Throughput Based Study of UWB Receiver Modem Parameters

Byoung-Jo Choi, *Member, KIMICS*

Abstract—The MB-OFDM based UWB communication system is a personal area network specification aiming to provide 480Mbps peak data rate over 528 MHz spectrum. As the corresponding baseband modem operates at high clock rate, its complexity should be optimized for low power consumption. A set of modem design parameters is suggested including the AD bit width, the clipping level and the quantization level at the Viterbi decoder input as well as the trace-back depth of the Viterbi decoder. The data throughput is used to evaluate the performance of the receiver and a recommended set of design parameter values is presented to aid efficient modem implementation.

Index Terms—MB-OFDM, Modem, UWB, Viterbi decoder

I. INTRODUCTION

Although the term 'UWB' is relatively new, the history of ultra-wideband communication dates back to the early days of Marconi's wireless telegraph system, which employs simple on-off switching. These switched pulses take up very large RF spectrum. Since frequency becomes very scarce resource, many modern communication systems aim to use as small bandwidth as possible while transmitting the intended information. For example, GSM/EDGE transceivers are using 200 KHz bandwidth. Even the latest LTE (Long Term Evolution) standard will use at most 20MHz. On the other hand, spread-spectrum techniques, such as CDMA, have enjoyed wide-spread popularity for their robustness against interferences and accurate ranging capability. Their signals also display low power spectral density, which enables coexistence with other communication devices occupying the same frequency band.

In 2002 FCC allowed the commercial use of UWB, which had been restricted to military use [1-3]. A UWB signal is defined such that it occupies more bandwidth than 20% of the center frequency or its bandwidth exceeds 500MHz. Currently FCC is restricting the USB transmission signal power below -41.25dBm over the spectrum spanning from 3.1GHz to 10.6GHz [3]. As WiMax and WiFi devices are expected to operate within this spectrum as well, UWB employs DAA (Detect and Avoid) not to interfere with these devices [4]. The DAA enabled UWB devices will become the first commercial example of much touted cognitive radios [4]. Two competing technologies have been proposed for UWB communications; impulse radio and MB-OFDM (Multi-Band Orthogonal Frequency Division Multiplexing) [5]. Impulse radio is a time domain technique employing very short pulse, hence its name. On the other hand MB-OFDM employs a frequency domain technique. The MB-OFDM based UWB specification is targeting to provide high data rate up to 480 Mbps over several tens of meters, thus replacing wired USB with wireless counterpart [5]. As an MB-OFDM based UWB modem operates at high clock rate, its power consumption should be minimized [1]. As a general rule, the power consumption is proportional to its complexity. Some key design issues related to the MB-OFDM based UWB systems was presented in [1]. However, the detailed study on the baseband modem design issues was omitted. The ADC requirement of MB-OFDM based UWB systems was also studied in comparison to OFDM-based WLANs [8]. Our main focus here is to study the effect of modem design parameters, such as the clipping level at ADC as well as at Viterbi decoder input, the ADC bit-width, the trace-back depth of Viterbi decoder, on the receiver performance in terms of the throughput. We developed a fixed point model as well as a floating point model to evaluate some modem design parameters. The model represents a complete chain of a transmitter, UWB indoor wireless channel and the receiver.

A brief overview of MB-OFDM based UWB specification is presented in Section II. Our UWB transceiver model is presented in Section III, where the transmitter, the receiver and the UWB indoor channel are detailed. The effects of various modem design parameters are evaluated in Section IV in terms of the receiver throughput. Our conclusion is presented in Section V with the recommended modem design parameters.

II. OVERVIEW OF MB-OFDM BASED UWB

The frequency band and band groups are depicted in Fig. 1 [5]. The entire UWB spectrum spanning from 3.1GHz to 10.6GHz is divided into 14 bands of 528MHz each. Two or three bands form a band group. Frequency hopping between bands within a band group may be used to take advantage of frequency diversity. When a legacy device is using a specific band, the band may be marked

Manuscript received February 9, 2008; revised May 5, 2008. Byoung-Jo Choi is with Multimedia Systems Engineering Dept., University of Incheon, Incheon, 402-749, Korea (Tel: +82-32-770-8765, Fax: +82-32-770-8760, Email: bjc97r@incheon.ac.kr)

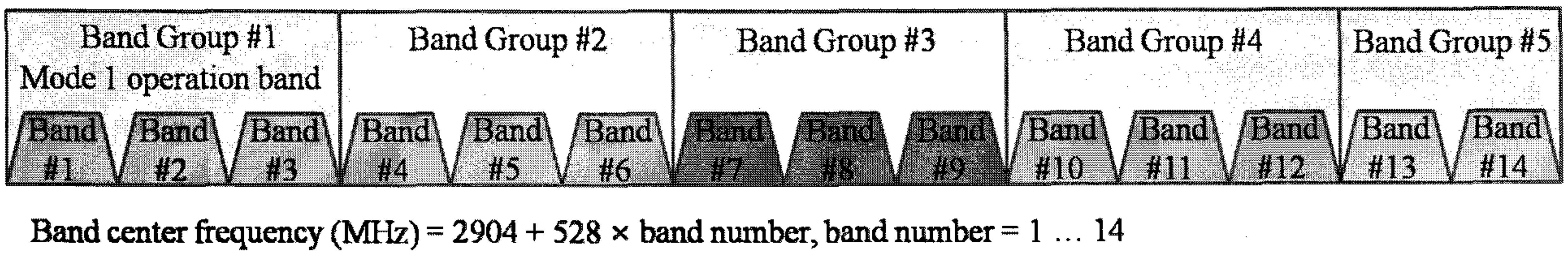


Fig. 1 Frequency band of MB-OFDM based UWB system

as 'not available' in order to avoid service disruption at the device due to a UWB device. It is expected that the bandwidth used by a legacy device is much smaller than the overlapping 528MHz. In this case a so-called active interference cancellation technique [6] may be employed at a MB-OFDM based UWB device in order to create a deep null at the overlapped portion of the spectrum with the entire band of 528MHz.

Fig. 2 exhibits a stylized block diagram of a typical MB-OFDM based UWB transceiver. As one can observe in the figure, a convolutionally encoded and interleaved binary stream is mapped into each subcarrier for OFDM transmission. The IFFT block transforms a set of frequency domain symbols into a time domain signal using 128-point inverse FFT operation. Unlike a traditional OFDM transmitter employing a CP (cyclic prefix), an MB-OFDM based UWB transmitter inserts ZPX (Zero Padded suffiX) at the end of each OFDM symbol. While a ZPX assisted OFDM signal exhibits a slightly high PAPR (Peak-to-Average Power Ratio) in comparison to a CP assisted OFDM signal, it saves the transmission power and the corresponding receiver performance is comparable to that of a CP assisted receiver [1,7].

Time domain spreading and/or frequency domain may be applied to a set of modulated symbols obtained from the constellation mapping block in order to increase the transmission reliability incorporating additional diversities. This operation is controlled by TFC (Time-Frequency Code) depending on the intended data rate. These rate-dependent parameters are summarized in Table 1 [5]. Time domain spreading is achieved by transmitting the same information on the consecutive OFDM symbols twice. On the other hand, frequency domain spreading repeats the modulated symbols twice over the subcarriers after complex-conjugation operation. The same information bearing symbols are symmetric to the DC subcarrier and hence generate a real signal without any imaginary part. This symmetric arrangement reduces the hardware complexity of the transceiver. The data rates shown in Table 1 are decided by the corresponding coding rate as well as time-frequency spreading schemes. They all share the same convolutional mother code of rate 1/3 but employ different puncturing patterns, which enables a receiver to decode all the encoded data with different data rates with a single Viterbi decoder.

A set of physical layer parameters for MB-OFDM based UWB systems is depicted in Table 2. The bandwidth of each frequency band is 528MHz and there are 128 subcarriers separated by 4.125MHz between them. Among these 128 subcarriers information bearing symbols are mapped on to 100 data subcarriers and pilot symbols are interspersed over 12 subcarriers. In order for reducing interference to adjacent bands MB-OFDM based UWB systems employ 10 number of guard subcarriers and 6 number of null carriers. An OFDM symbol interval is given as 312.5 ns by adding a FFT period of 242.42 ns and ZPX duration of 70.08 ns. When the channel delay spread exceeds the ZPX duration, there may be inter-symbol interference causing some performance degradation.

Table 1 Rate-dependent time-frequency spreading parameters

Data Rate (Mbps)	Modulation	Coding Rate	FDS	TDS
53.3	QPSK	1/3	YES	YES
80.0	QPSK	1/2	YES	YES
106.7	QPSK	1/3	NO	YES
160	QSPK	1/2	NO	YES
200	QPSK	5/8	NO	YES
320	DCM	1/2	NO	NO
400	DCM	5/8	NO	NO
480	DCM	1/2	NO	NO

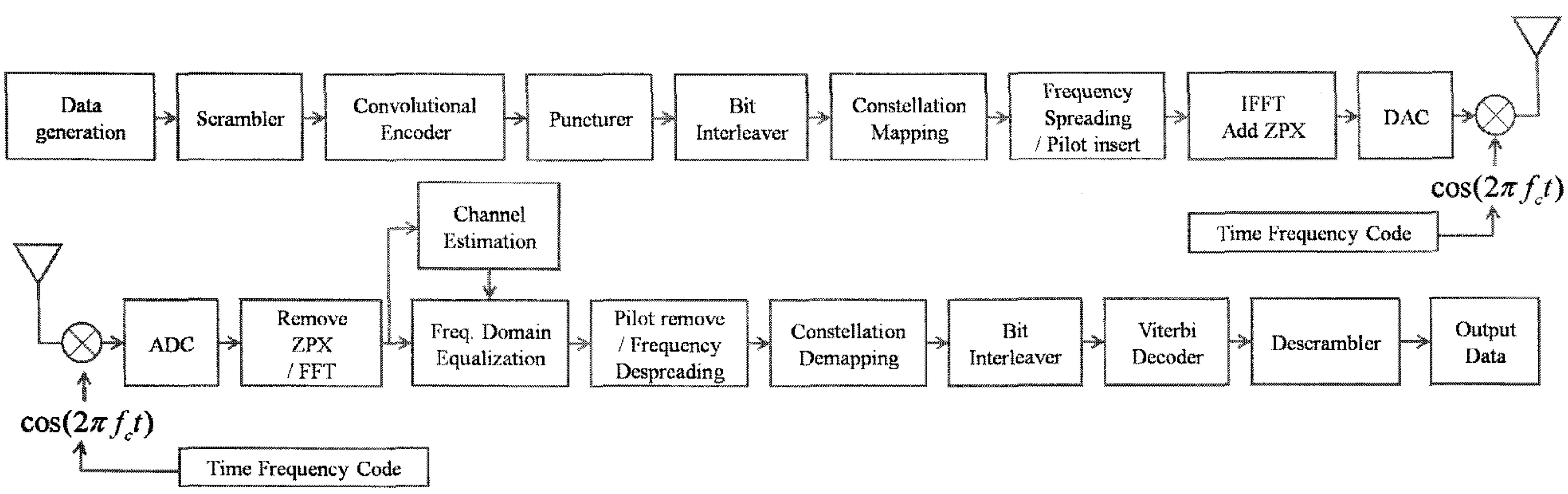


Fig. 2 A stylized block diagram of a typical MB-OFDM based UWB transceiver

Table 2 Physical layer parameters of MB-OFDM based UWB system

Parameter	Value
Bandwidth	528 MHz
FFT size	128
Number of data subcarriers	100
Number of pilot subcarriers	12
Number of guard subcarriers	10
Subcarrier frequency spacing	4.125 MHz
FFT period	242.42 ns
OFDM symbol interval	312.5 ns
Modulation	QPSK/DCM

The frame structure of MB-OFDM based UWB signal is depicted in Fig. 3. A frame consists of a PLCP (Packet Layer Convergence Protocol) preamble, a PLCP header and a PSDU (PHY Service Data Unit). The PLCP preamble is used for timing synchronization, carrier frequency offset correction and channel estimation. The first two parts depicted in Fig. 3 [5], namely a packet synchronization sequence and a frame synchronization sequence, are time-domain generated signals. On the other hand, the third part of PLCP preamble is OFDM-based frequency-domain generated signals like PLCP header and PSDU symbols. The PLCP header carries a PHY header and a MAC header is double-protected by convolutional code as well as Reed-Solomon code. Tail bits are inserted after the PHY header and the MAC header in order to enable the receiver to decode each header separately. The last part of the frame carries a variable length payload data and the checksum of the data for error detection.

III. MODELING AN MB-OFDM BASED UWB TRANSCEIVER

The authors implemented a fixed point model as well as a floating point model of an MB-OFDM based UWB transceiver including UWB channel for link simulation. Our transmitter model conforms to ECMA standard [5] and our receiver model assumes perfect synchronization and channel estimation. The implemented channel model represents various indoor scenarios at UWB frequency bands. Depending on the distance between the transceivers and on the existence of an LOS (line-of-sight) signal, the UWB channels are categorized as CM1~CM4 [9]. For example, CM1 represents the scenario where the distance lies between 0~4m and an LOS signal is available, while CM4 corresponds to the scenario where no LOS signal is available and the distance ranges between 4~10m [1,9].

Fig. 4 illustrates our receiver operation to detect one OFDM symbol. The receiver samples the received signal at 528 Msps and applies AD conversion. The data part depicted in Fig. 4 represents 128 samples of IFFT output at the transmitter and the ZPX part represents a period where no signal exists. The UWB channel effectively performs a linear convolution operation on the transmitted signal and the channel impulse response. The CP-assisted OFDM systems convert this linear operation into a circular convolution such that each frequency domain symbol may be represented as a simple product of the original transmission symbol and the frequency response of the channel at the corresponding subcarrier. One-tap frequency domain equalizer may be used for CP-based OFDM systems due to this circular convolution property. Since MB-OFDM based UWB systems use ZPX instead of CP, we need some mechanism which can convert the linear convolution of the channel into a circular one.

Our receiver model employed OLA (overlap and add) scheme [7], which copies the last 37 received samples and adds to the first 37 samples. The OLA scheme makes ZPX-assisted OFDM system equivalent to CP-assisted OFDM using a simple operation. We applied FFT to 128 samples obtained through OLA operation in order to obtain frequency domain symbols. A one-tap frequency domain equalizer was used to compensate the effects of the channel fading on the received frequency domain symbols.

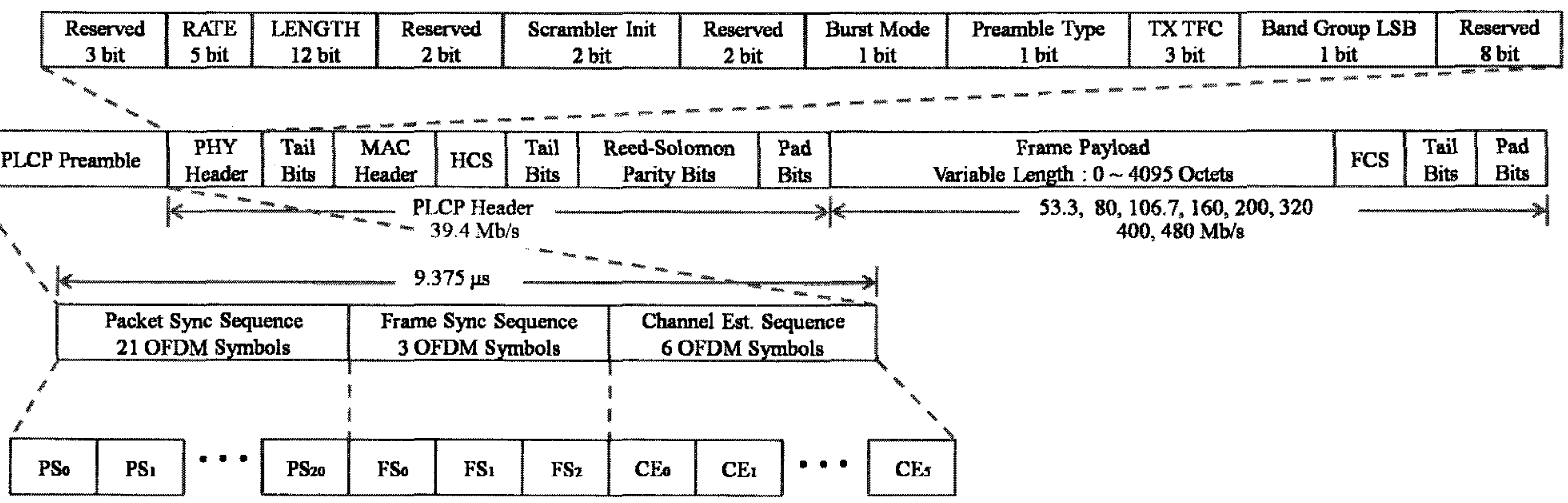


Fig. 3 Frame structure of MB-OFDM based UWB signal

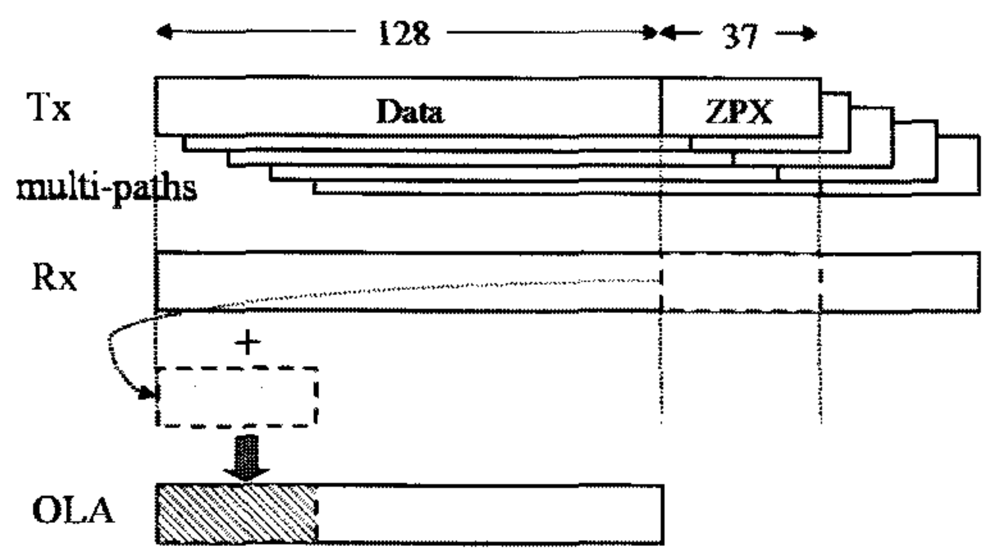


Fig. 4 Overlap and add operation at our MB-OFDM UWB receiver

These channel-compensated frequency domain symbols are combined according to the time-frequency spreading rule depicted in Table 1. When FDS is applied, two symbols bearing the same information are transmitted using an OFDM symbol but at two different subcarriers. These two received symbols are combined after complex-conjugation operation. When TDS is applied, two symbols bearing the same information are transmitted over two consecutive OFDM symbols. In this case, a pair of OFDM symbols is processed together to get combined frequency domain symbols. These combined symbols are de-interleaved and de-punctured to arrive at the Viterbi decoder.

IV. EVALUATION OF DESIGN PARAMETERS

The receiver performance in terms of its data throughput was evaluated for various set of fixed-point design parameters. The data throughput may represent the corresponding user experience more accurately than the other performance criteria, such as BER (bit error rate) or BLER (block error rate). Firstly, the floating point performance was evaluated, as it corresponds to infinite resolution fixed point scenario. We restrict our attention to the devices supporting data rates up to 200 Mbps supporting QPSK modulation only.

A. Floating-Point Performance

The data throughput was evaluated for the five number of different data rates transmitting over AWGN channel using our floating point receiver model. Fig. 5 depicts our results where the actual throughput was drawn against SNR values. Since the channel is assumed to be AWGN, the SNR values depend on the distance from the transmitter. Specifically high SNR values correspond to the scenario where the receiver is near to the transmitter and low SNR values corresponds to the opposite scenario.

The figure illustrates the benefit of adaptive coding combined with time-frequency spreading. The two low-rate schemes, namely 53.3Mbps and 80.0Mbps, both use FDS as well as TDS as described in Table 1. The data rate difference comes from their different coding rates. One can observe in Fig. 5 that when the SNR becomes higher than -3.6dB it is advantageous to use 80.0Mbps scheme in terms of the data throughput in comparison to

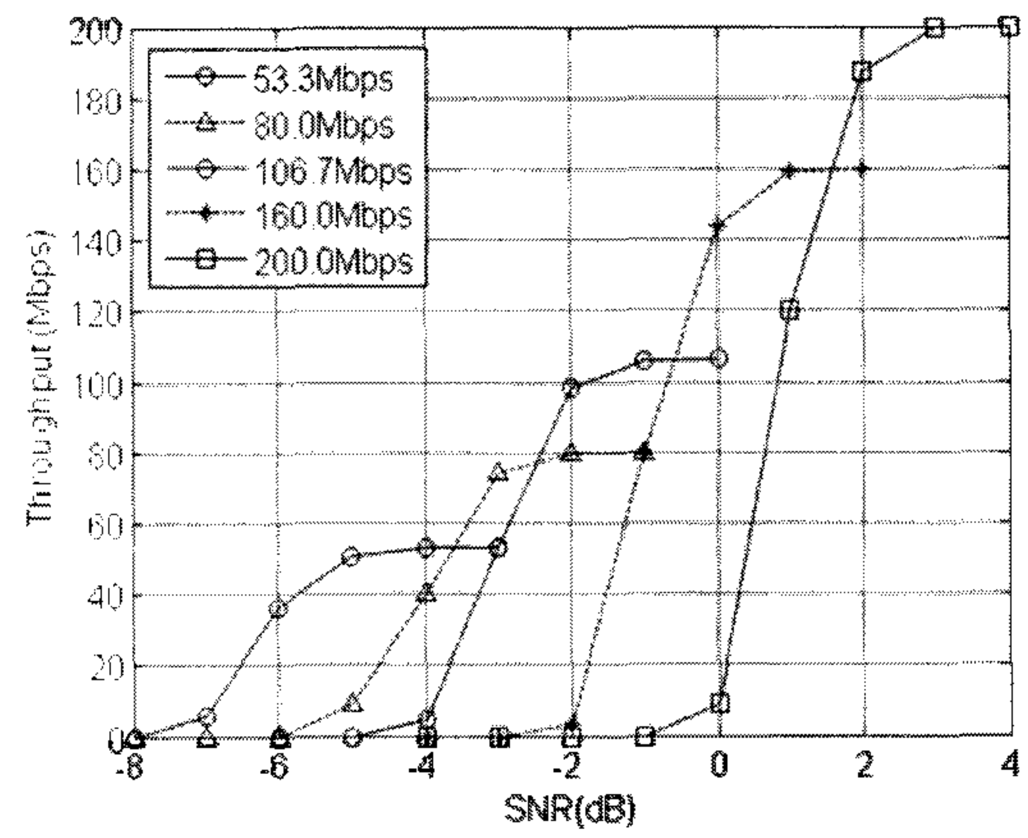


Fig. 5 Throughput performances of floating-point receivers over AWGN channel

using 53.3Mbps scheme. The next two higher data-rate schemes, namely 106.7 Mbps and 160 Mbps, employ the same coding rates as 53.3Mbps and 80.0Mbps, respectively. However, they do not use FDS unlike the two lower data-rate schemes. Sacrificing the additional frequency domain diversity, they exhibit double the data rate when the SNR value is high enough. Lastly, when the SNR value is greater than 1.5dB, the 200Mbps scheme exhibits the highest throughput among the investigated schemes.

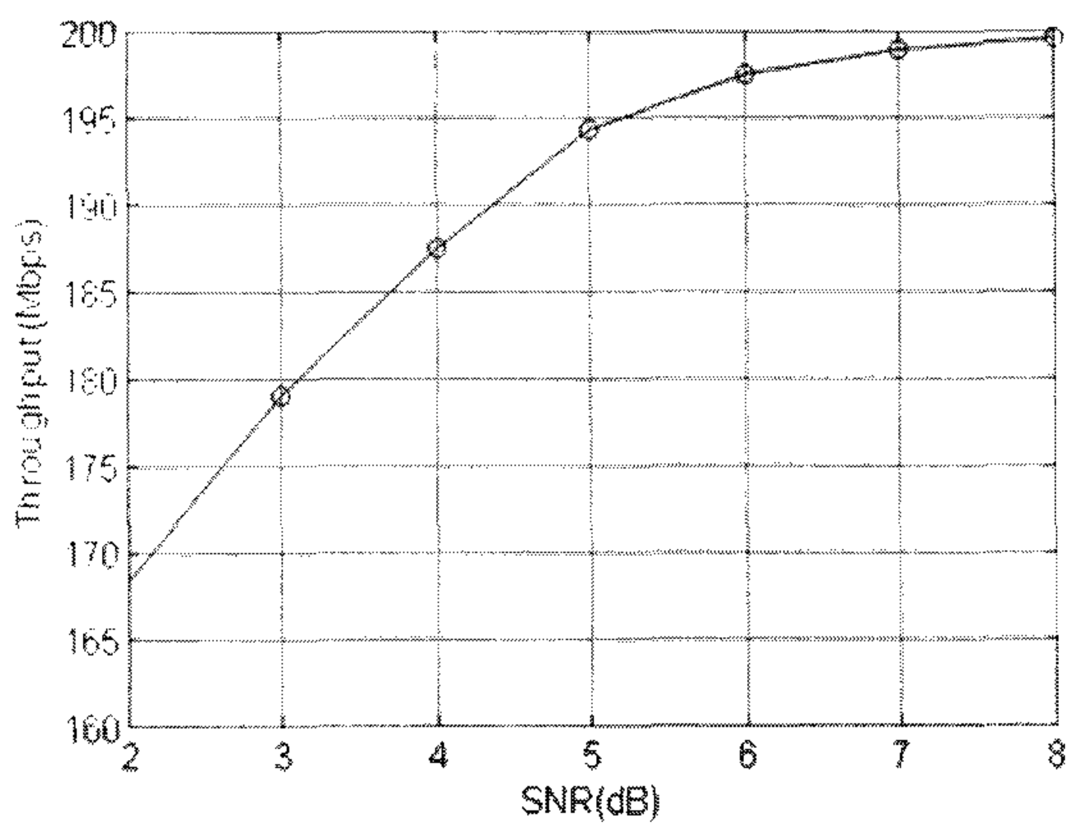


Fig. 6 Throughput performance of floating point receiver: CM1 channel, 200Mbps

Fig. 6 depicts the data throughput of the 200Mbps scheme operating over CM1 UWB indoor channel. Comparing the right-most throughput curve in Fig. 5 and the curve in Fig. 6, we can observe that CM1 channel degrades the through performance. The throughput values depicted in Fig. 6 represent the upper-bound for fixed-point receivers with various design parameters investigated in the next subsection.

B. Fixed- Point Performance

At the forefront of any digital modem is an AD converter. The most important design parameters for the AD converter are the sampling frequency and the bit resolution. As the sampling frequency is given as 528Msps, we investigated the effect of the bit resolution on the throughput performance. The OFDM signal is known to exhibit high PAPR resulting in high dynamic range in its magnitude [10]. Evaluating the signal distribution, we found that the magnitudes of OFDM signals followed a Gaussian distribution. Clipping at the highest 5% signal values and the lowest 5% signal values, we could reduce the dynamic range of signal by half. We applied this clipping scheme throughout our evaluations.

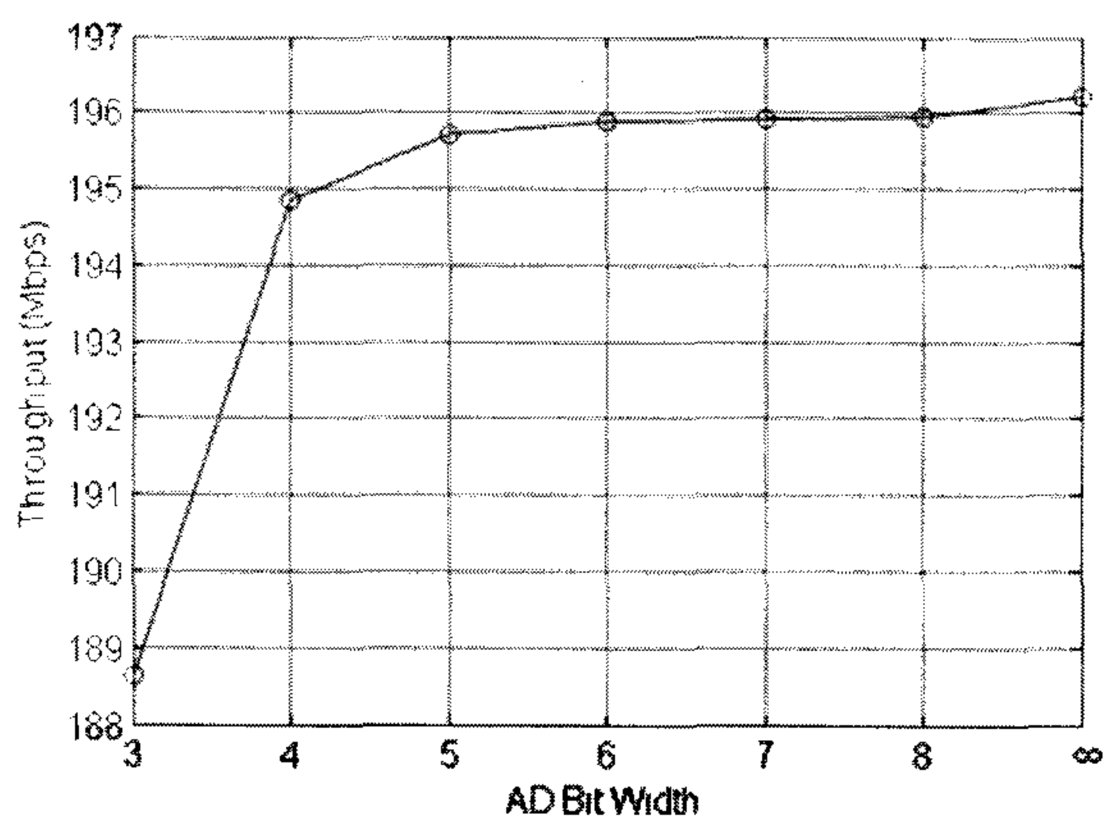


Fig. 7 Throughput performance of fixed-point receiver: CM1 channel, 200Mbps, SNR=5.5dB

Fig. 7 depicts the data throughput of the 200Mbps scheme operating over CM1 channel for the AD bit resolution values ranging from 3 bits to 8 bits when the SNR was set to 5.5dB. The remaining blocks were left floating point in order to isolate the effect of AD converter alone. The right-most value, marked as ∞ corresponds to that of the floating point receiver. It was observed that the AD resolution of 4 bit is as good as higher 5 to 8 bits exhibiting less than 0.5% throughput degradation. On the other hand, the 3 bit AD resulted in 3.5% throughput degradation.

The next fixed-point design blocks following the AD converter include a frequency domain equalization block, a TDS/FDS combining block and a FFT block. The fixed-point design parameters of these blocks may be dependent on the employed specific algorithms. Instead of investigating these individual blocks, let us focus on the combined bit resolution right before the Viterbi decoder, leaving all the intermediate blocks between the AD converter and the Viterbi decoder as floating-point blocks. The measured PDF (probability density function) of the signals at the Viterbi decoder input is depicted in Fig. 8. The PDF would have followed a combined distribution of two Gaussian variables centered at a positive and a negative mean value if the channel were AWGN. It should be noted that the values at the x-axis of the PDF may vary up to a scaling factor depending on the implementation of the blocks between the AD converter and the Viterbi decoder. Once again clipping was introduced for the values in order to reduce the overall dynamic range. Various values of clipping levels were investigated and two clipping levels were chosen for evaluating the throughput performance against the soft-decision bits at the Viterbi decoder.

Fig. 9 depicts the evaluated throughput performance for the various soft-decision bit resolutions at the Viterbi decoder input. The values marked as 'Max' correspond to the scenario where 5-bit AD is used while floating-point soft-decision input is applied to the Viterbi decoder. The right most values marked as ∞ correspond to the floating-point receiver. Two of clipping levels were considered. When the clipping level was increased beyond 0.02, the throughput performance was degraded. The lower clipping level than 0.015 also resulted in reduced throughput performance. It is interesting to note that these two clipping levels are lower than the conjectured mean value range, which is thought to be around 0.03. It can be observed in Fig. 9 that the 3-bit soft-decision degrades the throughput performance by 8% in comparison to the ideal case, while 4-bit results in less than 1% penalty, when used with the clipping level of 0.015.

The effect of the Viterbi decoder trace-back depth on the throughput performance is shown in Fig. 10. It has been reported that the trace-back depth of 4~5 times the constraint length is sufficient for Viterbi decoding. As the constraint length of the convolutional code employed in MB-OFDM based UWB is 7, our 4-bit results corroborate the literature showing that the trace-back lengths of 24, 32 and 48 resulted in 3.1%, 1.3% and 0.3% throughput degradation in comparison to the case for the length of 96.

V. CONCLUSIONS

We developed a fixed-point model as well as floating-point model of an MB-OFDM based UWB transceiver in order to evaluate the fixed-point modem design parameters in terms of data throughput performance. Restricting our attention to a low cost model supporting up to 200 Mbps data rate, a set of parameters was evaluated including the AD converter resolution, the Viterbi decoder soft-decision resolution and the trace-back depth as well as various saturation levels. It was found that the AD bit resolution of 3 bit resulted in 3.7% throughput degradation, while 4 bit resulted in 0.6% degradation, in comparison to the case employing 8 bits. For the Viterbi decoder soft-decision resolution, it was found that 3 bits and 4 bits resulted in 8% and 1% performance degradation in comparison to the case employing infinite resolution. The saturation levels for reducing the signal dynamic range and, hence, for better use of bit resolution were studied as well and 5% clipping was recommended at the AD converter and clipping at 0.015 at Viterbi input in our context was reported to yield the best trade-off.

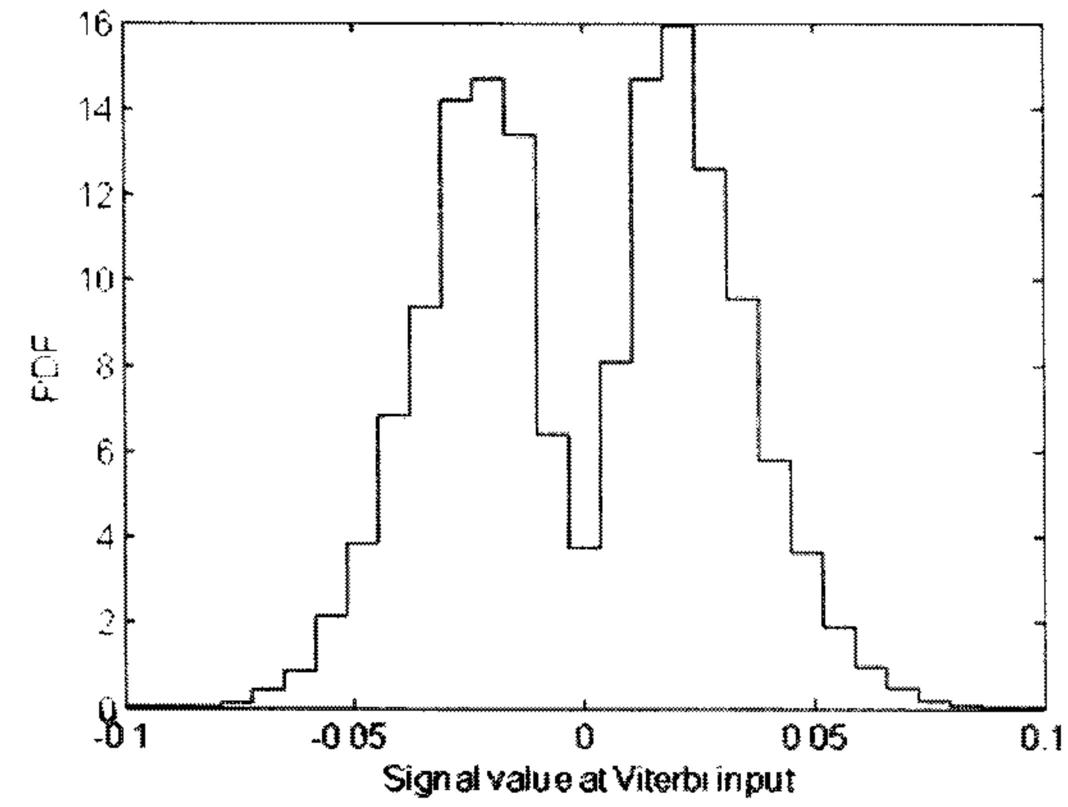


Fig. 8 PDF of signal at Viterbi input; CM1 channel, 200Mbps, SNR=5.5dB

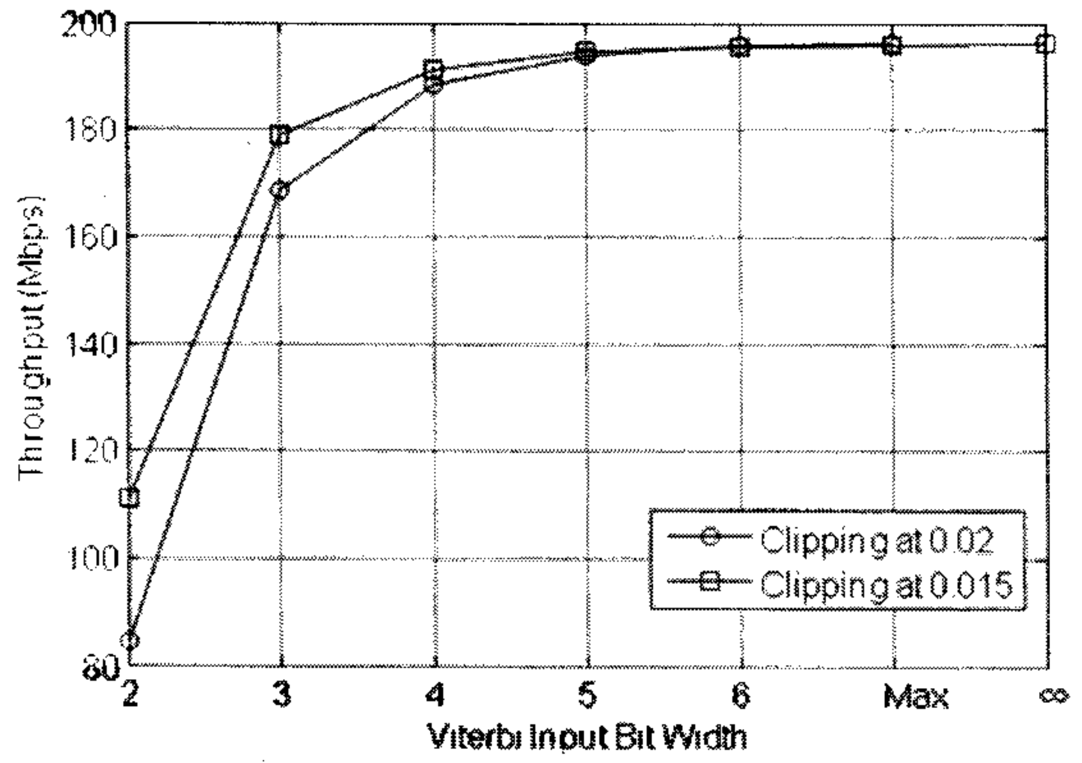


Fig. 9 Effect of soft-decision bit resolution at the Viterbi decoder input: CM1 channel, 200Mbps, SNR=5.5dB

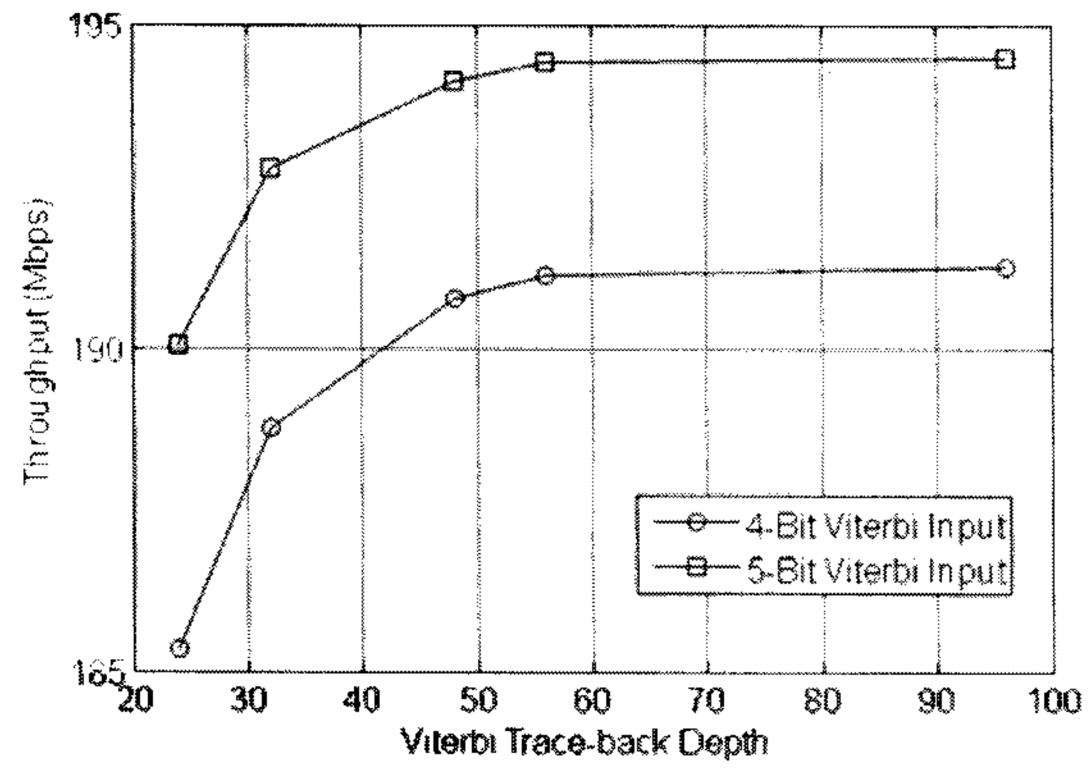


Fig. 10 Effect of the Viterbi decoder trace-back depth: CM1 channel, 200Mbps, SNR=5.5dB

ACKNOWLEDGMENT

This work was supported by the University of Incheon Research Grant in 2006.

REFERENCES

[1] A. Batra, J. Balakrishnan, G. R. Aiello, J. R. Foerster, and A. Dabak, "*Design of a Multiband OFDM System for Realistic UWB Channel Environments*," IEEE Tr. on Microwave Theory and Techniques, Vol. 52, No. 9, September 2004, pp. 2123-2138,

[2] D. Procino and W. Hirt, "*Ultra-Wideband Radio Technology: Potential and Challenges Ahead*," IEEE Commun. Magazine, July 2003, pp. 66-74

[3] FCC, *Rev. of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems*, First Report and Order, ET Docket 98-153, FCC 02-8, adopted/released Feb.14 / Apr. 22, 2002

[4] S. Siddharth and R. Aiello, "*Detect and Avoid (DAA) Techniques – Enabler for Worldwide Ultr Wideband Regulations*," The institution of Engineering and Technology Seminar on Ultra Wideband Systems, Technologies and Applications, April, 2006, pp. 21-29

[5] ECMA-368: *High Rate Ultra Wideband PHY and MAC Standard*, Dec. 2005

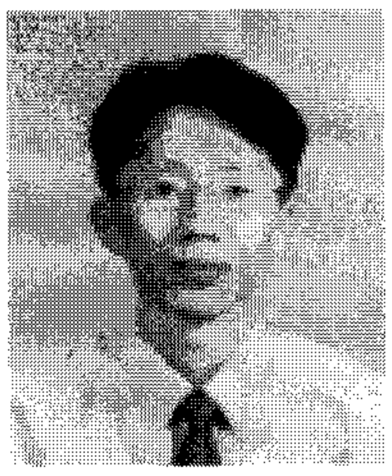
[6] H. Yamaguchi, "*Active Interference Cancellation Technique for MB-OFDM Cognitive Radio*", 34th European Microwave Conference, Amsterdam, 2004, pp.1105-1108

[7] J. H. Manton, "*A Channel Coded CP-OFDM Interpretation of TZ-OFDM Systems*", Proc. of the 11th IEEE Signal Processing Workshop on Statistical Signal Processing, August 2001, pp. 405-408

[8] Y. Chen, J. Zhang and A. D. S. Jayalath, "*Multiband-OFDM UWB vs IEEE 802.11n: System Level Design Considerations*," IEEE VTC 2006 Spring, May 2006, pp. 1972-1976

[9] A. Saleh and R. Valenzuela, "*A Statistical Model for Indoor Multipath Propagation*," IEEE JSAC, Vol. SAC-5, Feb., 1987, pp. 128-137

[10] L. Hanzo, M. Munster, B. J. Choi and T. Keller, *OFDM and MC-CDMA for Broadband Multi-User Communications, WLANs and Broadcasting*, IEEE Press and John-Wiley, 2003



Byoungjo Choi
received the B.Sc. and M.Sc. degrees in electrical engineering from KAIST, in 1990 and 1992, respectively, and the Ph.D. degree in mobile communications from the University of Southampton, Southampton, U.K. He was a Postdoctoral Research Assistant at the University of Southampton from 2001 to 2002. He is a recipient of the British Chevening Scholarship awarded by the British Council, U.K. He worked for LG Electronics as a research staff from 1992 to 2005. He is now an assistant professor at the University of Incheon. His research interests are related to mobile communication systems design with emphasis on adaptive modulation aided OFDM, MC-CDMA, and W-CDMA as well as GERAN evolution and LTE.