

# Low Bit Error Rate ZigBee Baseband Transceiver Design for IEEE 802.15.4

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**Abstract**—In this paper the Zigbee baseband transceiver for Residue number system are simulated. Here the improved pn sequence of 32 bit are generated. The created pn sequence is having less correlation between each bit. The Bit error rate of the PN sequence is less as compared to the Standard IEEE 802.15.4. The performance of the sequence is tested in MATLAB. The baseband design is coded in hardware description language verilog HDL and simulated in modelsim simulator. The PN sequence generated for the different symbols of the ZigBee standard are performs better than the defined ZigBee standard for the transceiver.

**Index Terms**—ZigBee transceiver, IEEE 802.15.4., Residue Number System, PN Sequence.

## I. INTRODUCTION

ZigBee standard is particularly designed for low data rate, short range wireless communication. The application of Zigbee is for wireless sensing of different parameters of the required object or any living element. since 2003 the standard starts develop from stage to stage till now. The standard has three band of frequencies as given in table I. ZigBee networking protocol layers are based on the open system interconnect(OSI) layer. the upper layer of the networking protocol layers are defined by ZigBee alliance group, the lower layers such as medium access control(MAC) layer and physical layer are defined by IEEE 802.15.4 standard. the radio transceiver designed is based on the IEEE 802.15.4. IEEE 802.15.4 has three frequency band of operation like for 2.4GHz, 915MHz, 868MHz. The different band has different specifications as given in Table I. the standard has tremendous application in the area of wireless sensor networks. The structural strength of a building can be evaluated by fitting ZigBee devices at the different joints of the building. In medical application the wireless ZigBee devices can be fitted in the patients body to study the various parameters of the patient such as blood pressure, pulse rate etc. The ZigBee device in patients body transmits the necessary parameters in wireless to a personal computer in the cabin, from there the information sent to the physician via broadband communication [1].

Along with zigbee the IEEE 802.11 standard also operates with 2.4 GHz band [2]. The IEEE 802.11b has a high data rate of 11 Mbps for which it is mainly used for wireless internet connection. The indoor range of the standard is 30 to 100 meters [3]. Bluetooth has a indoor range of 2 to 10

meters and the data rate of less than 3 Mbps. As compared to all these standards, ZigBee has lower data rate with indoor coverage of 100 meters and low power consumption. Hence the battery life time of ZigBee devices is more with low data rate and less complexity. The Zigbee standard is suitable for the transmission and reception of simple commands which is again a suitable application in defence. Keeping in view this ZigBee standard provides the most cost efficient and power efficient solution compared to Bluetooth and IEEE 802.11 [3] [4].

The standard has different frequency bands of operation as mentioned in Table I.

The ZigBee alliance group uses direct sequence spread spectrum(DSSS) technique in the transmitter end for data spreading. Multi access interference (MAI) and multi path interference (MI) makes the DSSS system interference limited. DSSS system uses random sequences for spreading. The random sequence generator may be of orthogonal code or Pseudo noise sequences (PN sequence). In DSSS wireless communication system, PN sequences are preferred to orthogonal sequences as the performance of orthogonal sequences is degraded in asynchronous communication. PN sequences exhibit uniform performance in synchronous and asynchronous communication system. IEEE 802.15.4 standard provides symbol to chip conversion codes (Based on PN sequence) which are quasi orthogonal to each other [2]. In this paper a new PN sequence based on Residue Number System (RNS) is used as symbol to chip conversion code [5]. The RNS is based on residue arithmetic.

The paper is organized as follows. Following this the section II describes the spreading and despreading. Section III describes the generation of RNS based PN sequence. The paper describes all stages of baseband transceiver design such as symbol to chip conversion, serial to parallel conversion along with pulse shaping of even bit stream and odd bit stream. In reception the design includes even bit and odd bit separation along with the decoding of input data bit. In decoding the chip to symbol process obtained by matching bit to bit of chip sequence at the receiver with the chip sequence transmitted by the transmitter. The performance analysis of RNS based PN sequence with IEEE 802.15.4 chip sequence in AWGN channel with rayleigh fading transmission and reception are

TABLE I  
SPECIFICATIONS FOR THREE FREQUENCY BAND OF IEEE 802.15.4  
STANDARD

frequency	No of Channels	Modulation	Bit Rate	Spreading Method
2.4GHz	16	OQPSK	250	16 array orthogonal
868MHz	1	BPSK	20	Binary DSSS
915MHz	10	BPSK	40	Binary DSSS

presented in section IV, V, VI. The modelsim simulation and Virtex 5 FPGA board results are presented in Result section. Finally the paper concludes in section VIII.

## II. RESIDUE NUMBER SYSTEM

In this section the paper describes the residue number system(RNS)[6], and generates 32 different chip sequence based on residue arithmetic. The 32 bit different chip sequence generated are used for respective four bit symbol are mentioned in Table III.

Residue Arithmetic based PN sequence generation for multiple scenario are mentioned here. The inputs to the block of RNS generation consists of spread factor  $\beta$  and the cross correlation threshold, T. A moduli set is selected according to the requirement of no of bits in PN sequence. The moduli set is selected either by consecutive method or by exponential method [7]. Here the consecutive method is used. The various moduli sets at different dynamic range  $R$  for various spreading factors ( $\beta$ )are mentioned in TableII [7].

As mention above the Primal is randomly selected from the range  $R$  given by  $R = \prod_{i=1}^n p_i$ , where  $p$  is the moduli set and is represented as  $p = \{p_1, p_2, p_3, \dots, p_n\}$ [7][6]. Let  $A$  be a set of primals choosen from range  $R$  and is expressed as  $A = x_1, x_2, x_3, \dots, x_n$ . Defining  $J$  to be set of residues given by  $J(i, j) = |x_j, p_j|$  for  $i = 1, 2, \dots, n$  and  $j = 1, 2, \dots, k$ . So  $J$  can be represented as given in equation 1

$$J = \begin{pmatrix} \text{mod}(x_1, p_1) & \text{mod}(x_1, p_2) & \dots & \text{mod}(x_1, p_n) \\ \vdots & \vdots & \ddots & \vdots \\ \text{mod}(x_n, p_1) & \text{mod}(x_n, p_1) & \dots & \text{mod}(x_n, p_1) \end{pmatrix} \quad (1)$$

Each row of  $J$  is then represented by 8 bit binary representation, the the entire row is termed as the desired length of the PN sequence. The generated sequences are tested for their cross correlation as following.

- Correlation between  $c_i$  and  $c_j$  for  $i = j$  has to be one.
- Correlation between  $c_i$  and  $c_j$  for  $i \neq j$  must be less than a threshold value  $T$ . The value of  $T$  can vary depending on the application. This process is continued till the required number of PN codes are generated.

For ZigBee standard 16 different PN codes of length 32 bit are required, so in this paper the RNS based PN sequence of  $16 \times 32$  is generated[5].

TABLE II  
GENERATED MODULI-SET AND DYNAMIC RANGE FOR DIFFERENT  
SPREADING FACTORS

Spreading Factor( $\beta$ )	Moduli-set( $p$ ) $\{p_1, p_2, p_3, \dots, n\}$	=	Range( $R$ )
8	[255]		255
16	[255 254]		64770
32	[255 254 253 251]		4113089310
64	[255 254 253 251 247 241 239 233]		$\cong 10^{19}$
128	[255 254 253 251 247 241 239 233 229 227 223 217 211 199 197 193]		255

TABLE III  
SYMBOL TO CHIP MAPPING OF RNS CODE FOR 2.4 GHZ BAND

Data Symbol(Binary)	Chip values ( $C_0 C_1 \dots C_{31}$ )
0000	1110101111101110111000111110111
1000	11001101110101001101101111101001
0100	11010110110111011110010011110010
1100	1011111111001010101010111101011
0010	11000000110010111101011011101100
1010	1001110010101110111101011011000
0110	101010101110011100100011100110
1110	11111011000011110010001001001000
0001	10011001101011001011111111100101
1001	10100001101101111100110111111001
0101	11011001111011110000100000110110
1101	00101000001111110101011010000100
0011	01101110100001011001110011001010
1011	10101111110010011110001100011100
0111	10111001110100111110110100100110
1111	11100111000000110001111001010100

## III. SPREADING

IEEE 802.15.4 [2] standard uses the spreading methods to increase the effect of receiver sensitivity, jamming resistance, and also to reduce the effect of multipath. The spreading method used here is the Direct sequence spread spectrum(DSSS) [8] as shown in Table 1. In this standard every four incoming data bit is combined together to form a four bit symbol and this four bit symbol is mapped into an unique 32 chip sequence in a look up table. Hence there are sixteen different 32 bit chip sequences as shown in Table IV. The chip sequences are also known as Pseudo noise random sequence (PN sequence). The chip sequence is the collection of zeros and ones randomly(random noise) which leads up to some extent that this chip sequences may become similar to each other. To avoid the similarity between any two chip sequences, the standard follows a procedure or algorithm of doing the cross-correlation between the chip sequences. The cross-correlation is calculated by multiplying the sequences together and then calculating the summation of the result. The 32 bit chip sequence contains a sequence of zeros and ones in unipolar form. Before calculation of the cross correlation the unipolar sequence is converted to bipolar sequence ie a '0' is represented by '-1' and '1' is as it is. If  $X(n)$  and  $Y(n)$  are two sequences then the cross correlation of  $X(n)$  and  $Y(n)$

TABLE IV  
SYMBOL TO CHIP MAPPING FOR 2.4 GHz BAND

Data Symbol(Binary)	Chip values ( $C_0 C_1 \dots C_{31}$ )
0000	11011001110000110101001000101110
1000	11101101100111000011010100100010
0100	00101110110110011100001101010010
1100	00100010111011011001110000110101
0010	01010010001011101101100111000011
1010	00110101001000101110110110011100
0110	11000011010100100010111011011001
1110	10011100001101010010001011101101
0001	10001100100101100000011101111011
1001	10111000110010010110000001110111
0101	01111011100011001001011000000111
1101	01110111101110001100100101100000
0011	00000111011110111000110010010110
1011	01100000011101111011100011001001
0111	10010110000001110111101110001100
1111	11001001011000000111011110111000

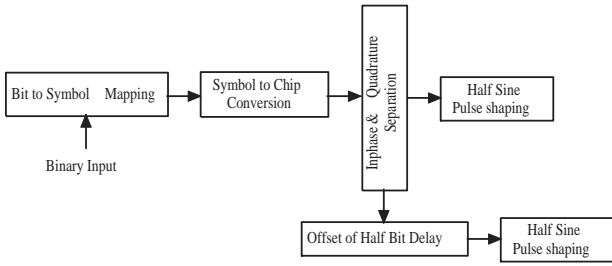


Fig. 1. ZigBee baseband Transmitter

calculated by using the following equation 2 [1].

$$r_{xy}(0) = \sum_{n=-\infty}^{n=\infty} x(n)y(n) \quad (2)$$

The above equation calculates the cross correlation of  $X(n)$  and  $Y(n)$  where neither of these sequences shifted. Hence it defines that the two sequences are dissimilar to each other. In this case the sequences are known as orthogonal to each other and termed as orthogonal sequences. The sixteen pseudo noise sequences used in the standard IEEE 802.15.4 are not completely orthogonal to each other and called as quasi orthogonal or nearly orthogonal. The cross correlation of other Pseudo Noise(PN) sequences are calculated by shifting one sequence with a margin of time period  $k$  hence the equation is written as:

$$r_{xy}(k) = \sum_{n=-\infty}^{n=\infty} x(n)y(n-k) \quad (3)$$

By using the above equation the standard IEEE 802.15.4 has different sets of symbol to chip mapping for three bands of frequency such as 868 MHz, 915 MHz and 2.4 GHz. All the sixteen combination of symbol to chip mapping for 2.4 GHz frequency band are mentioned in Table IV.

#### IV. TRANSMITTER DESIGN

The baseband transmitter implementation is shown in Figure 1, with the various blocks of the transmitter section such as

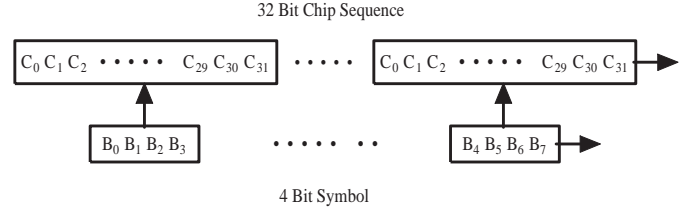


Fig. 2. 4 Bit Symbol

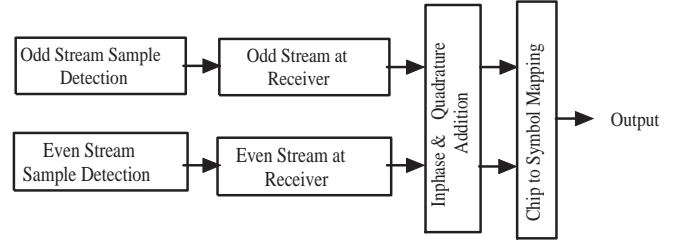


Fig. 3. ZigBee Baseband Receiver

bit to symbol mapping, symbol to chip conversion, serial to parallel conversion, half-sine pulse shaping etc are shown.[9]

The input bit stream in digital form like digital '1' and digital '0'. The four input bits are combined to form a four bit symbol. The input bit is at a data rate of 250 Kbps which means in every 4 micro second one digital input is coming ie either '0' or '1'. So combining four input bits one symbol forms and as per the standard IEEE 802.15.4 the symbol to chip sequence is taken. The symbol to chip conversion performs DSSS spread spectrum baseband modulation to avoid loss at the baseband. The four bit symbol is mapped to respective 32 bit chip sequence in a lookup table. Hence there are sixteen different combination of 32 chip sequences or pseudo noise random sequence (PN sequence) as shown in Table 2. The 32 bit chip sequence are in unipolar form, that is digital '1' or digital '0' but during the DSSS spreading there is a loss during binary bit '0'. So in the verilog HDL design spreading occurs as per the bipolar chip sequences. The serial chip sequence data stream obtained becomes a 2 Mbps.

The 32 bit chip sequences represents the different four bit symbol are modulated using OQPSK modulation scheme for 2.4 GHz unlicensed band. The even and odd indexed chips are separated into two streams having two bit period extended at the same time the even bitstream is having half a bit delay to the odd bitstream. The even and odd bitstreams are transmitted along with the pulse shaping stage to reduce the inter-symbol interference (ISI). Finally the resultant signal having even and odd stream are transmitted by the RF transmitter.

#### V. RECEIVER DESIGN

The figure 3 shows the design of ZigBee baseband receiver, which includes the sample detection, extraction of even bit

TABLE V  
SAMPLES FOR PULSE SHAPING

Sampling time in <i>ns</i>	Sample value for bit 1	Sample value for bit 0 in twos complement
100	00000000	00000000
200	00010000	11110000
300	00100000	11100000
400	00110000	11010000
500	00111000	11001000
600	01000000	11000000
700	00111000	11001000
800	00110000	11010000
900	00100000	11100000
1000	00010000	11110000

stream and odd bit stream, addition of odd bit stream data and decoding of input digital signal. [9]

Assuming the reception to be synchronous, the pulse shaping output at the transmitter is fed to the input of the receiver. The pulse shaping of even bit and odd bit are sampled with the ten samples as given in table V. For ten samples the sampling time for each sample is 100 ns because the chip duration is 1000 ns so to accommodate ten samples in one bit, the sampling time is 100 ns taken.

The samples are considered as the decimal values. It can also be the integer values to multiply with every bit of even stream and odd stream to get the ZigBee pulse shaping. In the Verilog FPGA design the samples are stored in a memory and then the samples are read from the memory according to the parallel stream chip bit '1' and '0' simultaneously. Since we need to multiply the samples with the bipolar chip having the amplitude varying from '+1' and '-1' for the pulse shaping filter. Notably the pulse shaping filter is used to reduce the Inter Symbol Interference (ISI) by converting the pulses into the half sine shapes. The chip bit here are unipolar so for the chip '0' the negative samples stored in the memory are read instead of multiplying the samples with the '-1' because chip '-1' is represented as '0'. Similarly for chip '1' the positive samples stored in the memory are read instead of multiplying the samples with the chip '1'.

## VI. DECODING

The serial data after addition of I-phase and Q-phase data reforms into a 2 Mbps data transmitted by the transmitter. This serial data includes the input data along with noise added by various stages of the transceiver mainly by the communication channel. The decoding process extracts the input data from noise.

The serial data is stored in a 32 bit register as per the clock signal used in the verilog-HDL design of the transceiver. The 32 bit PN sequence used at the transmitter for spreading is reused at the receiver for despreading.

The sixteen PN sequences used at the transmitter and the serial data stored in 32 bit register are XNORed to each other bit by bit to check the mismatch of the data bit. Sixteen different counters or flag registers of six bits are used to count minimum up to 32 in decimal, because the 32 bits of the serial data are checked with all sixteen quasi orthogonal

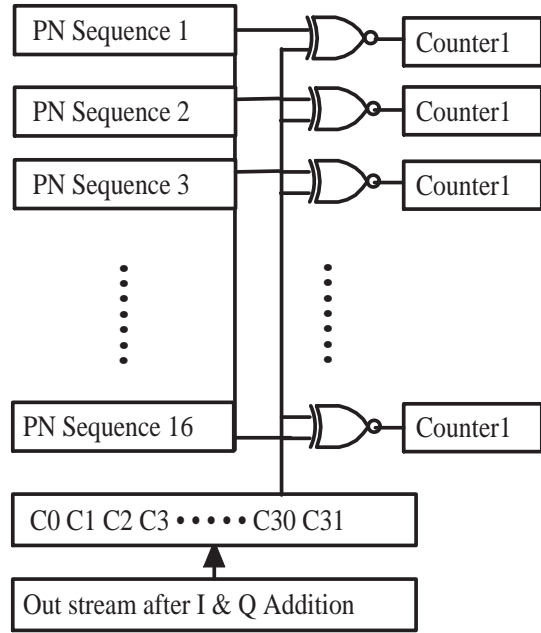


Fig. 4. Decoding process

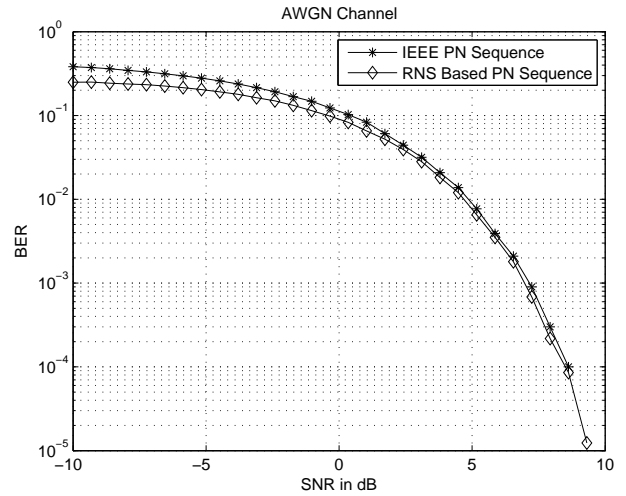


Fig. 5. Performance comparison of RNS PN code versus ZigBee Chip sequence in Matlab

PN sequences at a time. In XNOR operation, when both the bits of serial data and PN sequences are same the counters are increased by one and if both the bits are different the counters stores the same value. So after finishing the XNOR operation of all the 32 bits of the serial data the counter values are checked for the maximum value. The counter which stores the maximum value as comparing to all other counters indicates the highest level of matching. Hence the respective PN sequence with maximum counter value is referred as the chip sequence which was transmitted by the transmitter. Later

on the different symbols are extracted from a look up table which contains the chip to symbol mapping. In receiver the MSB of decoded symbol gives the expected output.

### VII. RESULTS

In this paper the performance analysis IEEE 802.15.4 standard with the generated PN sequence tested. In the MATLAB simulation it is observed that the bit error rate(BER) of created PN sequence performs better in comparison to defined IEEE 802.15.4 standard chip sequence.as shown in figure. The Bit Error Rate performance analysis with awgn noise and rayleigh fading is shown in figure 5 and 6.

### VIII. CONCLUSION

In this paper the ZigBee baseband transceiver for IEEE 802.15.4 standard is simulated and implemented in VIRTEX 5 FPGA Board. The paper describes the behavior of bit to symbol, symbol to chip, pulse shaping, chip to symbol in verilog HDL. The different blocks are integrated in the design to complete the baseband module. It is observed that the Implemented baseband transceiver recovers the input data bit successfully as per the input. The 32 bit PN sequence generated by the method of residue arithmetic in MATLAB performs better bit error rate performance in comparison to IEEE 802.15.4 defined pn sequence. So here the paper concludes that it is better to implement the new developed PN code for the transceiver implementation. using the new PN sequence the baseband transceiver simulated in modelsim simulator. In simulation the input data bit received successfully.

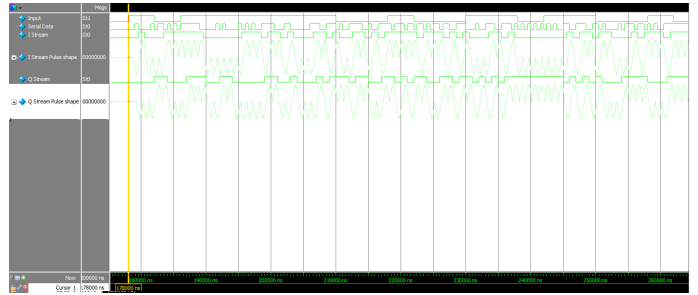


Fig. 7. Transmitter simulation in Modelsim

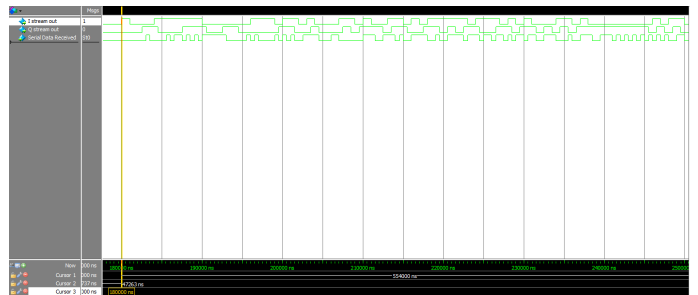


Fig. 8. I Q Detection at Receiver

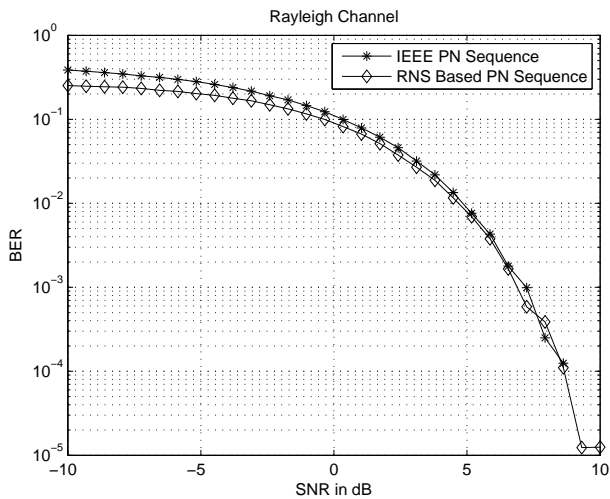


Fig. 6. Performance comparison of RNS PN code versus ZigBee Chip sequence in Matlab

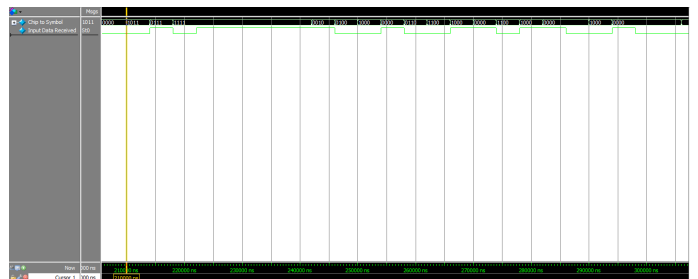


Fig. 9. Data bit received

## IX. FUTURE SCOPE

The BER plot shows that the performance of PN sequence generated by residue arithmetic method performs better against the defined PN sequence at low Signal to Noise ratio(SNR). So the scope of the work can be extended for the implementation in VIRTEX 5 FPGA board with the new generated PN code.

## REFERENCES

- [1] S. Farahani, *ZigBee wireless Network and Transceivers*. Newnes, USA, 2008.
- [2] *IEEE Standard for Local and metropolitan area networks Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*, IEEE Computer Society Std.
- [3] J.-S. Lee, Y.-W. Su, and C.-C. Shen, "A comparative study of wireless protocols: Bluetooth, uwb, zigbee, and wi-fi," Taipei, Taiwan, 2007, pp. 46 – 51.
- [4] C. Park and T. Rappaport, "Short-range wireless communications for next-generation networks: Uwb, 60 ghz millimeter-wave wpan, and zigbee," *Wireless Communications, IEEE*, vol. 14, no. 4, pp. 70 –78, august 2007.
- [5] R. Chithra, P. Maji, S. Patra, and G. Rath, "A pn sequence generator based on residue arithmetic for multi-user ds-cdma applications," pp. 26–31, June 2012.
- [6] A. Omondi and A. Benjamin Premkumar, *Residue Number Systems: Theory and Implementation*, ser. Advances in Computer Science and Engineering Texts. Imperial College Press, 2007. [Online]. Available: <http://books.google.co.in/books?id=q-vA1124oFYC>
- [7] P. Maji and G. Rath, "A novel design approach for low pass finite impulse response filter based on residue number system," in *Electronics Computer Technology (ICECT), 2011 3rd International Conference on*, vol. 3. IEEE, 2011, pp. 74–78.
- [8] U. Madhow, *Fundamentals of Digital Communication*. Cambridge University Press, 2008.
- [9] N.-J. Oh and S.-G. Lee, "Building a 2.4-ghz radio transceiver using ieee 802.15.4," *Circuits and Devices Magazine, IEEE*, vol. 21, no. 6, pp. 43 – 51, jan.-feb. 2005.