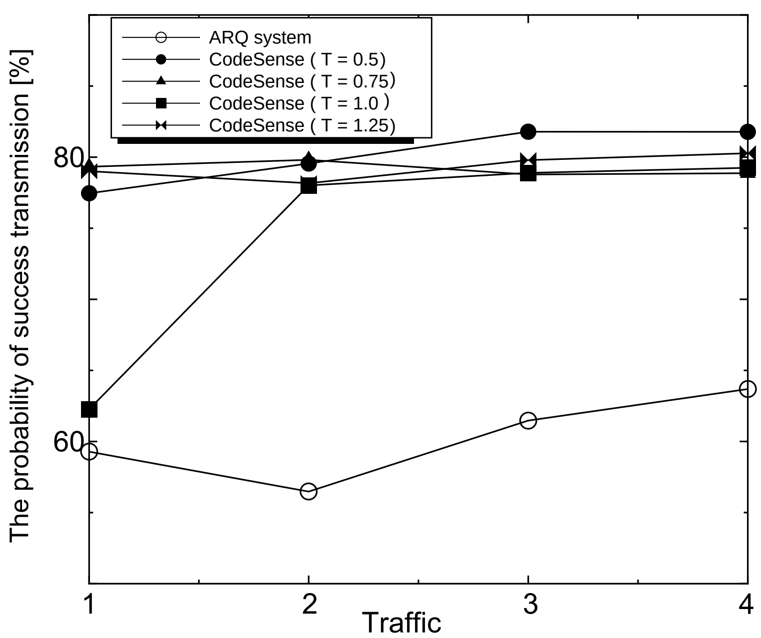

Figure 4.16: Probability of a successful transmission with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 10 [m] (Location estimation error $< \pm 50$ [cm]).

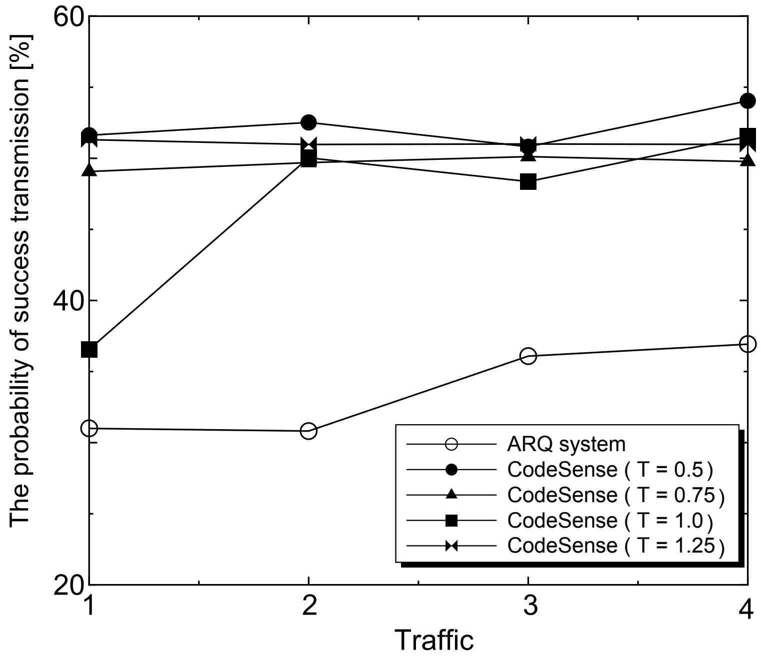

Figure 4.17: Probability of a successful transmission with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 20 [m] (Location estimation error $< \pm 50$ [cm]).

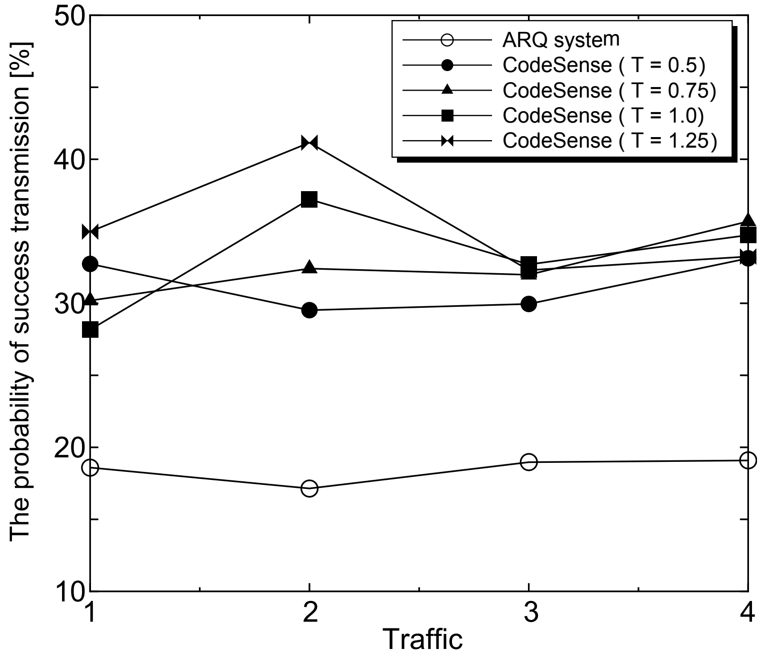

Figure 4.18: Probability of a successful transmission with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 30 [m] (Location estimation error $< \pm 50$ [cm]).

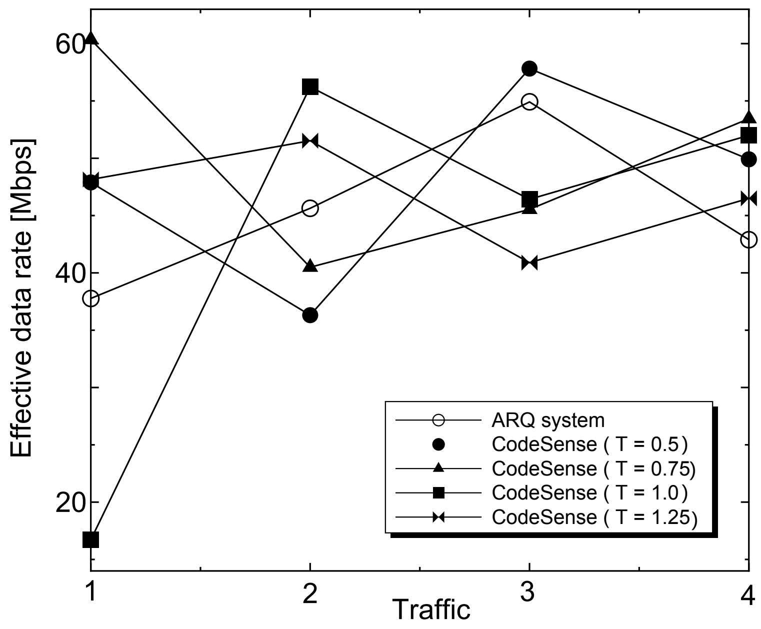

Figure 4.19: The effective data rate with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 10 [m] (Location estimation error $< \pm 50$ [cm]).

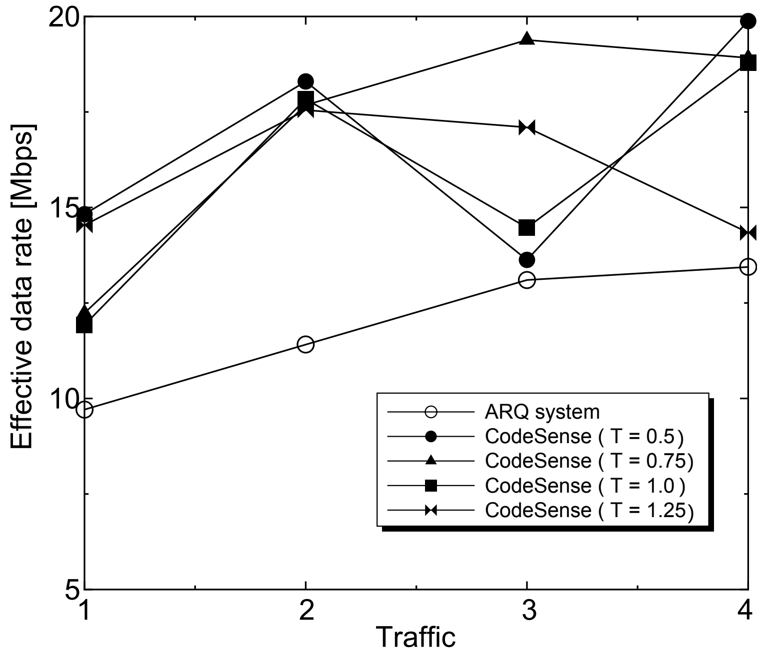

Figure 4.20: The effective data rate with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 20 [m] (Location estimation error $< \pm 50$ [cm]).

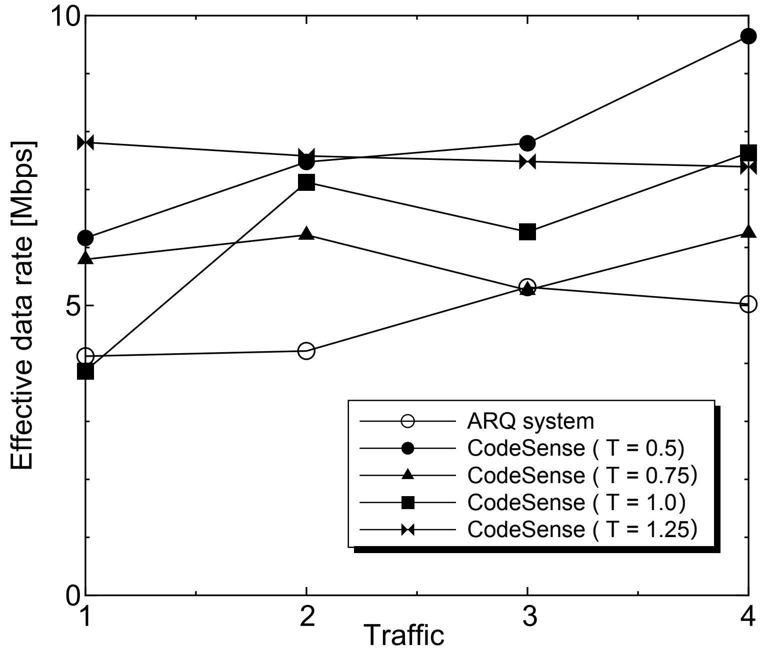

Figure 4.21: The effective data rate with ARQ and code sense systems vs. the traffic of a network when the transmission distance between the nodes is 30 [m] (Location estimation error $< \pm 50$ [cm]).

4.5 Conclusions

DS-UWB ad-hoc network with variable spreading code has been proposed to extend the communication range and keep high transmission data rate. In general, retransmission is required in packet communications in order to compensate for the packet loss and improve the network throughput. The common way through retransmission is requested is an ARQ system with ACK and NACK signaling packets. These methods can improve the throughput and reliability of the network, but the extra packets required increase the total system interference. To reduce the influence of the number of ACK packet, the retransmission scheme with code sense scheme has been proposed. The performance of code sense has been shown through simulations. Our proposed code sense scheme has been able to outperform the conventional ARQ retransmission system. The probability of a successful transmission with code sense is about 20 % better than that with the conventional retransmission system.

The proposed scheme is based on the correlation of the spreading codes. Therefore, the performance of the code sense scheme depends on the orthogonal of the spreading codes. This has used combinations of hadamard and m-sequence codes. Large improvement in the system performance can be succeeded by changing the spreading factor more precisely according to the distance. Besides, if nodes will move randomly, the performance of the code sense scheme will decrease because of reducing the accuracy of the node location estimation. Therefore, we have to correspond to the case that the nodes are moving.

Chapter 5

Performace of Two Stage Acquisition Scheme with Squared Circuit for Impulsed-Based UWB System on Several Environments

In this chapter, the two-stage acquisition scheme has been proposed to reduce the mean acquisition time of the sliding correlator in impulse based ultra wide band (UWB) systems. This scheme is optimized to IR-UWB systems. The advantage of this scheme can avoid searching the all frame of sequence codes. We have not consider other UWB modulation schemes such as MB-OA. The aim of this chapter is to investigate the performance of this scheme in several channel models such as resident, industrial or office environments. An IEEE802.15.4a channel model is used as multipath conditions. This scheme is evaluated through the simulation. The best parameters of the two-stage acquisition scheme are shown in this chapter.

5.1 Introduction

In spread spectrum communication systems, the acquisition of the sequence is required at the receiver side. The aim of acquisition is to find the phase of the sequence at the initial stage of signal reception. Many kinds of acquisition schemes have been proposed. They are mainly classified into two kinds [1]. One is based on a matched filter and the other is based on a correlator [12], [13], [6], [7], [8], [9], [11]. In the acquisition scheme based on a matched filter, the hardware is more complex and expensive. On the other hands, the scheme based on a correlator is simpler in terms of the hardware. Therefore, this scheme is less expensive and suitable for UWB. The serial search scheme is known to be the simplest one in the schemes based on a correlator. The serial search scheme searches the synchronization point by shifting the phase of the local spreading sequence with the fixed size. This scheme requires long time to achieve the acquisition. To improve the acquisition time, random search algorithm has been proposed in [10]. This scheme searches the synchronization point by shifting the random size. However, compared to the serial search, the acquisition time of the random search algorithm increases as E_b/N_o decreases.

Therefore, the two stage acquisition scheme has been proposed. The aim of this scheme is to reduce the acquisition time with the comparable complexity compared to the serial search. This scheme has the timing detection and the phase synchronization stage. In the timing detection stage, the timing of the pulse signal is detected. Based on the pulse timing information, the phase of the sequence is acquired in the second stage. The proposed scheme can quit the phase acquisition process at the timing when no pulse signal is received. In this chapter, two stage acquisition scheme with the squared circuit is evaluated under AWGN environment and multipath environments through simulations. An IEEE802.15.4a channel model is used as multipath conditions.

5.2 System Model

5.2.1 Signal Model

The monocycle waveform $w(t)$ of the transmitted signal is given as follows [37], [36].

$$w(t) = \left\{1 - 4\pi\left(\frac{t}{\tau_m}\right)^2\right\} exp\left\{-2\pi\left(\frac{t}{\tau_m}\right)^2\right\} \tag{5.1}$$

where, τ_m, is the scale of pulse width. The monocycle waveform is shown in Fig. 5.1. The transmitted signal is modulated with BPSK and the frame time is T_f as shown in Fig. 5.2. Spreading factor is N_s. Spreading code of each user is unique. The transmit waveform of k^{th} user is expressed as

$$s^k(t) = \sum_{j=0}^{N_s-1} w(t - jT_f) \tag{5.2}$$

Therefore, the transmitted signal for the k^{th} user is given by

$$x^k(t) = \sum_i d_{[i/N_s]} s^k(t - N_s T_f) \tag{5.3}$$

where bipolar modulated sequence $d \in \{-1, 1\}$ is the bit information, and $[z]$ = integer part of z. The data rate is given by $R_s = 1/N_s T_f$ [37].

For example, the transmitted signal is shown in Fig. 5.3, when the monocycle pulse is assumed as Eq. 5.1. In this figure, the normalized frame time, T_f, is 10.0 [ns] and the length of sequence, N_s, is 7.

5.2.2 Correlation Scheme

The sliding acquisition scheme has been used in many spread spectrum communication systems. In the sliding acquisition schemes, the serial search is the most simple and famous scheme. In this section, we introduce the correlation scheme by the example of the serial search. In the

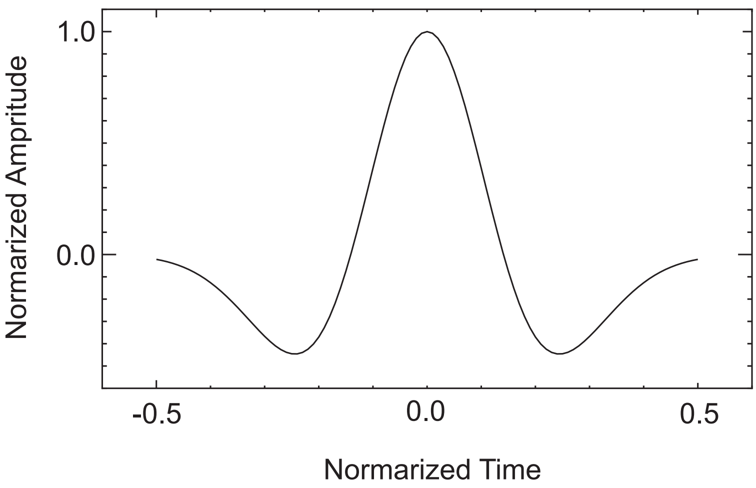

Figure 5.1: Normalized Monocycle Pulse

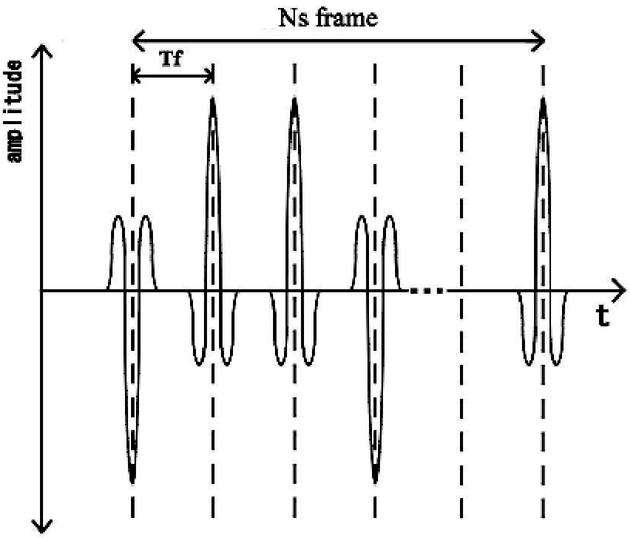

Figure 5.2: Signal for Information Transmission

serial search, the correlation value of the received signal with the template signal is compared to the threshold. Suppose that the received signal, $r(t)$, is given by

$$r(t) = s(t) + n(t) \tag{5.4}$$

where, $n(t)$, is the AWGN with zero mean and one-side power spectral density, N_0. The template signal is locally generated signal in the receiver. The template signal, $g(t)$, is given by

$$g(t) \quad = \quad \sum_{j=0}^{N_s-1} c_j w(t - jT_f - \tau)$$

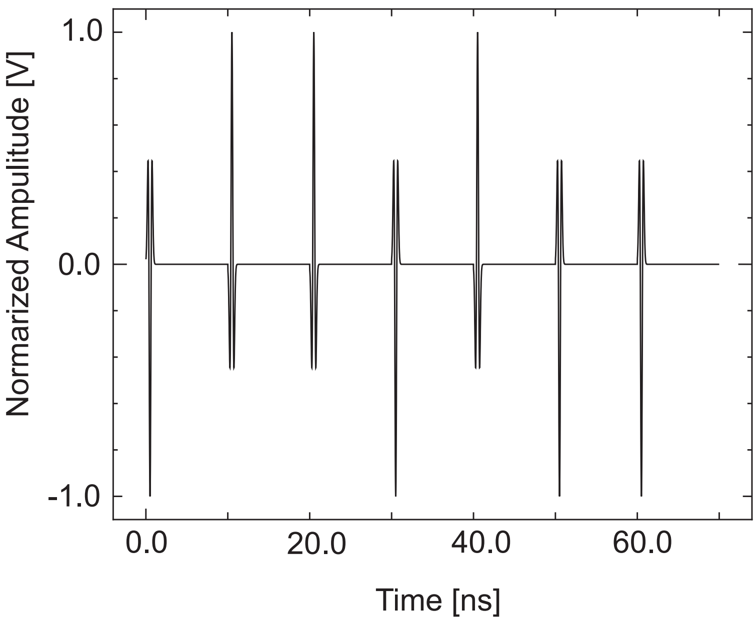

Figure 5.3: Transmitted Signal

$$= \quad s(t-\tau) \tag{5.5}$$

where τ is the phase difference between the received signal and the template signal. The correlation of the received signal with the template signal, $Z(\tau)$, is given by

$$Z(\tau) = \int_0^{T_i} r(t)g(t)dt \tag{5.6}$$

where T_i is the dwell time. The dwell time is the time period required to integrate the received signal with the template signal and the correlation value, $Z(\tau)$, is compared to the threshold in order to check if the transmitted signal exists at that timing. The correlation value of the transmitted signal with the template signal, $Z(\tau)$, changes with the phase difference, τ. The autocorrelation value of the monocycle pulse, $R_{mono}(\tau)$, is given by

$$R_{mono}(\tau) = \frac{1}{T}\int_0^{T} w(t)w(t+\tau)dt \tag{5.7}$$

where T is the pulse duration. The autocorrelation value of the monocycle pulse is shown in Fig. 5.4. The autocorrelation value of the transmitted signal over one sequence period is given by

$$R(\tau) = \frac{1}{N_sT_f}\int_0^{N_sT_f} s(t)s(t+\tau)dt, \tag{5.8}$$

which is shown in Fig. 5.5.

5.2.3 Step Size and Threshold

There are many papers about the analysis of the acquisition probability. Those papers use a rectangle shape of waves as a pulse waveform or employ one sample per one pulse for analyzing

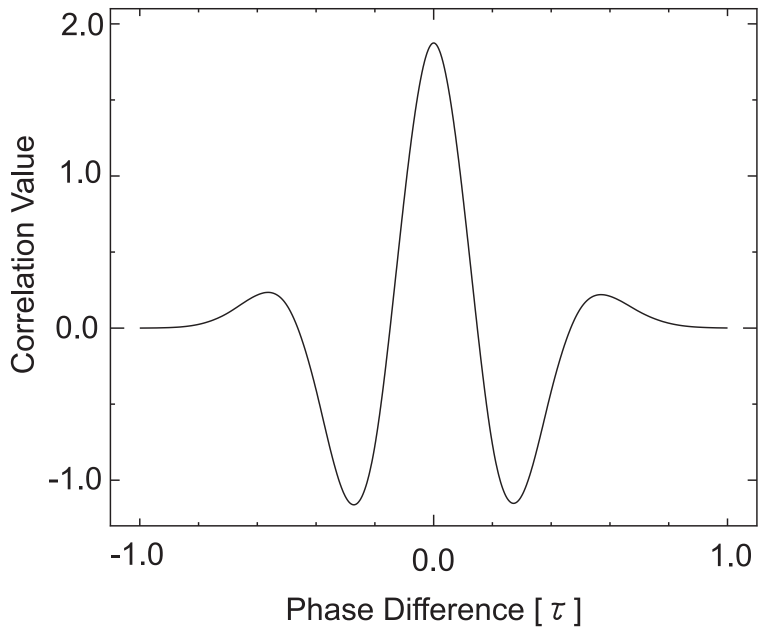

Figure 5.4: Autocorrelation Value of Monocycle Pulse.

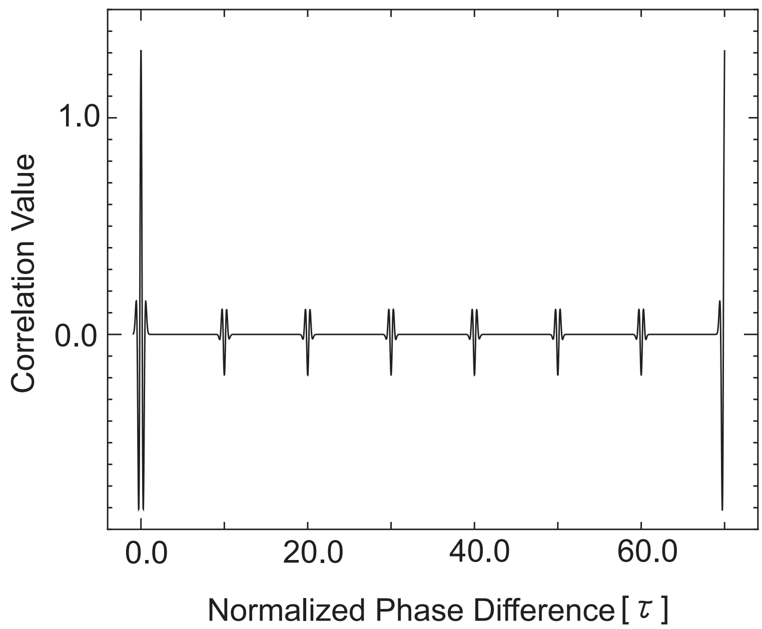

Figure 5.5: Autocorrelation Value.

the probability of acquisition. However, the shape of a pulse is never a rectangle shape and the number of sampling one pulse is more than one. The acquisition probability $P(n, j, k)$ is as follows.

$$P(n, j, k) = \prod_{k=0}^{K-1}(1 - P_{fa}^{k}(Th)) \prod_{l=0}^{L-1}(1 - P_{d}^{l}(Th))P_{d}^{L}(Th), \tag{5.9}$$

P_d^l is the probability to detect a signal in the l-th cell within the synchronous range. P_{fa}^k is the probability of false alarm and false detection in the k-th cell without the synchronous range.

$$P_d^l(Th) = \int_{Th}^{\infty} \frac{1}{\sqrt{(2\pi)}\sigma} \exp(-\frac{(x-e_l)^2}{2\sigma^2}), \tag{5.10}$$

$$P_{fa}^l(Th) = \int_{Th}^{\infty} \frac{1}{\sqrt{(2\pi)}\sigma} \exp(-\frac{x^2}{2\sigma^2}), \tag{5.11}$$

where σ is the variance and e_l is the energy of the l-th sample of the pulse. Therefore, the threshold Th to do the best performance is as follows.

$$\frac{d}{d(Th)}(\sum_{l=0}^{L} P(k,l,Th)) = 0, \tag{5.12}$$

5.2.4 Mean Acquisition Time

In the serial search the mean acquisition time is given by [1],

$$\bar{T_s} = (C_s - 1)(T_i + T_{fa}P_{fa})\left(\frac{2-P_d}{2P_d}\right), \tag{5.13}$$

where C_s is the number of cells to be searched, P_{fa} is the probability of false alarm, P_d is the detection probability, T_i is the dwell time, and T_{fa} is the penalty time.

The number of cells C_s is given by $\Delta T/\Delta t$. ΔT is one sequence period. Δt is the step size. The detection probability P_d is the probability of detection when the correct cell is evaluated. The probability of false alarm P_{fa} is the probability of detection when the correct cell is being evaluated. The dwell time T_i is the time which is integrated with the received signal and the template signal. The penalty time T_{fa} is the time required to reject an incorrect cell when a false alarm occurs. The penalty time T_{fa} may be much larger than T_i, so that false alarms are undesirable events.

5.3 Proposed Acquisition Scheme

The proposed receiver architecture is shown in Fig. 5.6. In the proposed scheme, the search algorithm has two stages. The first stage is the timing detection stage and the second stage is the sequence acquisition stage. In the first stage, the SPDT (Single Pole Double Throw) switches select the paths so that the received signal and the template signal are both put into the square circuits. In this stage, the receiver detects the timing of the pulse signals. In the second stage, the SPDT switches select the other paths and the received signal is directly multiplied by the template signal. In this stage, based on the timing information of the pulse signals, the receiver finds the phase of the sequence.

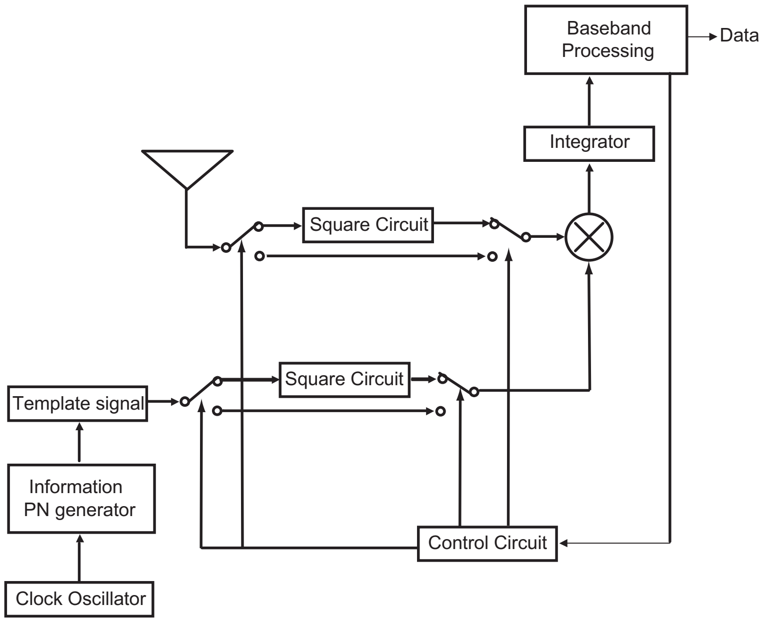

Figure 5.6: Receiver Structure of the Proposed Scheme

5.3.1 Algorithm of the Proposed Scheme

The flowchart of the proposed acquisition scheme is shown in Fig. 5.7. The proposed scheme has two stages as shown in Fig. 5.7. The concept of the first stage is shown in Fig. 5.8. First, the squared received signal is correlated with the squared template signal. If the correlation value is lower than the threshold, the phase of the template signal is shifted by the step size, Δt. This process continues until the correlation value exceeds the threshold. If the correlation value exceeds the threshold, the acquisition process switches to the verification mode.

The verification mode in the first stage of the proposed scheme is the same as the serial search. The squared template signal is correlated with the squared received signal n times without shifting the phase of the squared template signal. If all of n correlation values exceed the threshold, the acquisition process proceeds to the second stage. If any of the correlation values does not exceed the threshold, the phase of the template signal is shifted and the search mode is restarted.

The concept of the second stage is shown in Fig. 5.9. At the end of the first stage, the receiver can only detect the timing of the transmitted pulses as the received signal is squared. In the second stage, based on the timing information in the first stage, the phase of the sequence is examined. If the correlation value is lower than the threshold, the phase of the template signal is shifted by the step size of the frame time, T_f. This process continues until the correlation value exceeds the threshold. If the correlation value exceeds the threshold, the acquisition process in the second stage switches to the verification mode.

The verification mode of the proposed scheme in the second stage is the same as that in the first stage. The template signal is correlated with the received signal n times without shifting the phase of the template signal. If all of n correlation values exceed the threshold, the acquisition of the sequence is assumed to be achieved. If any of the correlation values does not exceed the threshold, the phase of the template signal is shifted and the search mode is restarted.

In the proposed scheme if the receiver investigates a wrong cell as a candidate for the acquisition point in the first stage, the receiver will not be able to find the correct phase of the sequence. Therefore, in the second stage if the receiver can not complete the acquisition within a certain period, the acquisition process needs to be returned to the first stage after the certain time is spent for searching the phase of the sequence. In this chapter, this period is defined as the return time, T_r.

As the receiver knows the timing of the pulses with the proposed scheme, the receiver does not have to search the cells in which the pulse signal does not exist in the second stage.

5.3.2 Correlation with Squared Circuit

In the timing detection stage of the proposed scheme, the template and the received signal are put into the square circuits in order to detect only the phase of the received pulses (pulse-level synchronization). If there is no the square circuits, the detection of the phase of the received pulse cannot be done without the code sequence synchronization. The correlation value between the squared received and the squared template signal is compared to the threshold. The correlation value between those signals is given by

$$Z_{pro}(\tau) = \int_0^{T_i} r^2(t) g^2(t) dt. \tag{5.14}$$

The autocorrelation function at the first stage of the proposed scheme is given by

$$R_{pro}(\tau) \quad = \quad \frac{1}{N_s T_f} \int_0^{N_s T_f} s^2(t) s^2(t+\tau) dt. \tag{5.15}$$

5.4 Simulation Results

5.4.1 Simulation Results on AWGN Environment

5.4.1.1 Performance Analysis without AWGN

In this section, the performance of the serial search and the proposed scheme are evaluated under no AWGN condition.

In the serial search the mean acquisition time is given by [1], [5]

$$\bar{T}_s = (C_s - 1)(T_i + T_{fa} P_{fa}) \left(\frac{2 - P_d}{2 P_d} \right) + \frac{T_i}{P_d}, \tag{5.16}$$

where P_{fa} is the probability of false alarm, P_d is the probability of detection, T_i is the dwell time, T_{fa} is the penalty time, and C_s is the number of cells to be searched.

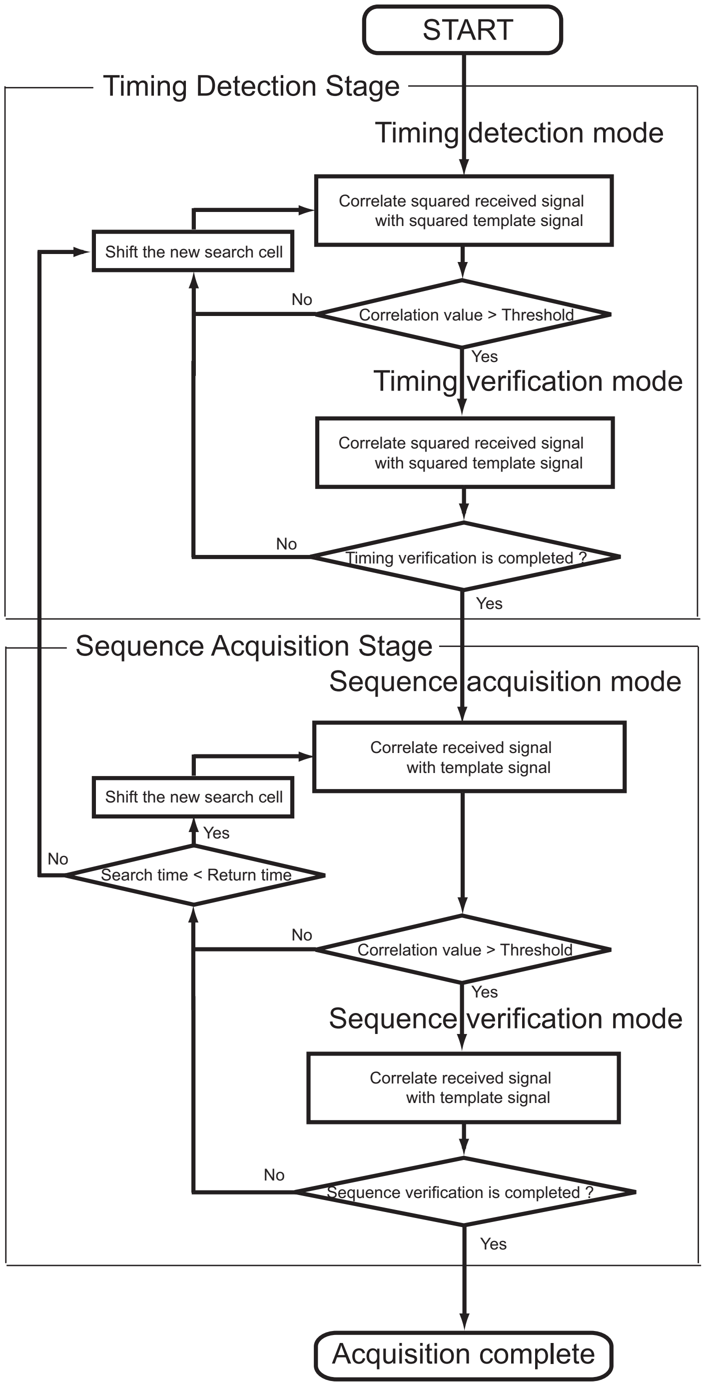

Figure 5.7: Algorithm of Proposed Acquisition Scheme

In order to compare the proposed scheme with the conventional scheme, here, an ideal channel without noise is assumed for simplicity. The acquisition time on the ideal channel ($P_d = 1$ and $P_{fa} = 0$) is given by

$$\bar{T_s} = \frac{C_s + 1}{2} T_i \tag{5.17}$$

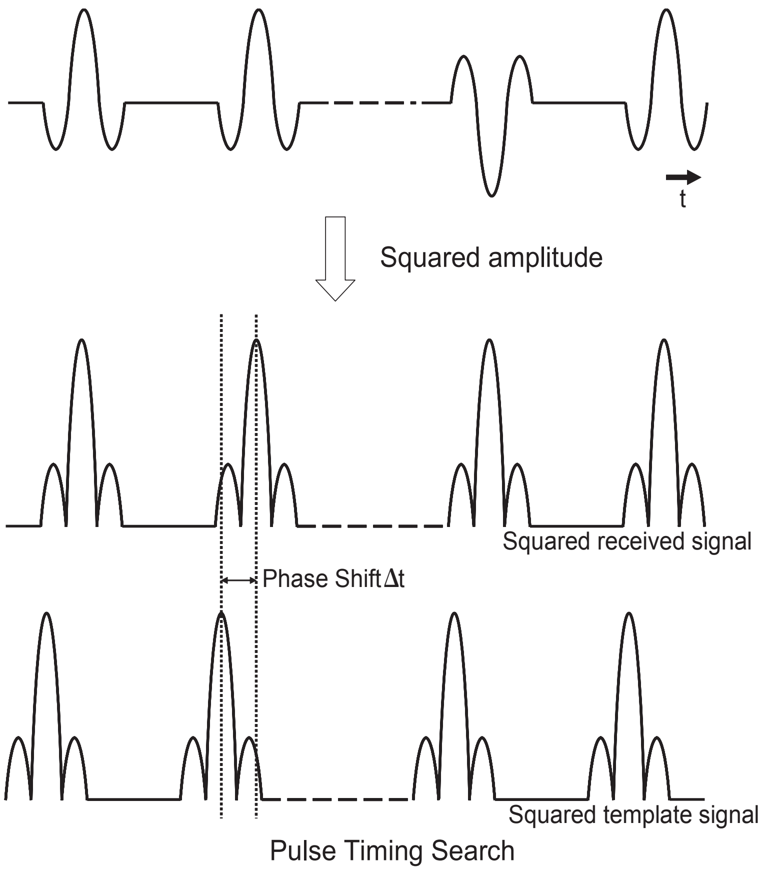

Figure 5.8: Concept of the Pulse Detection Stage

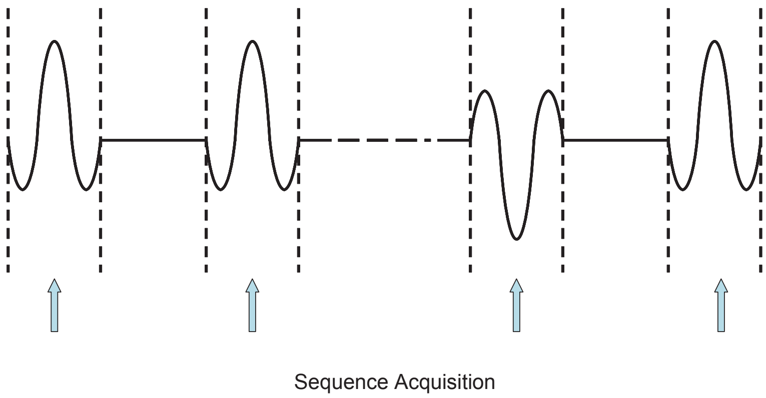

Figure 5.9: Concept of the Sequence Acquisition Stage

where C_s is given by

$$C_s = T_f N_s / \Delta t. \tag{5.18}$$

The acquisition time of the proposed scheme, T_p, is given by

$$\bar{T_p} = T_{first} + T_{second} \tag{5.19}$$

where T_{first} is the mean acquisition time in the first stage and T_{second} is the mean acquisition time in the second stage. Each acquisition time in the first stage and the second stage are calculated by Eq. (5.17). On the ideal channel, the mean acquisition time of the proposed scheme in the first stage is given by

$$\bar{T}_{first} = \frac{C_{first} + 1}{2} T_i \tag{5.20}$$

where C_{first} is given by

$$C_{first} = T_f / \Delta t \tag{5.21}$$

where T_f is the frame time and Δt is the search cell size. The mean acquisition time of the proposed scheme in the second stage is given by

$$\bar{T}_{second} = \frac{C_{second} + 1}{2} T_i \tag{5.22}$$

where C_{second} is given by

$$C_{second} = N_s \tag{5.23}$$

where N_s is the length of the sequence. Therefore, the mean acquisition time of the proposed scheme, T_p, is given by

$$\begin{aligned} \bar{T}_p &= \bar{T}_{first} + \bar{T}_{second} \\ &= \frac{C_{first} + 1}{2} T_i + \frac{C_{second} + 1}{2} T_i \\ &= \frac{C_{first} + C_{second} + 2}{2} T_i \\ &= \frac{C_p + 2}{2} T_i \end{aligned} \tag{5.24}$$

where C_p is $C_{first} + C_{second}$. In the proposed scheme, C_p is given as

$$C_p = T_f / \Delta t + N_s. \tag{5.25}$$

The mean acquisition time of the serial search, $\bar{T}_s$, and that of the proposed scheme, $\bar{T}_p$, are given by

$$\bar{T}_s = \frac{T_f N_s / \Delta t + 1}{2} T_i, \tag{5.26}$$

$$\bar{T}_p = \frac{T_f / \Delta t + N_s + 2}{2} T_i. \tag{5.27}$$

Here, it is assumed that

$$\Delta t \ll T_f. \tag{5.28}$$

Therefore, with the assumption of $N_s \ll T_f / \Delta t$, Eqs. (5.26) and (5.27) are approximated as

$$\bar{T}_s \approx \frac{T_f N_s / \Delta t}{2} T_i, \tag{5.29}$$

$$\bar{T}_p \approx \frac{T_f / \Delta t}{2} T_i. \tag{5.30}$$

Consequently the acquisition speed of the proposed scheme is N_s times faster than that of the serial search on the ideal channel.

5.4.1.2 Simulation Conditions

The performance of the proposed scheme on the AWGN channel has been evaluated through computer simulation.

The simulation conditions are shown in Table 5.1. The system is evaluated with the mean acquisition time and the probability of acquisition. The probability of acquisition is the probability with which the sequence acquisition is achieved in the limit time, T_l. The limit time in this section is set to $2000T_i$. The return time in the proposed scheme is set to $3N_sT_i$.

Table 5.1: Simulation Conditions on AWGN Environment

Radio System	IR-UWB
Channel	AWGN Channel
Modulation Format	BPSK
Spreading Sequence	M-Sequence
Length of the Sequence	7
Frame Time T_f	10 [ns]
Pulse Duration	1 [ns]
Step Size Δ_t	1/6 [ns] for Serial Search 1/7 [ns] for Proposed Scheme
Dwell Time T_i	70 [ns] (N_sT_f)
Return Time T_r	$3N_sT_i$
Number of trials	$10,000$

5.4.1.3 Step Size

The step size of the serial search is set to 1/6 and the step size for the pulse detection in the proposed scheme is set to 1/7. These step sizes are chosen from the numerical results shown in Fig. 5.10. In this figure, no noise is assumed. Also, the threshold of the serial search is set to $0.5R(0)$ and that for pulse detection in the proposed scheme is set to $0.5R_{pro}(0)$ as the starting point for optimization of the parameters. Generally, the step size should be as large as possible in order to reduce the number of search cells and shorten the mean acquisition time. However, from Fig. 5.10, if the step size increases, the probability of acquisition reduces for the both schemes. The reason is that the correlator output may not exceed the threshold if the large step size is employed. Fig. 5.11 shows the relation between the output of correlator and the step size. Fig. 5.12 shows the relation between the squared output of correlator and the step size. As the timing of the pulse is randomly given for each trial of the simulation, if the step size is too large, the receiver may not be able to pick up the top part of the autocorrelation of the received (or squared) pulse. The difference of the step size between the serial search and the proposed scheme comes from the difference of the waveform of the correlator output. The timing range with which the output of the correlator exceeds the threshold for timing detection,

$R_{pro}(\tau)$, is smaller than that with the threshold for the serial search, $R(\tau)$. Therefore, as shown in Fig. 5.10, the step size of the proposed scheme should be smaller than the serial search.

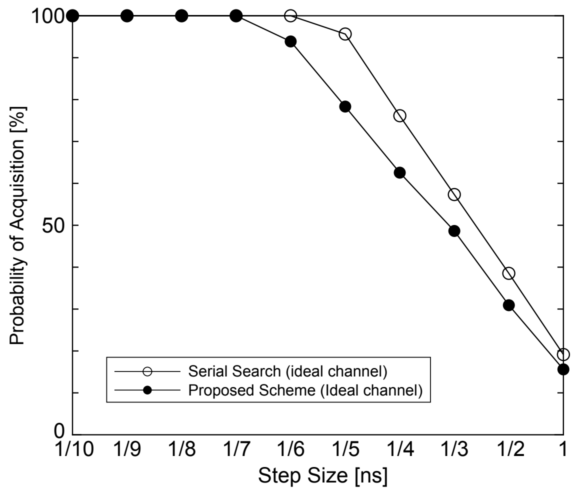

Figure 5.10: Step Size vs. Probability of Acquisition, Limit time is $2000T_i$

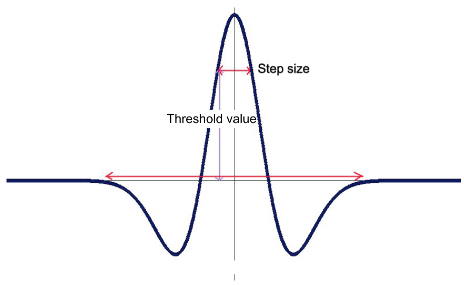

Figure 5.11: Relation between the output of correlator and the step size.

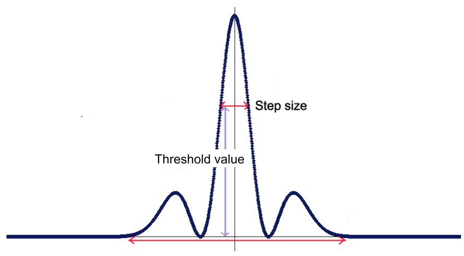

Figure 5.12: Relation between the squared output of correlator and the step size.

5.4.1.4 Numerical Results

5.4.1.5 Number of the Correlator Outputs and the Threshold of the Serial Search

The probabilities of acquisition for the serial search versus threshold value with the SNR of 0, 5, and 10 dB are shown in Figs. 5.13-5.15. Generally, the number of the correlator outputs should be large enough in order to reduce the probability of false alarm. However, from the figures, as the number of the correlator outputs increases, the probability of acquisition decreases. Thus, from these results, the number of the correlator outputs, n, is set to 4 and the threshold is set to $0.5R(0)$ for the serial search. Fig. 5.16 shows the probability of acquisition vs. limit time in the case that the SNR is 10 dB. Fig. 5.17 shows the probability of false alarm vs. threshold value with the SNR of 10 dB. From these figures, the threshold of $0.5R(0)$ shows the best performance with different limit times when the number of correlator outputs is 4.

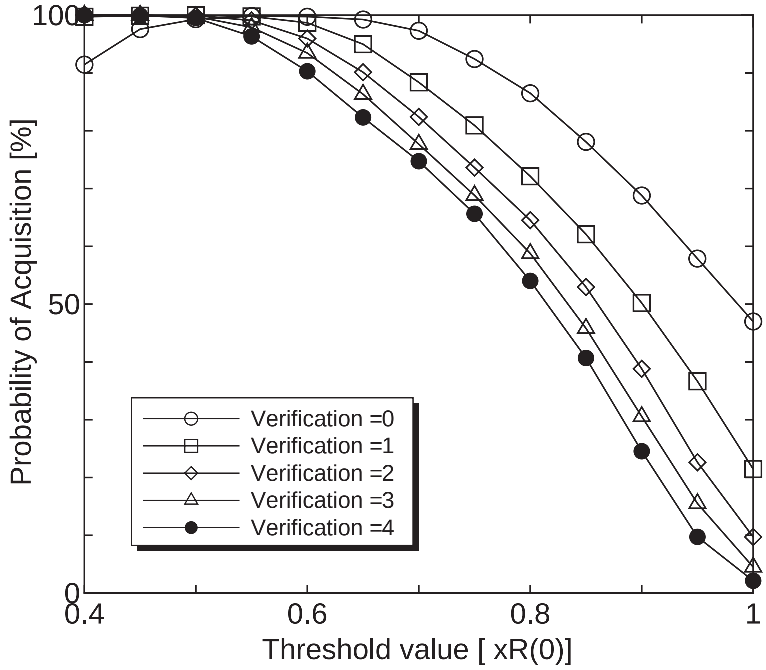

Figure 5.13: Probability of Acquisition vs. Threshold Value with SNR of 0 dB, Limit time is $2000T_i$

5.4.1.6 Number of the Correlator Outputs and the Threshold for Timing Detection

The probabilities of timing detection for the proposed scheme versus threshold values with the SNR of 0, 5, and 10 dB are shown in Figs. 5.18 - 5.20. The same as the serial search, the number of correlation values for verification should be large enough in order to reduce the probability of false alarm. From these figures, when the SNR is 5 dB and 10 dB, if the number of the correlation outputs is 2 and the threshold is less than $0.5R_{pro}(0)$, the probability of timing detection is close to 100%. Thus, the number of the correlator outputs is set to 2 and

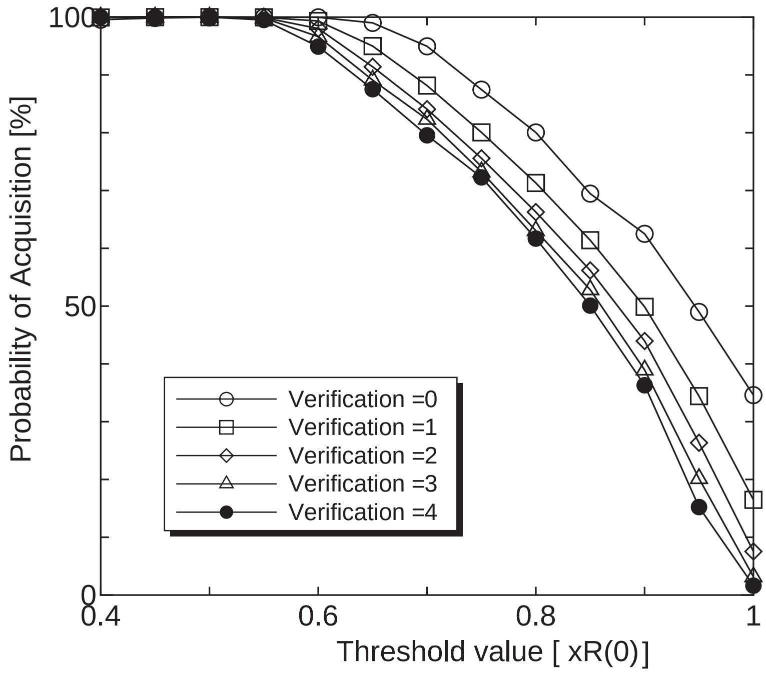

Figure 5.14: Probability of Acquisition vs. Threshold Value with SNR of 5 dB, Limit time is $2000T_i$

the threshold is set to $0.5R_{pro}(0)$ for timing detection of the proposed scheme. Though these values are not optimum when the SNR is 0 dB, IR-UWB is supposed to be operated under higher SNR conditions. Fig. 5.21 shows the probability of acquisition vs. limit time in the case that SNR is 10 dB. Fig. 5.22 shows the probability of false alarm vs. threshold value with SNR of 10 dB. From these figures, the threshold of $0.5R_{pro}(0)$ shows the best performance with different limit times when the number of correlator outputs is 2.

As for the sequence acquisition stage of the proposed scheme, the same threshold and the same number of correlator outputs are used as the serial search.

5.4.1.7 Mean Acquisition Time vs. Sequence Length

Fig. 5.23 gives the mean acquisition time versus the length of the sequence. It is assumed that the dwell time is $T_f N_s$ [s] which is the period of 1 bit signal. The acquisition speed of the proposed scheme is about N_s (the length of the sequence) times faster than the serial search. Consequently the proposed scheme is more effective as the length of the sequence increases.

The dwell time can be longer and the probability of false alarm can be reduced. However, from Fig. 5.23, it seems to be long enough as the mean acquisition time with and without AWGN is close for both the serial search and the proposed scheme. On the other hand, the dwell time should not be shorter than the 1 bit duration as it may lose the process gain in terms of the multiuser interference.

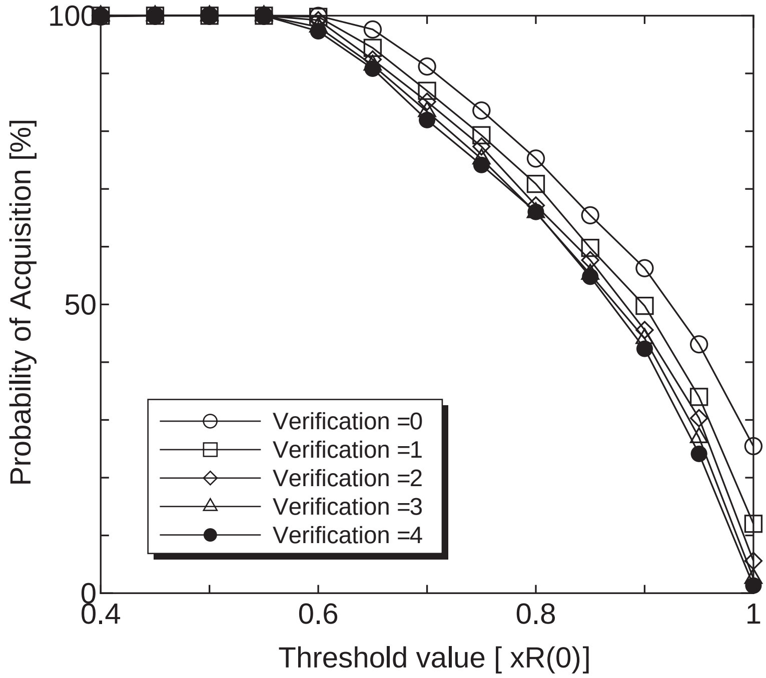

Figure 5.15: Probability of Acquisition vs. Threshold Value with SNR of 10 dB, Limit time is $2000T_i$

5.4.1.8 Mean Acquisition Time vs. E_b/N_o

The mean acquisition time for the proposed scheme and the conventional scheme versus E_b/N_0 is shown in Fig. 5.24. The length of the sequence, N_s, is 7, and the dwell time, T_i, is $N_sT_f = 70.0$ [ns]. From the figure, the proposed acquisition scheme achieves faster acquisition than the serial search at the high SNR range. On the other hand, under the low SNR condition, the mean acquisition time for the proposed scheme is worse than that of the serial search. This is because the received signal is squared in the timing detection stage of the proposed scheme. The squared signal suffers from the thermal noise as shown in Fig. 5.18.

5.4.1.9 Probability of Acquisition vs. E_b/N_o

The probabilities of acquisition for the proposed scheme and the serial search have been compared in different conditions. The probabilities of acquisition for the proposed scheme and the conventional scheme versus E_b/N_0 are shown in Figs. 5.25 and 5.26. The acquisition limit time, T_l, is $200T_i$ and $500T_i$ [s], the length of the sequence is 7, and the dwell time, T_i, is $N_sT_f = 70.0$ [ns]. From Figs. 5.25 and 5.26, the proposed acquisition scheme shows better probability than the serial search when E_b/N_0 is more than -3 dB with $T_l = 200T_i$ and -2.5 dB with $T_l = 500T_i$. When the limit time is $200T_i$, the proposed scheme shows better probability under the high E_b/N_0 condition. On the other hand, it is almost the same with the limit time of $500T_i$ under the high E_b/N_0 condition. In Fig. 5.25, the mean acquisition time of the serial search is longer as compared to that of the proposed scheme. Thus, the limit time $200T_i$ is not long enough to

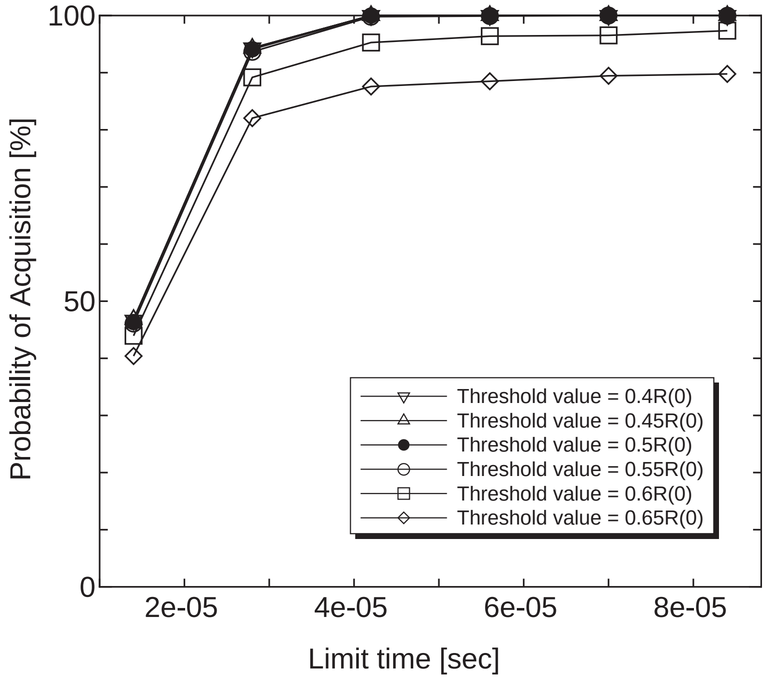

Figure 5.16: Probability of Acquisition vs. Limit time at SNR of 10 dB, Verification = 4.

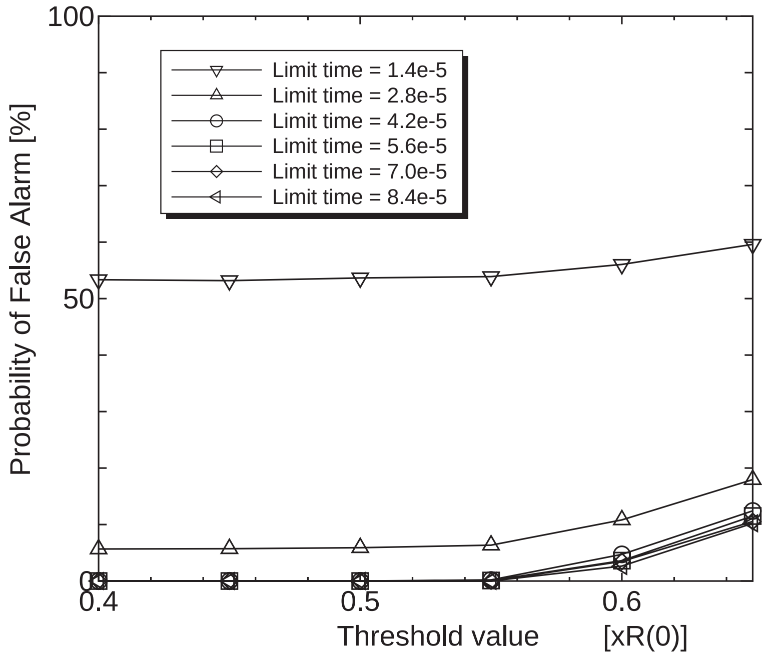

Figure 5.17: Probability of false alarm vs. Threshold Value with SNR of 10 [dB], Verification = 4.

complete the synchronization in the serial search. Therefore, the acquisition probability of the serial search is saturated with 50%. On the other hand, Fig. 5.26 shows that the limit time $500T_i$ is long enough to complete the synchronization in both schemes. On the other hand,

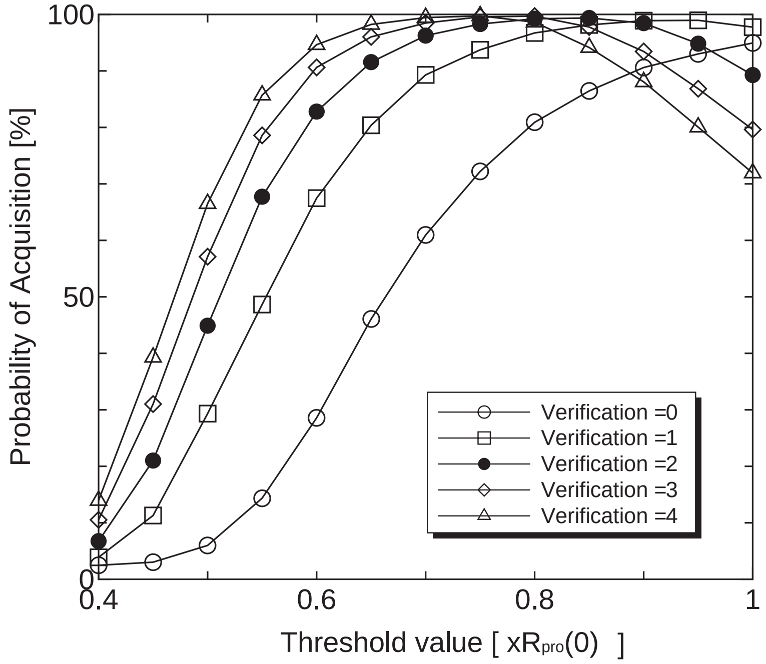

Figure 5.18: Probability of Timing Detection vs. Threshold Value with SNR of 0 dB, Limit time is $2000T_i$

under the low SNR condition, the probability of acquisition is lower for the proposed scheme as compared to the serial search. The same as the mean acquisition time, the squared signal suffers from the thermal noise and the probability of timing detection is small with low SNR.

5.4.1.10 Probability of Acquisition vs. Limit Time

The probability of acquisition versus the acquisition limit time, T_l, is shown in Fig. 5.27. E_b/N_0 is 10 dB. From the figure when the acquisition limit time is less than 25 [μs], the proposed scheme shows better probability. This is because the $\bar{T_p}$ in Eq. (5.30) is about 2.5 μs. Thus, with about 5 μs], the proposed scheme can search almost all the cells. On the other hand, $\bar{T_s}$ in Eq. (5.29) is about 15 μs, and it takes about 30 μs for the serial search algorithm to search all the cells.

Within a certain time period the proposed scheme has more chances of acquisition than the serial search because the mean acquisition time of the proposed scheme is much shorter than the conventional one. Therefore, in the same period the probability of the proposed scheme is better than the serial search.

5.4.1.11 Multiuser Condition

Figs. 5.28 and 5.29 show the mean acquisition time and the probability of acquisition with two users. The acquisition limit time, T_l, is $500T_i$ [s], the length of the sequence is 7, and the dwell time, T_i, is N_sT_f = 70.0 [ns]. The relative timing of the pulse signals from the two users is

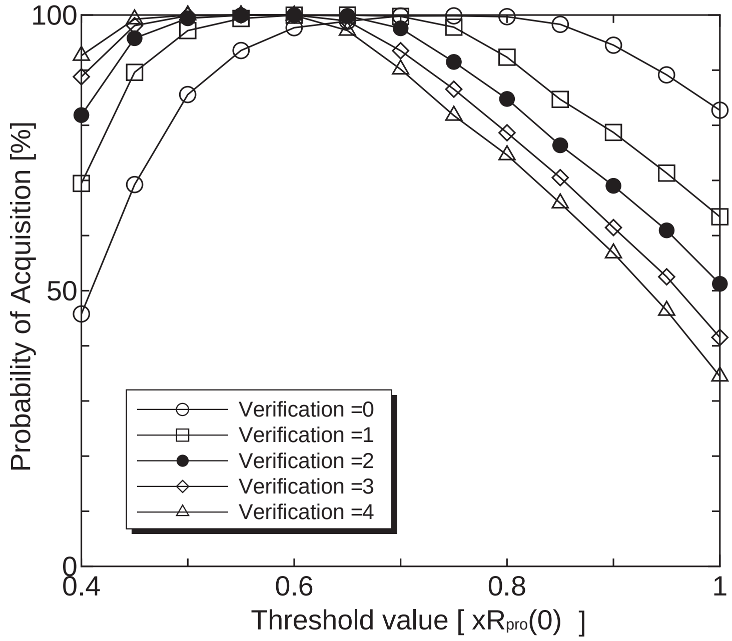

Figure 5.19: Probability of Timing Detection vs. Threshold Value with SNR of 5 dB, Limit time is $2000T_i$

randomly given for each simulation trial.

Under the multiuser environment, the first stage of the proposed scheme may detect the pulse signal from the undesired user. It then searches the phase of the sequence of the signal. After checking the phase of the sequence with the return time, it will start to search the next pulse signal. If $\{T_r/(N_sT_f)$ * (number of users)$\}$ is smaller than the number of cells to be checked in the serial search, the proposed scheme still can shorten the overall acquisition time.

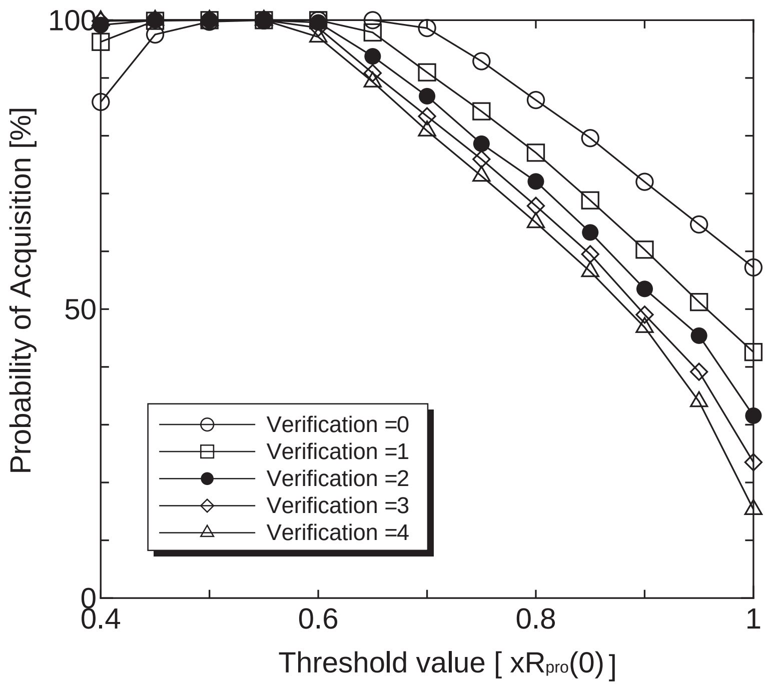

Figure 5.20: Probability of Timing Detection vs. Threshold Value with SNR of 10 dB, Limit time is $2000T_i$

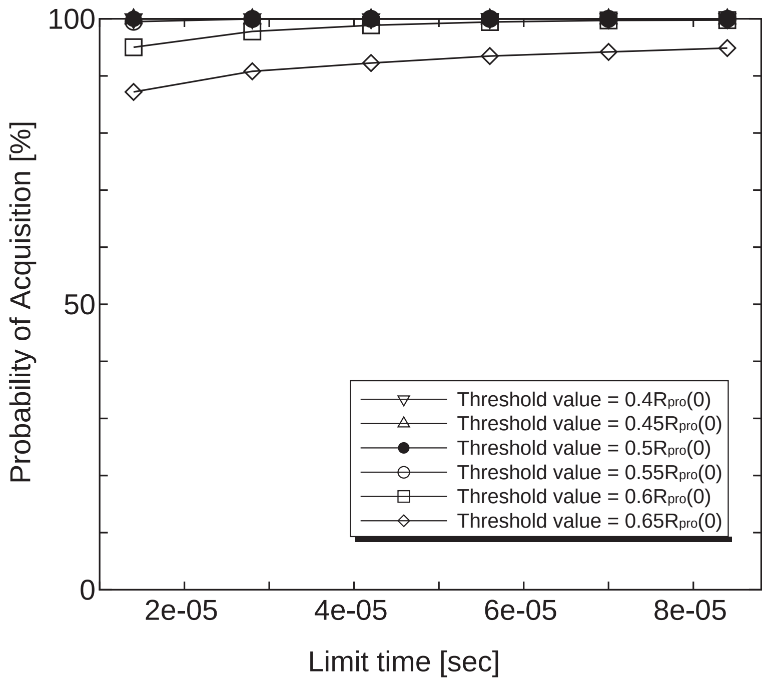

Figure 5.21: Probability of Acquisition vs. Limit time at SNR of 10 dB, Verification = 2.

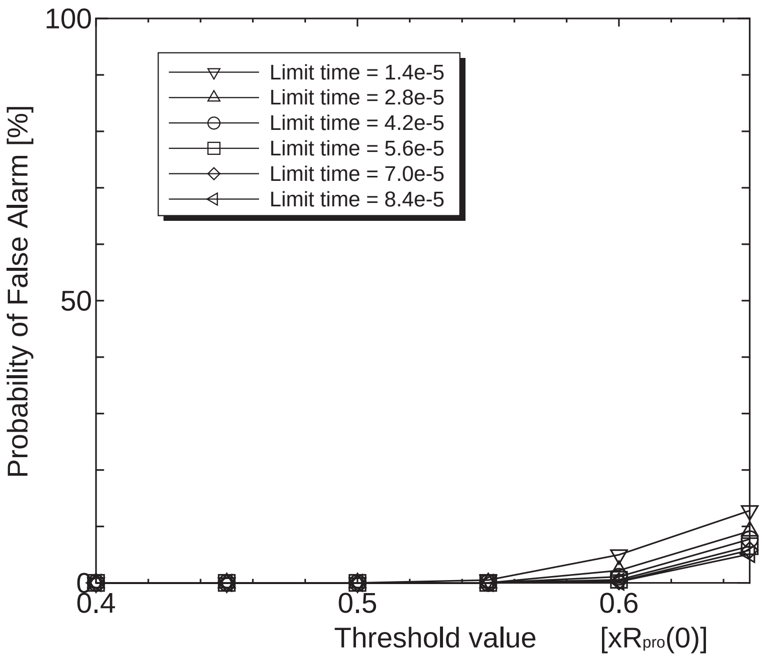

Figure 5.22: Probability of false alarm vs. Threshold Value with SNR of 10 dB, Verification = 2.

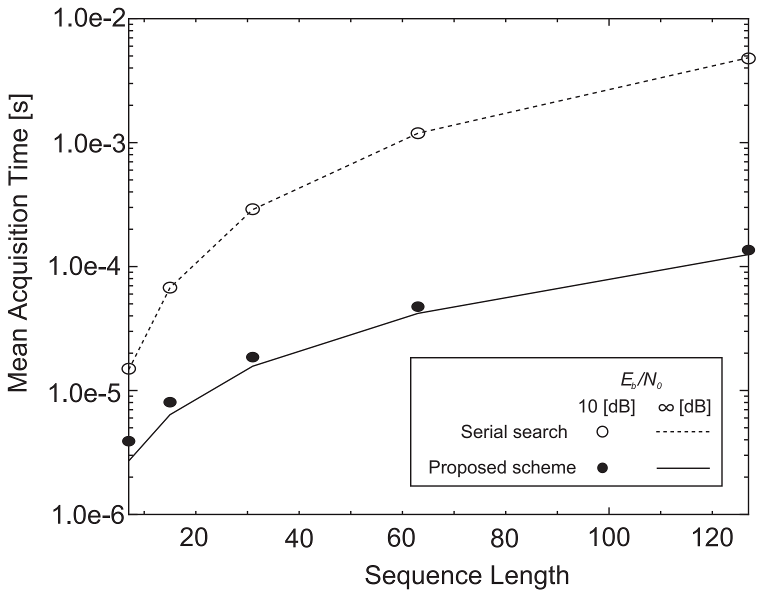

Figure 5.23: Mean Acquisition Time vs. the Length of the Sequence

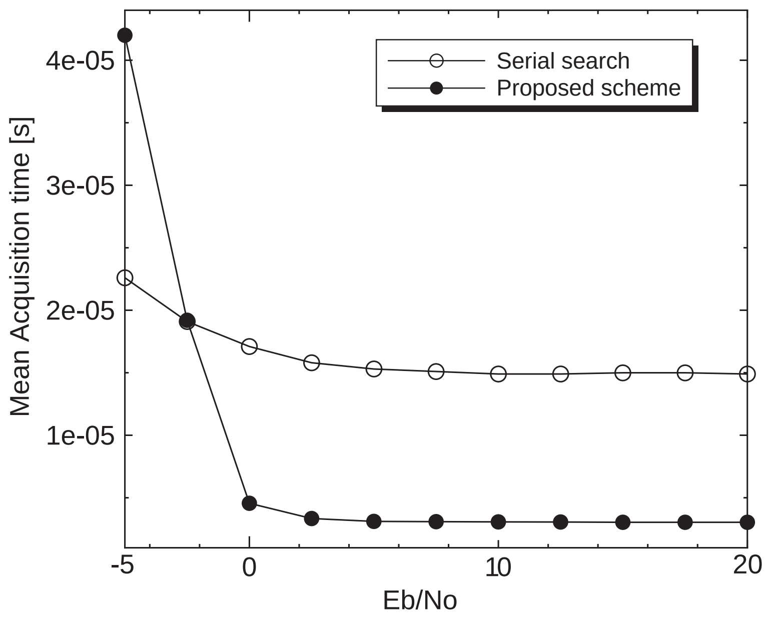

Figure 5.24: Mean Acquisition Time vs. E_b/N_0

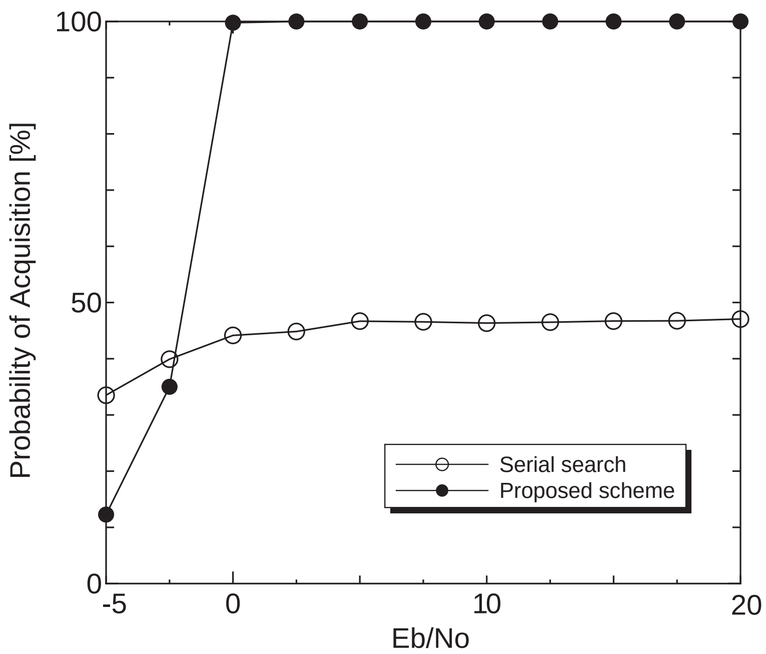

Figure 5.25: Probability of Acquisition vs. E_b/N_0, Limit time is $200T_i$

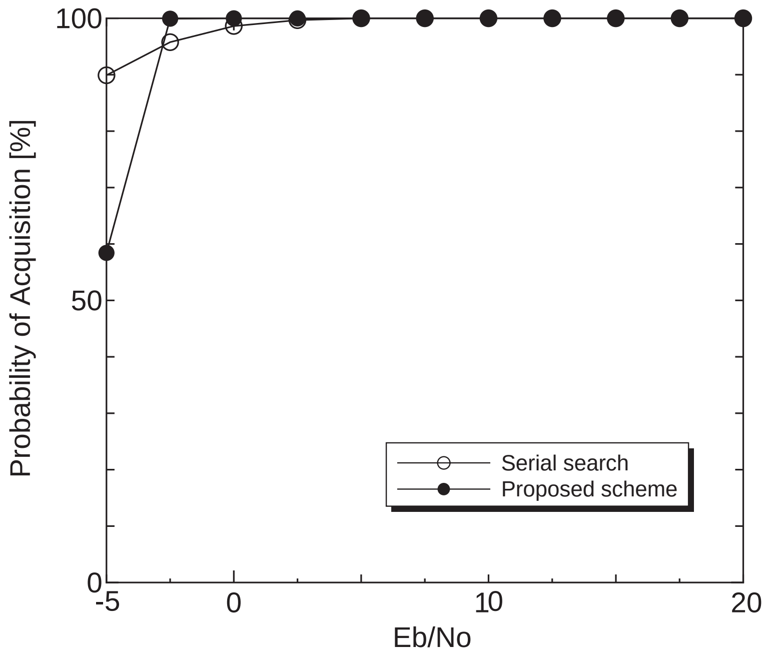

Figure 5.26: Probability of Acquisition vs. E_b/N_0, Limit time is $500T_i$

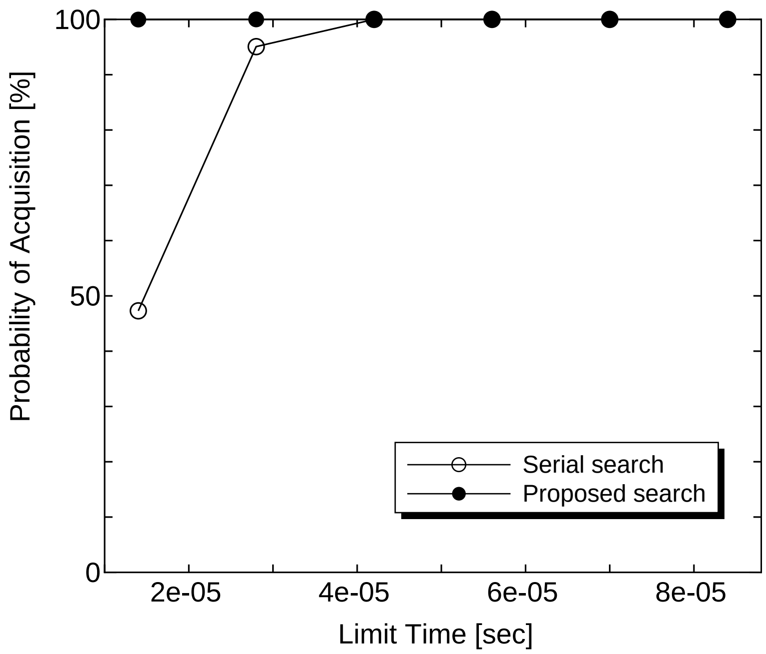

Figure 5.27: Probability of Acquisition vs. Acquisition Limit Time

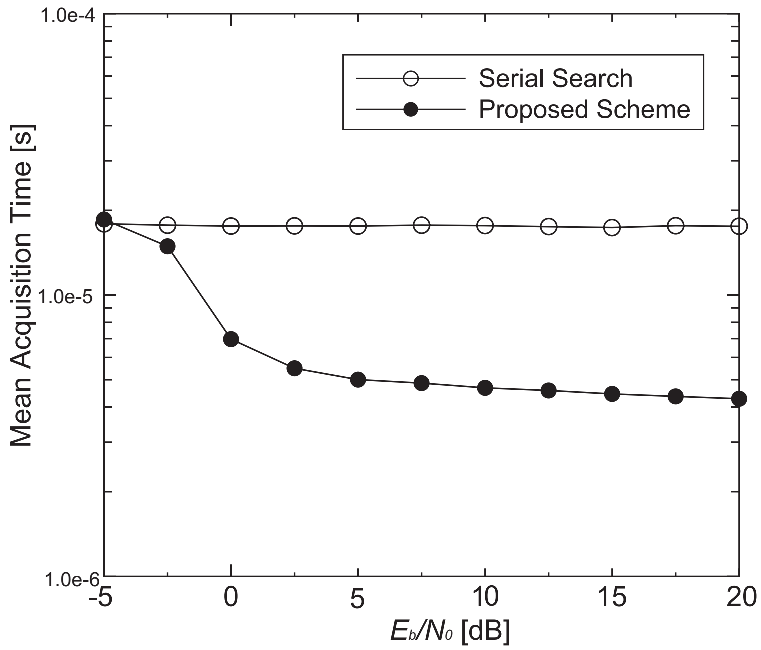

Figure 5.28: Mean Acquisition Time vs. E_b/N_0, 2 Users

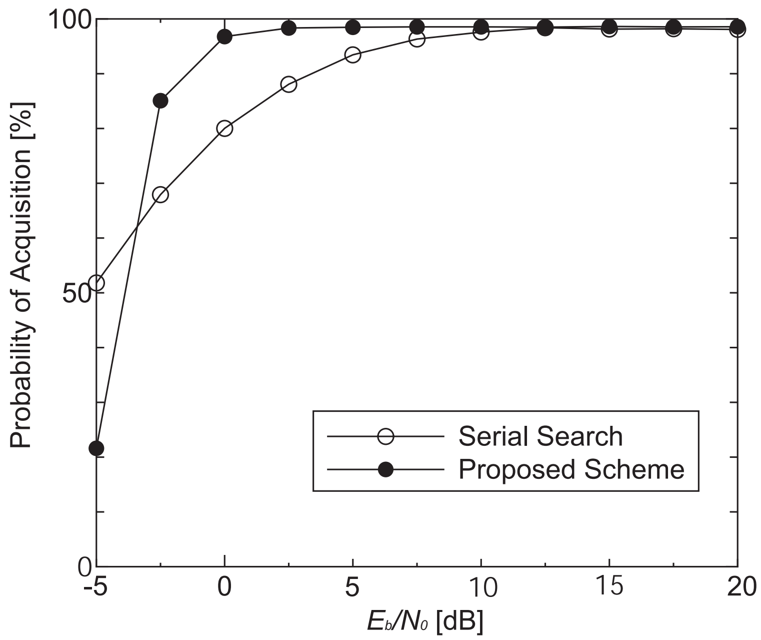

Figure 5.29: Probability of Acquisition vs. E_b/N_0, Limit time is $500T_i$, 2 Users

5.4.2 Simulation Results on Multipath Environments

5.4.2.1 Simulation Conditions

The simulation conditions are shown in Table 5.2. The threshold for the correlation value is changed as the stepsize is fixed to find the most suitable threshold in the conventional and the proposed acquisition scheme. Impulse responses in [34], sampling rate is fixed to 1/8 [ns]. Therefore, the stepsize is made 1/8. The value of the received SNR is more than the detection threshold, the acquisition is judged as success. According to [38], it is possible to achieve Bit Error Rate (BER) $< 10^{-5}$ if SINR ≥ 13.5 [dB]. Therefore, the detection threshold is set as SINR $= 13.5$ [dB].

Table 5.2: Simulation Conditions

1st Modulation	BPSK
2nd Modulation	DS-SS
Channel Model	IEEE802.15.4a [34]
Radio System	IR-UWB
Frame Time (T_f)	10.0 ns
Pulse Duration	1.0 ns
Step Size (Δt)	0.125 ns
Spreading Code	M-Sequence
Spreading Factor (N_s)	7
Number of Trials	$20,000$
Limit Time ($2 \cdot N_s T_f / \Delta t$)	1120 ns
Detection Threshold	$SNR = 13.5$ dB

5.4.2.2 Numerical Results

Fig. 5.30 shows the probability of success acquisition vs. E_b/N_0 on CM$1, 3, 5, 7$ which are the LOS. The probability of success acquisition of the proposed scheme has been improved 10 [dB] as compared to that of the serial search on CM1. The proposed scheme performs the same probability of success acquisition as the serial search on CM3, 5 and 7. Fig. 5.31 shows the mean acquisition time vs. E_b/N_0 on CM$1, 3, 5, 7$ which are the NLOS. Fig. 5.30 shows that the performance of the proposed scheme is 10 times better than that of the serial search on all the channels while the probability of success acquisition of both systems is not different on CM3, 5 and 7.

Fig. 5.32 shows the probability of success acquisition vs. E_b/N_0 on CM$2, 4, 6, 8$ which are the NLOS. The proposed scheme can reduce the required E_b/N_0 for 100 [%] acquisition from 2.5 [dB] up to 7.5 [dB] depending on the channel model. The proposed scheme is the same performance as serial search on CM4 when the probability of success acquisition is 100 [%]. Fig. 5.33 shows the mean acquisition time vs. E_b/N_0 on CM$2, 4, 6, 8$ which are the NLOS. The performance of the proposed scheme is 10 times better than that of the serial search on the all channels like LOS models.

Therefore, it is shown that the proposed system performs 10 times faster than the serial search on any channel models.

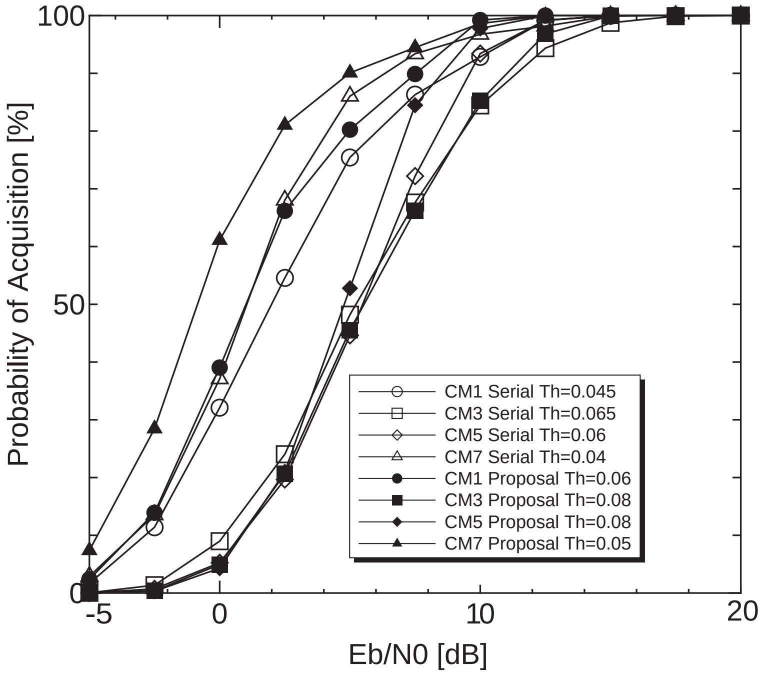

Figure 5.30: Success acquisition probability of the proposed scheme and the serial search vs. E_b/N_0 on CM1, 3, 5, 7

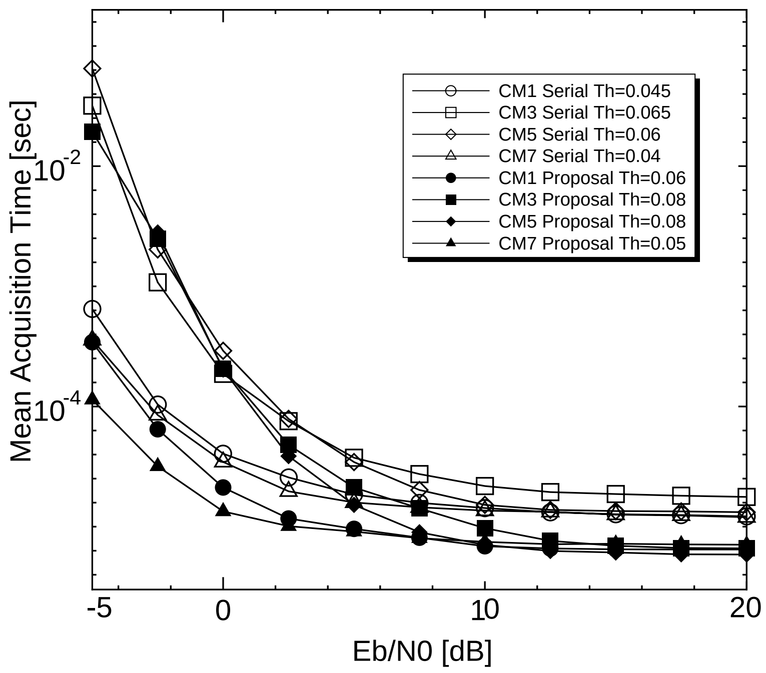

Figure 5.31: Mean acquisition time of the proposed scheme and the serial search vs. E_b/N_0 on CM1, 3, 5, 7

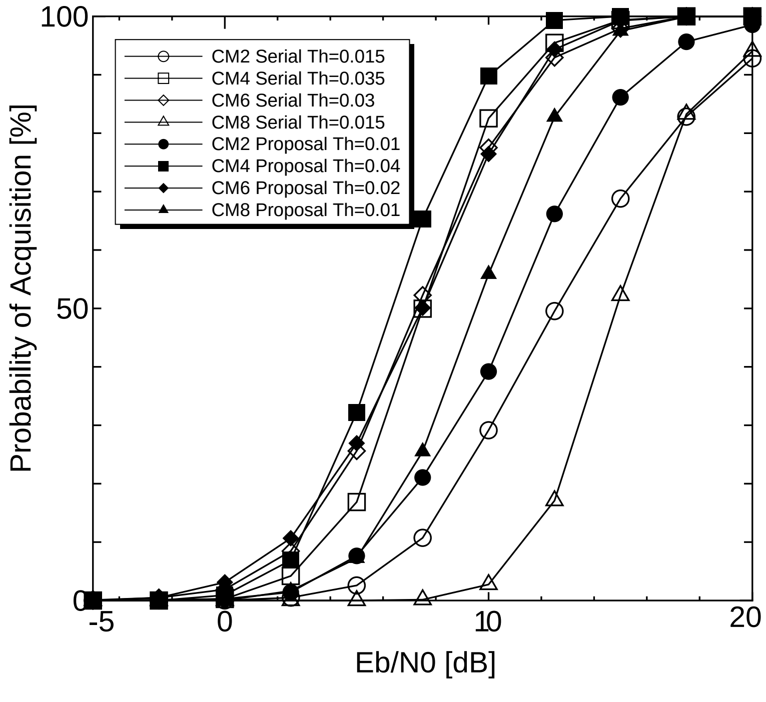

Figure 5.32: Success acquisition probability of the proposed scheme and the serial search vs. E_b/N_0 on CM2, 4, 6, 8

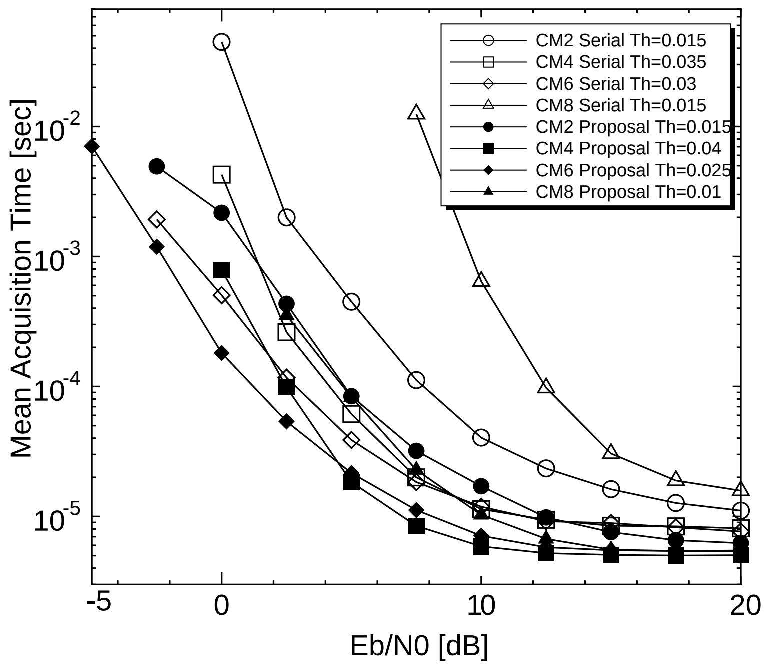

Figure 5.33: Mean acquisition time of the proposed scheme and the serial search vs. E_b/N_0 on CM2, 4, 6, 8

5.5 Conclusions

In this chapter, a novel initial acquisition scheme for the impulse based UWB system has been proposed and evaluated on the AWGN channel and the IEEE802.15.4a channel models through the computer simulations. The aim of the two stage acquisition scheme is to reduce the acquisition time with the hardware of the two stage acquisition scheme being the same complexity as that of the serial search. Actually the acquisition time of the proposed scheme can be shortened as compared to that of the serial search. Especially, the acquisition time of the proposed scheme can be shorter than that of the serial search in the case of the long spreading factor. In addition to the same acquisition period, the probability of acquisition of the proposed scheme is better than that of the serial search.

Chapter 6

Conclustions

6.1 Overall Conclusions

The aim of this thesis was to investigate and develop the optimal MAC protocols for UWB ad-hoc networks in order to extend the communication range and keep high transmission data rate. This thesis has proposed the MAC protocols including the routing and the retransmission system.

In the beginning of this thesis, the novel routing schemes for the UWB ad-hoc network have been proposed and evaluated. In the proposed scheme, variable spreading factor in proportion to the distance between nodes and packet forwarding zone have been implemented. This way of changing the spreading factor can extend the communication range with keeping Quality of Service (QoS) such as the received SNR. Our proposal is the location based routing system to adjust to the variable spreading factor. As the spreading factor becomes large, the power consumption increases and the transmission data rate decreases. The routing system is proposed to prevent the spreading factor from increasing. The results have shown that this way can solve the key issues of UWB systems such as the low transmission power of UWB systems. In addition, this proposed scheme has improved the effective data rates compared to the conventional routing systems, fixed spreading factor DS-SS systems and singlehop transmission. It has been shown that multi-hop transmission is very effective if the number of the node is many enough.

The above-mentioned system has used Pure ALOHA as MAC protocol. The number of packet loss is large. In general, mobile radio systems have used CSMA protocols. CSMA protocols are the standard protocol of IEEE802.11. However, UWB systems are quite different from other radio systems with the view of the low transmission power like noise and impulse shape wave. The conventional CSMA is not suitable for DS-UWB ad-hoc networks in term of the low transmission power. The conventional CSMA protocols cannot distinguish between signals and noise. The code sense scheme has been proposed as the novel MAC protocol for UWB systems. This scheme utilizes the correlation value among each sequence code. The correlation value can be got if the power of signals is less than that of noise. Thus, In order to show that code sense scheme can be used as MAC protocols for UWB systems like the conventional CSMA protocols for IEEE802.11 and the performance of code sense scheme is better than that of ALOHA systems, we have evaluated this scheme and ALOHA systems in UWB ad-hoc networks through computer simulations. As the result, this proposed scheme has shown better data rate performance compared to Pure ALOHA.

Moreover, we have investigated the retransmission scheme. Retransmission is required in packet communications in order to compensate for the packet loss and improve the network throughput. The common way through retransmission is requested is an ARQ system with ACK and NACK signaling packets. These methods can improve the throughput and reliability of the network, but the extra packets required increase the total system interference. To reduce the influence of the number of ACK packet, the retransmission scheme with CS scheme has been proposed. The performance of CS has been shown through simulations. Our proposed CS scheme has been able to outperform the conventional ARQ retransmission system. The probability of a successful transmission with CS is about 20 % better than that with the conventional retransmission system. This scheme can be used after communication links is established. We should consider the initial stage before communication link is established.

Finally, a novel initial acquisition scheme for the impulse based UWB system has been proposed. The acquisition time of the proposed scheme can be shortened as compared to that of the serial search. Especially, the acquisition time of the proposed scheme can be shorter than that of the serial search in the case of the long spreading factor. With the same acquisition period the probability of acquisition for the proposed scheme is better than the serial search.

This thesis has proposed basic ideas such as variable spreading factor, code sense, and the two stage acquisition scheme for UWB ad-hoc networks. The those proposals still have the problems which should be solved. Examples are shown as follows.

Our routing scheme can show better performance as compared to the conventional schemes. This thesis assumes that a packet is relayed after a node finishes to receive it perfectly in each hop. However, we have not considered about the time and the power spent by each hop. Also, we have not considered about the streaming communications. Besides, if nodes will move randomly, the performance of the code sense scheme will decrease because of reducing the accuracy of the node location estimation. We have to correspond to the case that the nodes are moving. Moreover, our proposed CSMA and retransmission scheme has been using the code sense scheme. The code sense scheme is based on the correlation of the spreading codes. The performance of the code sense scheme depends on the orthogonal of the spreading codes. Large improvement of the system performance will be able to be succeeded by changing the spreading factor more precisely according to the distance. On the other hand, this scheme assumes that each node knows the spreading code of other nodes. Originally, the spreading code of DS-SS systems has been used to protect the security of communications. This is because nobody can know other communications without its spreading code. We have to consider about the security problem. I would like to investigate this problem, the performance of code sense scheme in other conditions, the streaming transmission in UWB ad-hoc networks in future work.

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Chapter 7

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Chapter 8

List of Papers by Author

8.1 Transaction Papers

1. W. Horie, T. Inaba and Y. Sanada, “Performance of Two Stage Acquisition Scheme with Squared Circuit for Impulsed-Based UWB System,” submitted to IEEE Journal on Selected Areas in Communications.

2. W. Horie, K. Voulgaris, M. Ghavami and Y. Sanada, “Retransmission Scheme for DS-UWB Ad-hoc Networks with Variable Spreading Factor,” submitted to IEEE Journal on Selected Areas in Communications.

3. W. Horie and Y. Sanada, “Novel CSMA Scheme for DS-UWB Ad-hoc Network with Variable Spreading Factor,” IEICE Trans. on Fundamentals, Vol. E87 - A, No.10, pp.2615 – 2620, Oct. 2004.

4. W. Horie and Y, Sanada, “Novel Packet Routing Scheme based on Location Information for UWB Ad-hoc Network,” IEICE Trans. on Fundamentals (Japanese Edition)., vol. J86-A, no. 12, pp. 1493 – 1501, Dec. 2003.

8.2 International Conferences

1. W. Horie, T. Inaba, and Y. Sanada, “Performace of Two Stage Acquisition Scheme with Squared Circuit for Impulsed-Based UWB System on Multipath Environments,” in Proc. International Conference on Ultra Wideband 2006, pp.25-29, Waltham, USA, Sept. 2006.

2. K. Nishioka, W. Horie, and Y. Sanada, “Wireless and Battery-Less High-Speed Communication Module using Spread Spectrum Modulation,” in Proc. the Eighth International Symposium on Wireless Personal Multimedia Communications, vol. III, pp. 1920 – 1924, Aalborg, Denmark, Sept. 2005.

3. W. Horie, Y. Sanada, and M. Ghavami, “Retransmission Scheme with Code Sense for VSF/DS-UWB Ad-hoc Network,” in Proc. International Workshop on Wireless Ad Hoc

Networks 2005, London, United Kingdom, May. 2005.

4. W. Horie and Y. Sanada, “Retransmission Scheme for DS-UWB Ad-hoc Network with Variable Spreading Factor,” Proc. of the Seventh International Symposium on Wireless Personal Multimedia Communications, Vol. 2, pp. 154 – 156, Abano Terme, Italy, Sept. 2004.

5. W. Horie and Y. Sanada, “Novel CSMA Scheme for DS-UWB Ad-hoc Network with Variable Spreading Factor,” Proc. of Joint International Workshop on Ultra Wideband Systems & IEEE Conference on Ultra Wideband Systems and Technologies 2004, Kyoto, May 2004.

6. W. Horie and Y. Sanada, “Novel Packet Routing Scheme based on Location Information for UWB Ad-hoc Network,” Proc. of IEEE Conference on Ultra Wideband Systems and Technologies 2003, pp. 185 – 189, Reston, Nov. 2003.

8.3 Technical Reports and Other Presentations (in Japanese)

1. W. Horie, T. Inaba, and Y. Sanada, “Performace of Two Stage Acquisition Scheme with Squared Circuit for Impulsed-Based UWB System on Multipath Environments,” IEICE Technical Report, IT2005-70, ISEC2005-127, WBS2005-84, pp. 37 – 42, Dec. 2005.

2. W. Horie and Y. Sanada, “Retransmission Scheme for DS-UWB Ad-hoc Network with Variable Spreading Factor,” IEICE Technical Report, SIP2004-47, WBS2004-28, pp. 13 – 15, July 2004

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4. W. Horie and Y. Sanada, “Novel Packet Routing Scheme based on Location Information for UWB Ad-hoc Network,” IEICE Technical Report, WBS2003-4, MW2003-16, pp. 19 – 25, Apr. 2003