Flexible Chaotic UWB Communication System with Adjustable Channel Bandwidth in CMOS Technology

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***Abstract*—A flexible chaotic UWB (Ultra Wideband) communication system with an adjustable channel spectrum is proposed. Since the chaotic UWB bandwidth is independent of the data rate, the system band plan can be flexibly organized for various communication environments. The proposed system can overcome the spectral inefficiency and RF power wastage that is typically observed in conventional methods by utilizing adjustable channel allocations. A novel chaotic signal generator is designed with an adjustable frequency range of 3.5–4.5 GHz and bandwidth of 70–620 MHz. The chaotic UWB transceiver system is implemented in CMOS 0.18-μm technology, and it features tunable chaotic signal generation and adaptive detection. The system performance is evaluated for digital data transmission rates of up to 15 Mbps.**

***Index Terms*—CMOS Analog Integrated Circuits, Communication Systems, Chaos, Radio Communication, Signal Generators, Noise Generators**

I. Introduction

Since the introduction of Bluetooth services, wireless connectivity technologies have been rapidly developed for the purpose of short-range communication. Since such systems preferentially use the ISM (Industrial, Scientific and Medical) band at 2.4 GHz, they suffer from interference problems. In order to avoid co-existence, UWB systems have been researched based on spectrum overlay technology. The IEEE standards association has specified two types of UWB applications—high rate (HR) and low rate (LR). The IEEE 802.15.4a standard group has developed a new UWB PHY (Physical Layer) standard that features low data rates, longer range, low cost, low power consumption, and location awareness. In order to satisfy these requirements, several types of signal sources such as impulse, chirp and chaos have been proposed [1], [2].

A chaotic UWB communication system, considered to be an optional system in the IEEE 802.15.4a standard, is one of the promising solutions that has very low complexity and low power consumption. The chaotic UWB signal source resembles band-limited (colored) noise with a continuous non-periodic waveform and a naturally wideband spectrum. A chaotic UWB pulse modulated by a chaotic carrier makes the system robust against narrowband interference since the symbol energy is spread over the wideband spectrum [3], [4]. The feasibility of this system has been researched and verified for commercial connectivity applications [2]–[4]. However, this system continues to suffer from multiuser access problems and low spectral efficiency due to its non-coherent detection and use of the UWB spectrum for LR transmission. Additionally, because the chaotic signal is generated based on standard nonlinear chaos theory [5]–[8], it is difficult to control the spectrum of the chaotic carrier. Because the chaotic UWB system can control the radiation power by adjusting the bandwidth (BW) without changing spectral power, which is the uniqueness of the chaotic UWB signal, it has a great capability to enhance spectral efficiency. Therefore, the dynamic control technology for chaotic UWB systems must realize a spectral- and power-efficient connectivity solution.

In this paper, a chaotic UWB system with a flexible radio channel is proposed and implemented in CMOS technology. The adaptive RF band plan can enhance the system performance, spectral efficiency, and the battery life of mobile devices. Since this chaotic UWB system is unique in that the transmitting power is proportional to the bandwidth of the chaotic UWB carrier, controlling the carrier BW reduces power consumption, as well as co-channel interference for multiuser applications. Additionally, it can increase the number of users within a small cell by using flexible channel BWs. The proposed flexible system scheme is introduced in Section II. The system performance is evaluated for several channel environments in Section III. Section IV describes the proposed transceiver design that is implemented in CMOS 0.18-μm technology, and includes adjustable chaotic signal generation and adaptive detection. Finally, the commercial feasibility of the chaotic UWB systems is mentioned in the conclusion.

II. Flexible Chaotic Communication System with Adjustable Bandwidth

The system configuration and operation of the chaotic UWB communication system is shown in Fig. 1. The system architecture comprises a chaotic source generation module, a detection/decision module, and an RF front-end module. When the chaotic source is modulated by an LR time-limited digital pulse, the BW and spectral shape of the signal spectrum are retained due to the chaotic UWB carrier. This serves as a good design convenience for BW-dependent RF components. In the detection/decision module, the digital pulse shape is recovered by detecting the chaotic pulse at an envelope detector

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consisting of a nonlinear component and a lowpass filter. An adaptive algorithm is employed for reliable signal detection. The decision levels of a comparator are determined by measuring the received signal power of previous packets at the peak detector. The adaptive decision making is performed using an FPGA digital board that returns the decision level to the RFIC. The operation of the FPGA will be described in detail in Section IV. Despite the advantages of chaotic UWB, conventional chaotic UWB systems face difficulties in terms of the tunability of the chaotic spectrum and the possibly small number of users in a network. Other approaches, such as code-division multiplexing, have limitations such as high chip rate of PN (Pseudo Noise) codes and performance degradation due to co-channel interference.

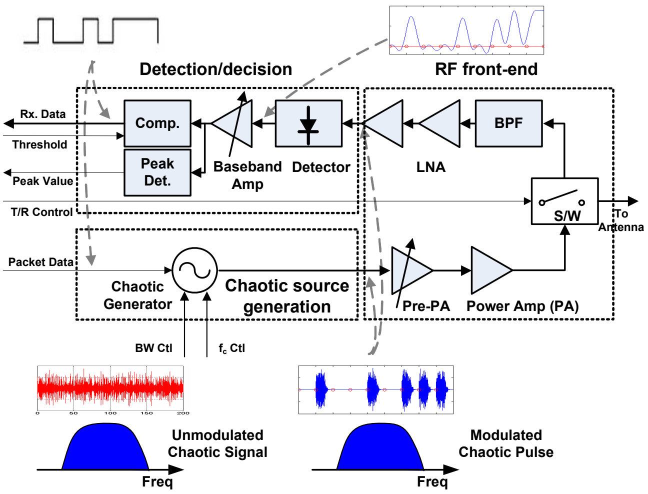


Fig. 1 System architecture and operation of the proposed flexible chaotic UWB communication.

This paper proposes a flexible chaotic UWB communication system with an adjustable channel BW and a quasi-cognitive access scheme. In this chaotic UWB communication scheme, the system BW is more strongly dependent on the chaotic carrier BW than the data rate. Due to these unique characteristics, the channel BW can be adjusted without degrading the system performance. Moreover, when the system retains the same power spectral density (PSD) regulated by the FCC spectrum mask, the total emitted power is proportional to the channel BW. The RF power can thus be controlled by adjusting the carrier BW. Therefore, variable channel BWs can be applied to the chaotic UWB system to accommodate channel environment variations.

The band plan of the proposed scheme is shown in Fig. 2. RF channel bands are assigned to "full bands" that are conventional UWB bands, and these bands are further divided into several "sub-bands" for adjusting the BWs of the channels. While one device occupies a small number of sub-bands in a clear radio channel or a short-distance connection, another requires several sub-bands or a full band in a busy radio channel or long-distance connection. When the system tries to access initially, it uses one full band radio channel. In this way, the system can reduce the number of occupied sub-bands according to variations in the wireless channel environment. In order to avoid channel collision, the spectral power for each band must be sensed. Basically, one user uses one band. If all bands are occupied, a new incoming user can temporarily use the empty sub-bands of a user who is utilizing a small number of sub-bands.

This spectrally efficient system can not only suppress co-existence interference but also increase the capacity of the number of users in a small service area. Moreover, the proposed flexible chaotic UWB system can reduce the power consumption of the chaotic transmitter by efficiently controlling the generator (which consumes DC power proportional to the output signal BW), a key issue of concern for current mobile devices used in connectivity services.

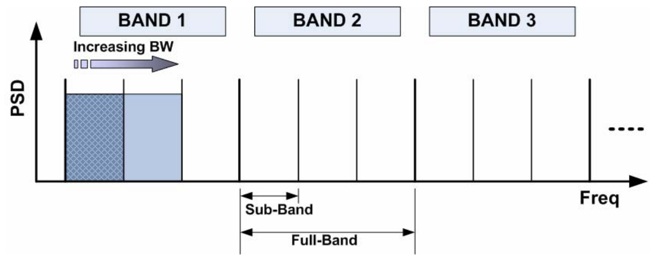


Fig. 2 Channel allocation in the flexible chaotic communication system with adjustable bandwidth.

III. Performance Evaluation of The Flexible Chaotic UWB System

A. System Performance Evaluation

The performance of the proposed system is evaluated for various channel BWs in practical propagation channel environments. First, bit error rates (BERs) are simulated for various energy per bit per noise power spectral densities (E_b/N_o) to investigate the data transmission performance over radio channels. Since the signal-to-noise ratio (SNR) of the chaotic UWB system is independent of the channel BW due to the equal contribution of signal and noise, E_b/N_o is a meaningful criterion for evaluating the proposed system [4].

The simulations are performed using MATLAB™ (MathWorks, Inc.). The experimental setup comprises a modulated chaotic pulse generation module, a radio channel module, and a detection module. A random bit sequence modulates a chaotic UWB carrier with constant spectral power. Multipath effects and AWGN are reflected in the radio channel module, and envelope detection/threshold decision is performed in the detection module. The full band is set to 500 MHz, while each sub-band is set to 100 MHz. The channel BW comprises one or more sub-bands from 100 MHz to 500 MHz in steps of 100 MHz. The following four propagation channel models are considered: indoor residential line-of-sight (LOS), outdoor LOS, industrial non-LOS (NLOS), and agricultural area. These four models are reliable propagation environments for practical use among the six models specified in the IEEE 802.15.4a recommendation [9]. A digital pulse stream with a data rate of R_s = 2.5 Mbps and a duty cycle of 25% was selected (i.e., one bit representation using a 100 ns pulse width and 300 ns guard interval). All calculations are performed for a constant PSD of –41.3 dBm/MHz.

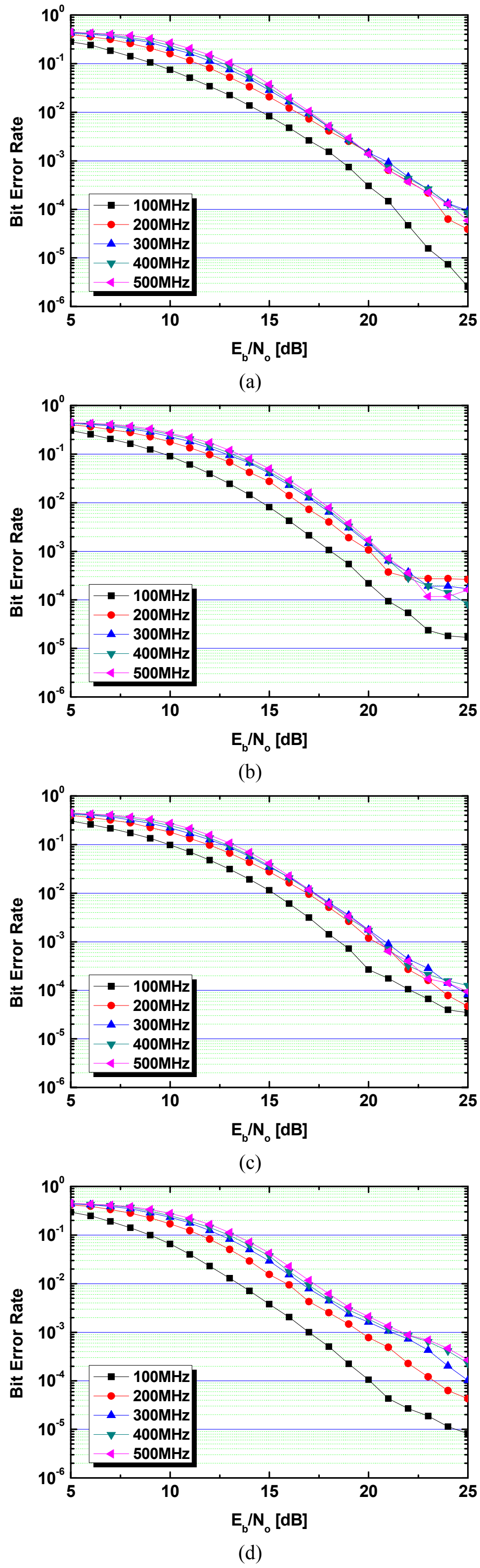


Fig. 3 System performance with various channel BWs for the following environments: (a) indoor residential LOS, (b) outdoor LOS, (c) industrial NLOS, and (d) agricultural area.

The simulation results are shown in Fig. 3. A BER of 10^{-3} is considered to be a reliable detection threshold based on an IEEE recommendation [10]. This reflects a packet configuration and channel coding in order to estimate a PER (Packet Error Rate) of 10^{-2} [10]. From the results of various propagation channels, it is observed that the E_b/N_o values are similar for each channel BW despite the spectral energy reduction. Additionally, a chaotic communication channel with the narrowest BW of 100 MHz has a gain of approximately 2 dB over those with the other BWs in E_b/N_o. The narrower the channel BW, the better is the detection performance. The largest gain difference of 5 dB is observed in an agricultural area without interference or blocking environments, as shown in Fig. 3(d).

B. *Communication Distance Evaluation*

Flexible channel BW of the proposed system plays a role in controlling the emission power, which can increase the number of users and reduce the co-channel interference. The communication distance was next investigated for each channel BW in the four propagation environments.

The relative E_b/N_o for the communication distance d is expressible as follows:

$$\frac{E_b}{N_o} = \left(\frac{E_b}{N_o}\right)_o + 10\log(B) + G_M - PL_o - 10n\log\left(\frac{d}{d_o}\right) - NF - M. \tag{1}$$

Here $(E_b/N_o)_o$ denotes the value of E_b/N_o at a 100 MHz BW, B is a multiple of the channel BW ($B \times 100$ MHz), G_M denotes the multipath gain, which is a factor for the power amplification from multipath effects [11], PL_o denotes the pathloss at the reference distance, d_o = 1 m, and n denotes the pathloss exponent that depends on the environment and on whether a LOS connection exists between the transmitter and receiver [11], NF and M denote the receiver noise figure of 7 dB and implementation margin of 5 dB, respectively, which are recommended values in [10]. From Eq. (1), the distance d can be expressed as a function of E_b/N_o that is related to the results of the previous section.

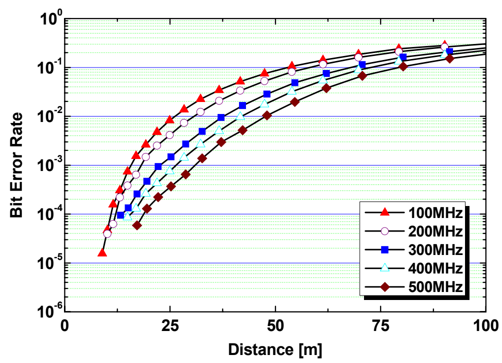
$$d = d_o 10^{\left((E_b/N_o)_o - (E_b/N_o) + 10\log(B) + G_M - PL_o - NF - M\right)/(10n)} \tag{2}$$

TABLE I
MULTIPATH GAINS FOR EACH CHANNEL BW AND PROPAGATION CHANNEL

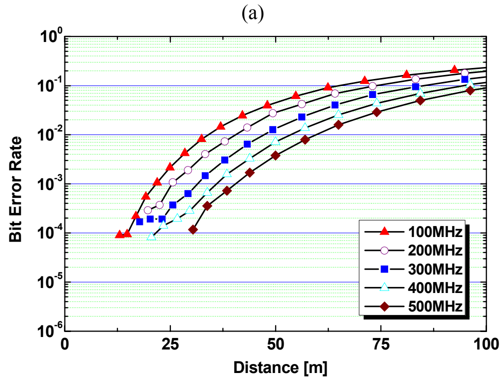
BW, MHz	Residential LOS	Outdoor LOS	Industrial NLOS	Agricultural Area
100	4.8	6.4	9.6	2.4
200	4.8	6.6	10	2.3
300	4.9	6.6	10.1	2.3
400	4.8	6.7	10.1	2.4
500	4.9	6.7	10.1	2.4

The $(E_b/N_o)_o$ is calculated from $E_b = P{\cdot}\Delta t$ [W·s] = –82.3 dBmJ (dB of mJ) and $N_o = k{\cdot}T$ [W/Hz] = –174 dBmJ (P = –12.3 dBm = –41.3 dBm/MHz (FCC limit) + 10log(100 MHz) + 6 dB (duty cycle, 1/4) + 3 dB (Tx./Rx. switching cycle) for Δt = 100 ns, k denotes the Boltzmann constant, and T denotes the room temperature). The multipath gain G_M is calculated for the chaotic UWB signals as shown in Table I [11]. The exponents used are $n = 1.79$ for indoor residential LOS, $n = 1.76$ for outdoor LOS, $n = 2.15$ for industrial NLOS, and $n = 1.58$ for an agricultural area [9]. The pathloss is calculated at the center frequency of 4 GHz. The experimental setup is the same as the previous one.

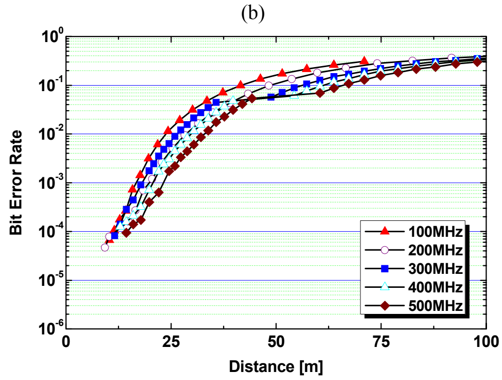
The communication distance variations for the channel BWs are shown in Fig. 4. The wideband chaotic pulse with higher transmitting power can reach farther mobile terminals. Communication range differences between the 100 MHz and 500 MHz BWs were found to be 16 m, 21 m, 7m, and 9m at the reference BER of < 10^{-3} for each environment, respectively. Therefore, the minimum channel BW of 100 MHz may be appropriate for the sub-band in short-range connectivity services. Furthermore, the flexible chaotic UWB system with adjustable channel BWs can increase the number of users by controlling the transmitting power as well as improving transmission quality by reducing co-existing interference.



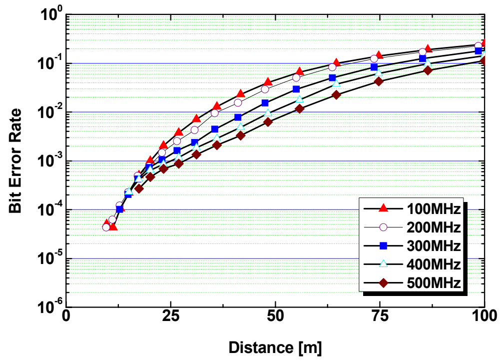
(a)



(b)



(c)



(d)

Fig. 4 Communication distance evaluation with various channel BWs for the following environments: (a) indoor residential LOS, (b) outdoor LOS, (c) industrial NLOS, and (d) agricultural area.

IV. FLEXIBLE CHAOTIC UWB TRANSCEIVER SYSTEM IN CMOS 0.18-μM TECHNOLOGY

A chaotic UWB transceiver system was designed for the proposed flexible chaotic UWB communication system. The key blocks of the system, such as the chaotic source generation module and the detection/decision module in Fig.1, are implemented in CMOS 0.18-μm technology. The tunable chaotic signal generator is designed with adjustable channel BWs and center frequencies. The transmission and detection performance of the transceiver system was first evaluated in [12].

A. Adjustable Chaotic Signal Generator Design

Various types of chaotic signal generators have been investigated in previous studies [5]–[8]. However, they have limitations in controlling the spectrum at GHz frequency bands due to the generation methods used in standard nonlinear chaos theories. Although the conventional methods have attempted to adjust the channel BWs by selecting BPFs from a filter bank, this introduces the problems of front-end size and BPF design in order to simultaneously satisfy wideband and high-rejection requirements.

In this paper, a flexible chaotic UWB signal generator with tunable BWs and center frequencies is proposed. The noise-like signal generation method enables the realization of a chaotic waveform that is the same as that from conventional sources. Additionally, the spectral characteristics can be electrically controlled by external signals without band-limiting filters. The architecture is comprised of general RF/analog devices and can be implemented with integrated circuits.

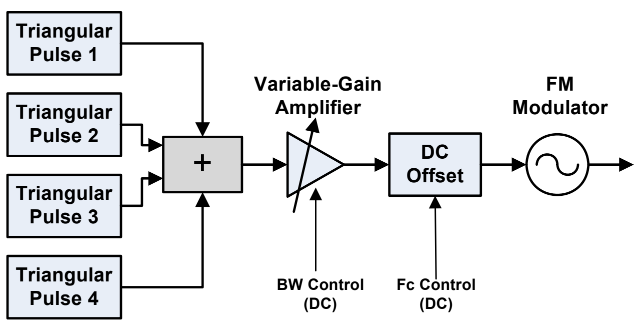


Fig. 5 Configuration of the flexible chaotic generator with variable center frequency and bandwidth.

The proposed chaotic signal generator consists of chaotic source generation, signal controls, and an amplitude-frequency converter, as shown in Fig. 5. The chaotic signal source is generated at baseband by a composite of four triangular pulses, which presents amplitude fluctuation to be converted to frequency variation. A triangular pulse can generate a sharper spectral shape than a rectangular pulse. Additionally, it is designed with incommensurate periods of prime numbers to generate noise-like signals. The number of triangular pulses was selected by the trade-off between the circuit size and the noisy characteristics at the generator output during circuit design. It was found that four pulses were enough to generate noise-like UWB signal. The baseband source exhibits fast amplitude variation with zero-crossing. At the control blocks, the chaotic source is modified for the purpose of amplification and DC offset by a variable-gain amplifier (VGA) and a bias-tee, respectively. The signal source is then converted to a chaotic RF signal by a voltage controlled oscillator (VCO). The spectrum is controlled by modifying the VCO input. The amplitude variation is converted to frequency variation by the VCO, while the output spectral power can maintain a constant PSD. When a chaotic source is amplified with a higher gain, the VCO widens the BW spectrum and vice versa. The center frequency of the VCO output is adjusted by controlling the DC offset of the input signal. Since the output frequency of the VCO is determined by the input voltage level, the input signal with DC offset can induce an oscillating frequency shift. During the signal up-conversion at the VCO, amplitude variation is converted to frequency-phase variation. Fig. 6 depicts a measured chaotic signal waveform of the proposed chaotic signal generator at the center frequency of 4 GHz. The chaotic signal exhibits a non-periodic continuous noise-like waveform in the time domain.

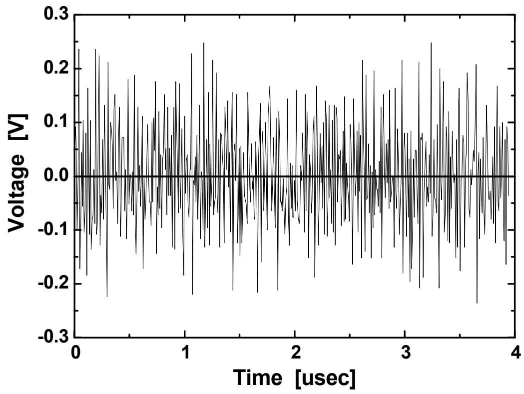


Fig. 6 Measured results of the chaotic signal waveform at f_c = 4 GHz and BW = 500 MHz.

The output spectrums are measured to investigate the adjustability of the chaotic signal generator. Chaotic signals are generated with BWs of 500 MHz from 3.5–4.5 GHz, which approximately satisfies the RF channel allocation of the IEEE 802.15.4a standard. The channel spectrum allocations of the IEEE 802.15.4a standard have center frequencies of 3494.4 MHz, 3663.6 MHz, and 4492.8 MHz and equal BWs of 499.2 MHz. Frequency control voltages of 0.955 V, 0.570 V, and 0.250 V are supplied for each channel, respectively, while a BW control voltage of 0.6 V is provided. The instantaneous spectra are measured by a spectrum analyzer (Agilent E4440) as shown in Fig. 7.

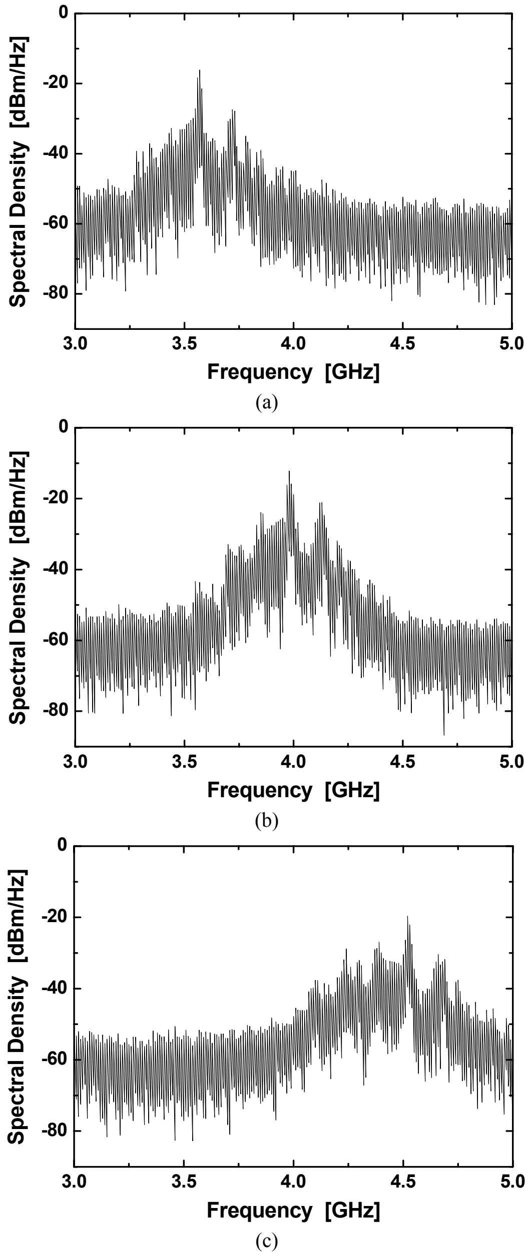


Fig. 7 Chaotic signal spectra for RF channels. (a) Channel 1 (f_c = 3.5 GHz). (b) Channel 2 (f_c = 4.0 GHz). (c) Channel 3 (f_c = 4.5 GHz).

The channel BW of the chaotic signal can also be controlled by changing the VGA gain. The BW can be varied continuously in the range from 70 MHz to 620 MHz by adjusting the control voltages from 0.731 V to 0.532 V. These minimum and maximum BWs at the center frequency of 4.5 GHz are shown in Fig. 8.

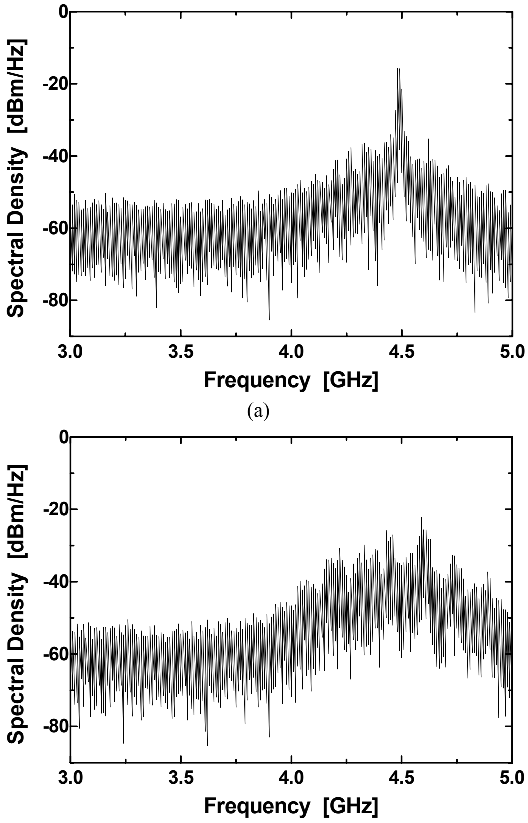


Fig. 8 Variable chaotic signal spectrums at f_c = 4.5 GHz with (a) min. BW and (b) max. BW.

B. Chaotic UWB Transceiver System in CMOS Technology

The chaotic UWB transceiver system was implemented using a flexible chaotic UWB CMOS RFIC and front-end devices, as shown in Fig. 1. The evaluation of the system performance reveals that the system is capable of transmitting digital data. The chaotic signal was generated at a center frequency of 4 GHz with a BW of 500 MHz. The chaotic pulses are modulated by switching the chaotic signal generator on/off based on the information data. The information data was obtained from a FPGA digital board. The modulated chaotic pulse waveform at the maximum data rate of 15 Mbps is shown in Fig. 9.

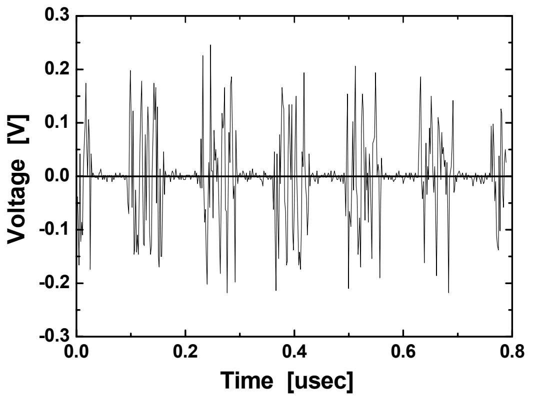


Fig. 9 Pulse-modulated chaotic signal waveform at the chaotic UWB transmitter output (R_s = 15 Mbps, f_c = 4 GHz, carrier BW = 500 MHz).

The envelope waveform of the received chaotic pulse is detected using an envelope detector. An adaptive detection algorithm is used to determine the decision levels of the comparator in order to follow the fluctuations in the received power. A peak detector measures the peak levels of the received pulses during a designated period, and provides them to the FPGA digital board. The appropriate decision levels are calculated by averaging several packets of data, which uses the difference of maximum and minimum detected levels, and then returning two decision threshold levels to the comparator, T_high for logical high ("1") and T_low for logical low ("0"). The modulated chaotic UWB pulse was transmitted through a coaxial cable to avoid providing other interference. The received power is adjusted by a variable attenuator inserted between the transmitter and receiver. Fig. 10 presents the measured result of a detected signal and threshold levels at the output of the CMOS circuit. From the measured results, the excellent signal generation and detection capabilities of the chaotic UWB transceiver were evaluated for up to 15 Mbps of digital data.

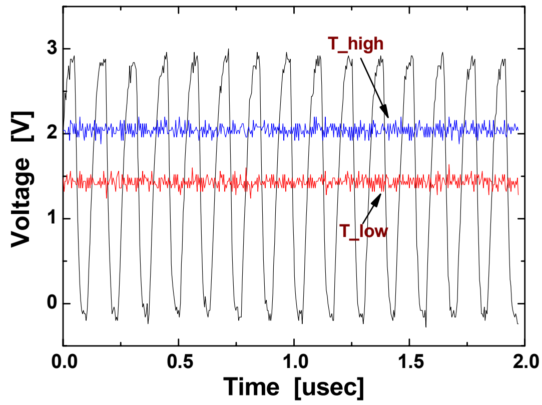


Fig. 10 Detected signal waveform at detector output of the chaotic UWB RFIC.

For the performance evaluation of the chaotic UWB system with flexible channel BWs, communication distances for variable channel BWs were measured. At first, the sensitivity level was measured for minimum detectable signal levels. A test setup was then constructed, consisting of the transmitter, a variable attenuator, and the receiver that were connected by coaxial cables to eliminate the effects of other interference. The received power at the receiver front-end was controlled by the variable attenuator. Because the receiver sensitivity level is determined by the total received power at a detector, it has the same value of –71.8 dBm for variable channel BWs.

For the consideration of RF analog signals in practical applications, E_b/N_o is converted to SNR from Eq. (1):

$$\left(\frac{S}{N}\right)_{req} = \left(\frac{S}{N}\right)_{gen} + G_M - PL_o - 10n\log\left(\frac{d}{d_o}\right) - NF - M \qquad (3)$$

The signal power $S = E_b{\cdot}R_s$ and noise power $N = N_o{\cdot}BW$ are converted for both the required and generated SNRs, that is, $(S/N)_{req}$ and $(S/N)_{gen}$. The BW multiplication factor B is included in the generated signal power S_{gen}. The gain G_M is reused from Table I to represent practical environments.

Because S_{req} means a minimum sensitivity level and N_{req} includes N_{gen}, NF and M, Eq. (3) can be simplified as follow:

$$S_{req} = S_{gen} + G_M - PL_o - 10n\log\left(\frac{d}{d_o}\right). \quad (4)$$

The distance d can be expressed as a function of the sensitivity level S_{req} and transmitted chaotic UWB signal power S_{gen} as follows:

$$d = d_o 10^{\left(S_{gen} - S_{req} + G_M - PL_o\right)/(10n)} \quad (5)$$

The generated chaotic UWB signal power was measured from a 100 to 500 MHz BW in steps of 100 MHz. The measurements were performed within specified channel BWs by a spectrum analyzer. While the transmitted power was considered for an ideal rectangular spectrum with –41.3 dBm/MHz × BW in the simulation analysis, the measured chaotic UWB signal power will be less than the ideal one due to the spectral gap between the chaotic pulse shape and a rectangular spectral mask. The transmitted powers for each channel BW are compared in TABLE II.

TABLE II
TRANSMITTED CHAOTIC UWB SIGNAL POWER FOR CHANNEL BWS

BW, MHz	Ideal Power, dBm	Measured Power, dBm
100	–21.3	–21.6
200	–18.3	–19.1
300	–16.5	–17.3
400	–15.3	–16.2
500	–14.3	–15.4

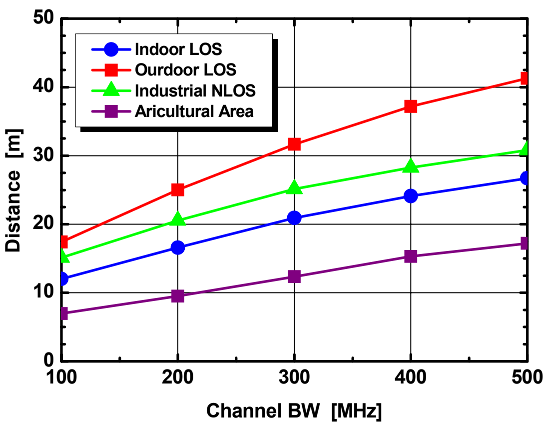


Fig. 11 Experimental results for communication distances corresponding to variable channel BWs.

The modulated chaotic UWB pulses were transmitted to the receiver for each channel BW. The received power was attenuated up to the sensitivity level. From these measured results, communication distances of the prototype system were estimated as presented in Fig. 11. When these results are compared to the simulated results in Fig. 4, the performance of the RFIC-based prototype system approached the theoretical predictions. In the exceptional case of an agricultural area, the measurement was not well matched, which was caused by estimation error of the theoretical multipath gain factor in a laboratory environment test. Even though the distances are not exactly the same, the measured results still validate the simulation analysis, and verify the merits and capabilities of controlling the communication distance of the proposed flexible chaotic UWB system. Compared with the simulated results in Fig. 4, the small performance degradation of the distance reduction was caused by poor detector sensitivity in the RFIC and the transmitted power drop in TABLE II. The microphotograph of the fabricated chaotic UWB transceiver IC is shown in Fig. 12.

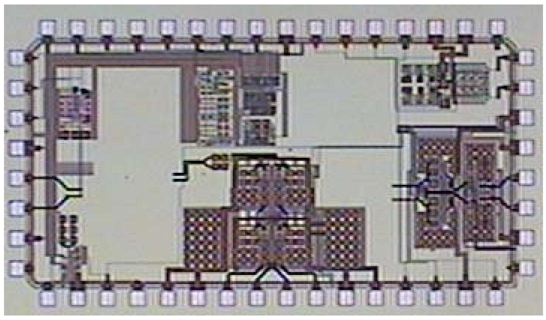


Fig. 12 Microphotograph of the CMOS RFIC for the flexible chaotic UWB system.

V. CONCLUSION

A flexible chaotic UWB communication system is proposed. Flexible BW allocation affords several advantages such as high spectral efficiency, automatic power control, low power consumption, co-channel interference avoidance, etc., in short-range connectivity networks. For the purpose of demonstrating the reliability of the system, a novel chaotic signal generator with tunable bandwidth and center frequency was designed. Furthermore, the proposed chaotic UWB transceiver system was implemented in CMOS technology. The evaluated results reveal an excellent communication performance from the viewpoints of adjustable chaotic signal generation and adaptive detection. The proposed flexible chaotic UWB system may be an excellent candidate for inexpensive, low-power solutions in mobile connectivity services based on the IEEE 802.15.4a standard.

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