Investigations on AQ-DBPSK Modulation based RF Transceiver for Wireless Sensor Communication Networks

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Abstract: -This research work demonstrates the simulation results of a Radio Frequency (RF) transceiver with Alternate Quadrature Differential Binary Phase Shift Keying (AQ-DBPSK) modulation at 2.4GHz. The RF transmitter consists of an AQ-DBPSK modulator, an up conversion mixer, a 2.4 GHz Band pass filter and a power amplifier. At the receiver RF front end, the Low Noise Amplifier (LNA), mixer with down conversion to Intermediate Frequency (IF), a Low Pass Filter (LPF) and an AQ-DBPSK demodulator is used. The block level parameters of the transmitter and receiver RF front end like Noise Figure (NF) and Gain are optimized to meet the transceiver specifications for the applications in Wireless Sensor Communication Networks.

Key-Words: AQ-DBPSK, Energy Efficient Modulation, RF Transceiver, Transmitter Efficiency, Wireless Sensor Communications.

1 Introduction

Wireless Sensor Network (WSN) consists of a dense network of randomly deployable sensor nodes. Each node is capable of extracting data from the environment, processing and transmitting the data for monitoring or networking purposes. There is an increasing demand for nodes that consume less power in WSN applications [1]. The block diagram for the core of a sensor node is shown in Fig.1. It is composed of a power unit, processing unit, sensing unit and transceiver unit. The transceiver unit which is the focus of this paper provides communication between the nodes in the network. The hardware design for such devices is difficult due to the decisions made at the system level and is thus highly dependent on the applications for which the system is intended. WSN caters for a wide variety of data rates and communication range, which gives rise to various proprietary architectures and standards [2, 3].

Various low power standards have been formulated to meet the low power and low cost applications. The IEEE 802.15.4 specifications [4]in the 2.4 GHz Industrial Scientific and Medical (ISM) band aims to provide low power short range control capability at low data rates. Since a node based on the IEEE 802.15.4 standard is designed to accommodate a wide range of applications, the cost is still high for wide consumer acceptance. Also the implementation flexibility for both indoor and outdoor applications place stringent demands in hardware and signal processing, thus increasing the cost.

Thus, our objective is to design an energy efficient wireless transceiver in order to set up a wireless network in indoor environment scenarios. By addressing various features such as architecture, frequency allocation, data rates, modulation technique used etc., of the transceiver system this goal can be achieved. While many transceiver architectures are used, the heterodyne architecture [5] still holds advantages in terms of image rejection and better selectivity. This research paper deals with the design and simulation of a 2.4 GHz Radio Frequency (RF) heterodyne transmitter and receiver based on Alternate Quadrature Differential Binary Phase Shift Keying (AQ-DBPSK) modulation and investigates the issues involved.

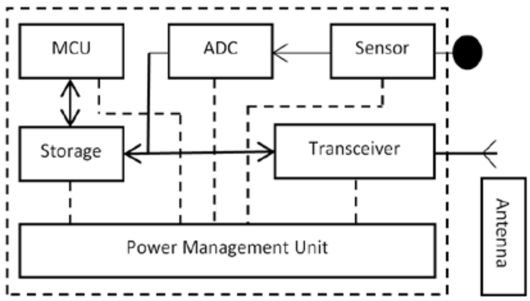

Fig.1 Core of a sensor network.

2 Related Work

In recent years, both academia and industry have shown interest in WSNs. Many techniques are used to simplify the transceiver structure. Rabaey et al. [6]have reported power oscillator based transmitter in which the oscillator is used instead of power amplifier. They have used an accurate 90μW FBAR1 reference oscillator to lock the power oscillator by injection process. Envelope detectors have been used widely in WSN receivers, not only as amplitude detectors, but also as nonlinear low pass filter to discriminate the FSK signals [7]. In [8], a direct controlled oscillator (DCO) is used in transmitter mode and IFLD is used in receive mode to reduce power consumption. At the base band level also, the modulation and demodulation techniques used provide high energy efficiency, fast synchronization and simplicity of modulator/ demodulators [9, 10]. There are systems developed by universities, which use very simple and low power modulation techniques like On–Off Keying (OOK), achieving very low energies near 1 nJ/bit [11].

In this paper, we present transceiver architecture suitable for indoor WSN applications based on AQ-DBPSK modulation at 2.4 GHz ISM band. By choosing AQ-DBPSK modulation, a simple transmitter with high efficiency and low spurious emissions can be realized. Also since this modulation scheme excludes the need for phase acquisition and tracking, the receiver simplicity is also obtained. Selection of the proper transceiver architecture depends on the requirements of the respective application. Traditionally used narrow band architectures [12] include super heterodyne, Zero-IF (Zero-Intermediate Frequency) and Low-IF architectures. The proposed transceiver employs heterodyne architecture, which has benefits in higher selectivity and zero dc offset. This paper is organized as follows: Section 3 presents the physical layer specifications required for the design. Link budget analysis and transceiver architecture are detailed insections 4 and 5. Simulation results and analysis are elaborated in section 6. Section 7 concludes the paper.

3 Physical Layer Specifications

The proposed physical layer specifications have the potential to provide wireless communication for dense WSN deployment in indoor environments.

3.1 Carrier Frequency

There are several bands allocated for unlicensed operation for wireless communications [13]. The 2.4GHz band with a total available bandwidth of 83MHz has been chosen since higher carrier frequencies have the main advantages of higher immunity and antenna integration possibility. Selecting Intermediate Frequency (IF) is a compromise between the image reject capability in one side, and the IF stages power budget and the detector performance, on the other side. Better image signal rejection is achieved in higher IF and better detection and more low power and flexible IF stage is obtained at lower IF frequency. The 70 MHz IF frequency provides a good compromise[5].

3.2 Data rate

Sensor networks typically have a low data rate, on the order of hundreds to thousands of bits per second. Low data rate transceivers have a strong correlation with low power consumption, due to simplified architecture and reduced bandwidth. However, for transmitter and receiver, increased energy efficiency can be achieved by using higher data rates and duty cycling the transceiver rather than using kbps data rates [14]. Hence, a data rate of 1 Mbps is proposed. Such data rate allows increased energy efficiency while not placing excessive demands on the transceiver. However for higher data rates, the sensitivity is reduced.

3.3 Modulation

There is a great need for a modulation and demodulation technique that is immune to noise and interferences while efficiently using the transmitted power and are simple to implement. The M-ary schemes are best suited for longer distances[9]. For short distances (10m - 20m), the binary schemes are more energy efficient [10, 14]. AQ-DBPSK has been developed with the basic concept of Differential Binary Phase Shift Keying (DBPSK) [15]. The basic principles of AQ-DBPSK are based on the quadrature phase difference phenomenon. The input bits are first divided into odd and even symbols. All odd symbols are sent in quadrature with the even symbols, so the data which is to be sent is achieved with a phase difference of 0° and 180° between the same parity symbols. Thus, this operation achieves $\pm 90^{\circ}$ phase transition between all adjacent symbols. Low peak factor of the system allows the transmission of signal in full-saturation mode without any additional regeneration of side lobes in power spectrum. Since regeneration of side lobes provides inefficient utilization of power by transmitter, AQ-DBPSK provides increased transmitter efficiency.

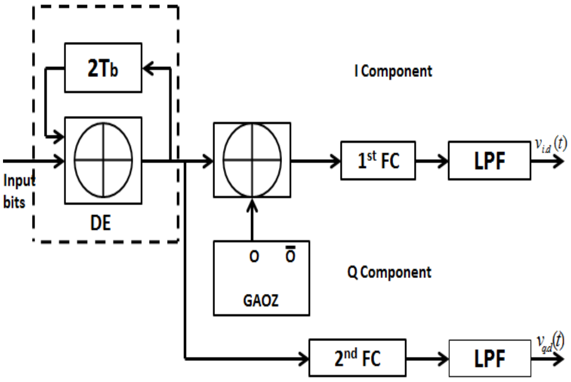

Fig.2 Block diagram of AQ-DBPSK Modulator.

The block diagram of the AQ-DBPSK modulator [15] is shown in Fig. 2. The input data bits of length T_b that contains the transmission data is fed to the Differential Encoder (DE). The DE contains a Modulo 2 summing and digital memory with two bit delay. The differentially encoded output describes the encoding bits using (1).

$$b_1 = a_1, b_2 = a_2, b_k = a_k \oplus b_{k-2} \qquad for \quad k \geq 3 \qquad (1)$$

Here k is the symbol number, a_k is the input of a DE and b_k is the differentially encoded output. The Generation of Alternating Ones and Zeros (GAOZ) block creates alternating sequence of ones and zeros. This sequence is summed modulo 2 with the differential encoded data. The Frame Converter (FC) then maps the data with two bit digital symbols according to the rule, ‘1’ to ‘-1’ and ‘0’ to ‘+1’. The I and Q component data are filtered using Low Pass Filters (LPF) to ensure suppression of side-lobes in the signal spectrum and also to provide ± 90° phase transition between adjacent symbols.

The advantages of the non-coherent AQ-DBPSK demodulator are that it simplifies the synchronization by excluding the need for phase acquisition and tracking. The only difference between DBPSK and AQ-DBPSK signals is a longer delay between the symbols carrying the data because DBPSK conveys the data by the phase differences between adjacent symbols, whereas AQ-DBPSK does it by the phase differences between the same parity symbols. Binary “0” in AQ-DBPSK is transmitted by the waveform represented by s_1 (t) [15]

$$s_1(t) = \begin{cases} s_o \sin(2\pi f_o t + \psi_o), & 0 < t < T_b \\ s_o \sin(2\pi f_o t + \psi_o), & 2T_b < t < 3T_b \end{cases} \qquad (2)$$

Binary “1” is transmitted by the waveform represented by s_2 (t)

$$s_2(t) = \begin{cases} s_o \sin(2\pi f_o t + \psi_o), & 0 < t < T_b \\ s_o \sin(2\pi f_o t + \psi_o), & 2T_b < t < 3T_b \end{cases} \qquad (3)$$

The block diagram of the noncoherent demodulator is shown in Fig. 3. The demodulator uses two correlators and differential decoder (DD) to retrieve the digital transmitted data.

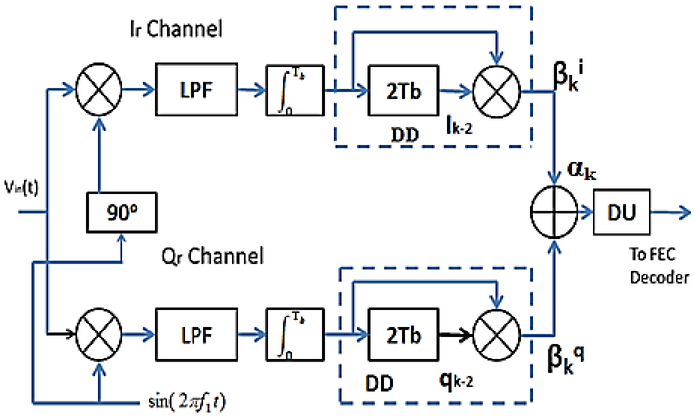

Fig.3Block diagram of AQ-DBPSK demodulator.

Both AQ-DBPSK and DBPSK use the symbols of the same length and convey the data by phase differences equal to 0° or 180°. Therefore, they have the same Euclidean distance. Since, their demodulation procedures are identical; they have the same energy efficiency in AWGN channels.The probability of error, P_b for AQ-DBPSK in AWGN channel [15] is given in equation (4) where E_b is energy per bit and N_0 is one sided noise power spectral density.

$$P_b = 0.5 \exp(-E_b / N_o) \qquad (4)$$

The BER curve for simulated AQ-DBPSK modulation is shown in Fig.4. To achieve the same BER of 10^{-3}, the E_b/N_o required in Rayleigh Fading channel is 21.6 dB. The poor error performance is due to the non-zero probability of deep fades when instantaneous BER can become very low.

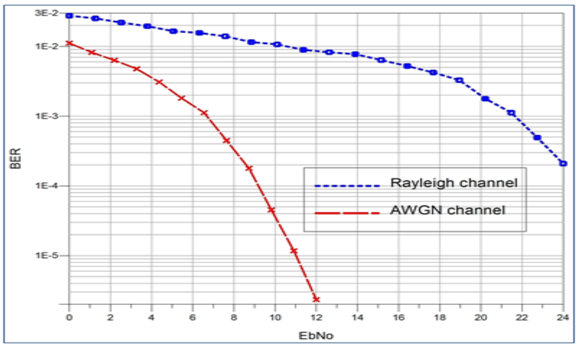

Fig.4. BER performance of AQ-DBPSK in AWGN and Rayleigh Fading Channel

4 Link Budget

The transmitter output power can be optimized to minimize the total power consumption in the transceiver system. At very low radiated power, the receiver will consume more power to increase its sensitivity [13]. So, there is an optimum level of transmitter output power, for which the total transceiver power consumption is reduced. For a given bandwidth and Signal to Noise Ratio (SNR) requirement in a receiver, the receiver Noise Figure (NF) determines the receiver sensitivity [16]. Then the NF determines the transmitter output power level for a given link budget.

The link analysis for indoor communication at 2.4 GHz, taking into account 30 dB fading margin and a communication range of 20 m is presented. Several parameters affect the signal on its propagation through a channel. The path loss increases when the range is increased. The attenuation loss L_{path}may vary depending on Line-Of-Sight (LOS) or Non LOS (NLOS) propagation. The LOS path loss can be expressed in terms of carrier frequency (f_c), distance between transmit and receive antenna (r) and r_0 is the reference distance for free-space propagation [17].

$$L_{path,LOS}[dB] = 27.56dB - 20\log_{10} f_c[MHz] - 20\log_{10}\frac{r[m]}{r_0[m]} \quad (5)$$

Using equation (5) the NLOS path loss can be expressed by equation (6)

$$L_{path} = L_{path,LOS} - 10n\log_{10}(\frac{r}{r_0}) \quad (6)$$

where$n$ is the path loss exponent, which indicates how fast the path loss increases with distance, $L_{path,LOS}$ is the corresponding propagation loss of the LOS path. For indoor scenarios [18], taking n=4 and assuming the reference distance as 3 m, the $L_{path,LOS}$is ≈ -56.52 dB and that of $L_{path}$is ≈ -89.4 dB.

The minimum received signal strength is the minimum signal the receiver should be able to detect and is called receiver sensitivity RX_{sens}. The receiver sensitivity can be expressed in terms of thermal noise power, receiver noise bandwidth (*BW*), required SNR at the input of the demodulator (SNR_{demod}) and receiver Noise Figure (*NF)* as given in equation (7).

$$RX_{sens} = 10\log_{10} \mathrm{BW} + SNR_{demod} + NF - 174[dBm] \quad (7)$$

The error probability, P_b of the AQ-DBPSK signal can be expressed using (4). The relation between SNR and E_b/N_0can be expressed using equation (8).

$$SNR = (E_b / N_0)\times(D/W) \quad (8)$$

Here D is the system data rate and W is the system bandwidth occupied by the signal in baseband. In order to achieve a data rate of 1 Mbps, the bandwidth required is 2 MHz [18]. For AQ-DBPSK modulation, to achieve BER of 10^{-3}, E_b/N_0 is 7 dB [20]. The required transmitter output power (P_{tx}) is given by

$$P_{tx} = RX_{sens} + L_{path} + F \quad (9)$$

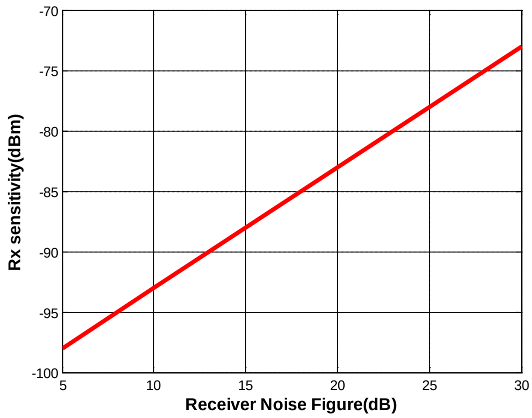

Fig.5 Receiver Sensitivity vs. Receiver NF for 10^{-3} BER

where F is the fading margin. In a rich-fading indoor environment, the signal fades by typically 30dB [13, 18]. Tradeoffs exist between receiver sensitivity, receiver noise figure and transmitter output power to obtain low power consumption. Fig.4 shows the receiver sensitivity versus receiver noise figure for BER of 10^{-3}. Fig.5 shows the receiver noise figure versus transmitter output power for 20m range. For a transmitter output power of 0dBm, according to

Fig.5 the receiver noise figure for 30dB fading margin is about 18dB and from Fig.4 the resultant receiver sensitivity is -83dBm.

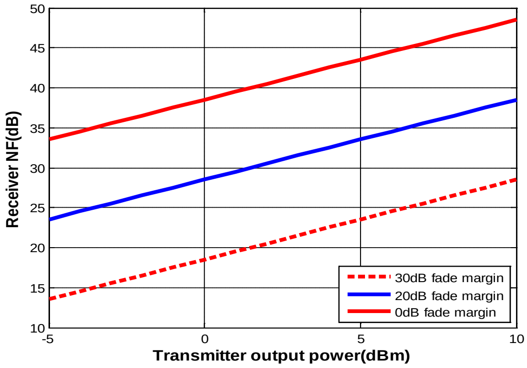

Fig.6 Receiver NF vs. Transmitter output power.

Based on the link budget analysis the transceiver specifications are tabulated in table 1

TABLE1
TRANSCEIVER SPECIFICATION

Parameters	Specifications
Frequency	2.4 GHz
Communication Range	20 m
Modulation Scheme	AQ-DBPSK
Data Rate	1Mbps
Transmitted Power	0 dBm
Channel Bandwidth	2 MHz
Receiver Sensitivity	-83dBm
BER	10^{-3}

5 Transceiver Architecture

The transceiver is designed for AQ-DBPSK modulation with a data rate of 1 Mbps. This data rate is more than sufficient for indoor WSN applications and is good enough for some basic multimedia applications [3]. The modulation technique used avoids carrier synchronization, allowing for simple non coherent detection. [9]. For a targeted Bit Error Rate (BER) of 10^{-3}, the operating range of 20 m can be achieved at transmit power of 0 dBm and receiver sensitivity of-83dBm. The proposed system ensures that power hungry phase locked loops are not used in the architecture.

5.1 Receiver Architecture

Fig.7 shows the architecture of the receiver. Its RF part includes a Band Pass Filter (BPF) for image rejection and a Low Noise Amplifier (LNA) to raise the signal level and screen the noise of the subsequent stages. The mixing stage down converts incoming signal of frequency f_{RF}, to Intermediate Frequency(IF) f_{IF}, using a Local Oscillator(LO) of frequency $f1 = f_{RF} - f_{IF}$. At IF, a second filter selects the channel and removes the unwanted mixing-product around $2f_{RF} - f_{IF}$. A subsequent high-gain amplifier, amplifies the IF signal to facilitate further treatment.

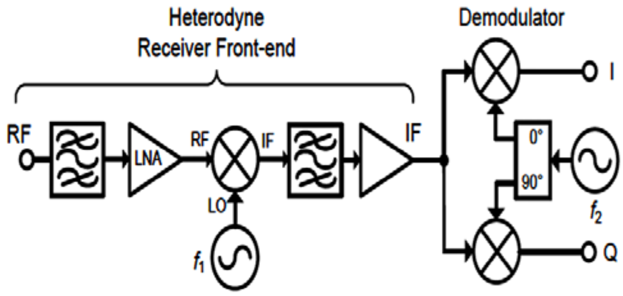

Fig.7 Block Diagram of Heterodyne Receiver Front-End with subsequent I/Q demodulator.

5.2 Transmitter Architecture.

Fig. 8 shows the block diagram of the transmitter. The first stage resembles a direct conversion transmitter, but converts to a lower Intermediate Frequency (f_{IF}) rather than directly to the output frequency. In addition to the first conversion, this part provides quadrature modulation. The second mixer up converts the signal to the output frequency (f_{RF}).

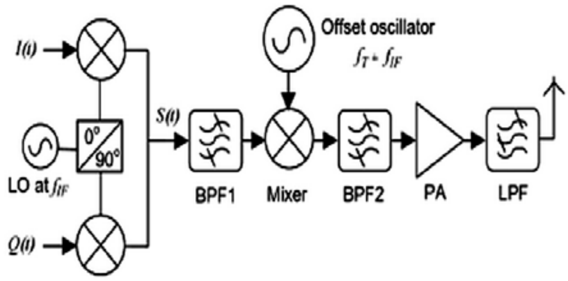

Fig.8 Block Diagram of Transmitter front end with subsequent I/Q modulator.

During this conversion, an unwanted image sideband is created, which has to be removed by a very selective band pass filter. Since both LOs work at lower frequencies compared to a direct conversion transmitter, I and Q matching achieved is superior and a higher spectral purity of the carrier can be achieved. The IQ demodulator added at the output of the heterodyne receiver front-end demodulates the complex baseband signal. While its topology resembles a direct conversion receiver, it does not exhibit its disadvantages because of the much stronger input signal due to the IF amplifier and the lower input frequency. The block level parameters of the transmitter and receiver are listed in tables II and III respectively.

6 Results and Discussions

The entire transceiver chain is designed in Agilent Advanced Design System (ADS) software tool and shown in Figure 9. The Signal constellation at the AQ-DBPSK modulator is shown in Fig 10. The signal points present in 1st quadrant and 3rd quadrants are even symbols whereas the points in 2nd and 4th quadrants represent odd symbols. So the phase shifts of adjacent symbols are +90° or -90° and phase shifts between symbols of same parity is 0° or 180°. Thus, ±90° phase transition allows the system to operate in full-saturation mode which will avoid the regeneration of the spectrum side-lobes. Also, the ±180° phase transition between same parity symbols allows the AQ-DBPSK modulation to provide high energy efficiency.

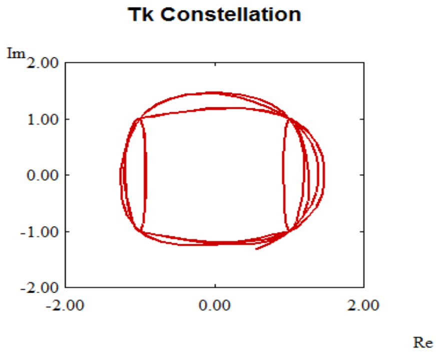

Fig.10 AQ-DBPSK signal constellation.

The Power spectrum of the AQ-DBPSK and DBPSK transmitted signal is shown in Fig 11. The Agilent Vector Signal Analyzer (VSA) 89600 software is used for this purpose. Since a rectangular pulse results in the generation of side lobes which is a major cause for inefficient utilization of transmitter power, a raised cosine pulse shaping is used. This gives maximum power in the main lobe and provides more power to the power amplifier, improving transmitter power utilization. The relative difference between the signal power in the main channel and the signal power in theadjacent or alternate channel are termed as

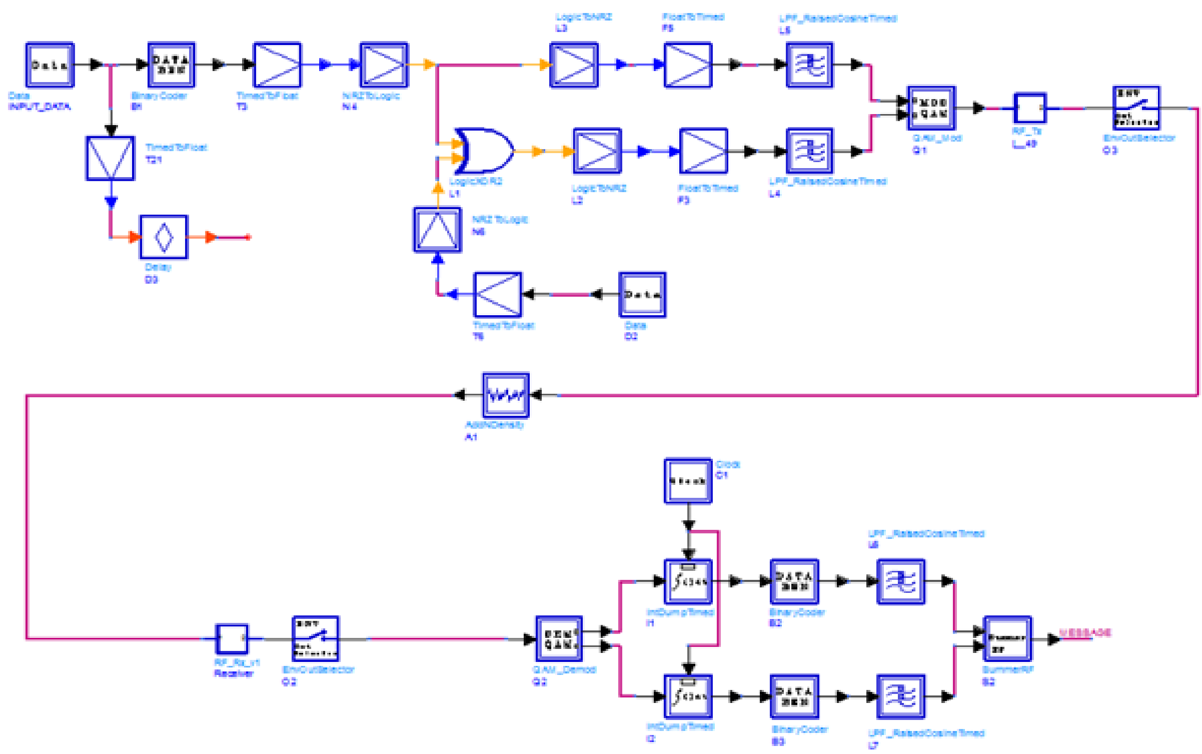

Fig.9 CompleteTransceiver Chain

TABLE 2
CIRCUIT BLOCK PARAMETERS OF TRANSMITTER

Mixer	Filter	Amplifier 1
Con gain=-8dBm	Fcenter=2.4 GHz	S21=13 dB
S11=-35 dB	BWpass=20 MHz	S11=-130 dB
S22=-35 dB	BWstop=40 MHz	S22=-30 dB
S33=-35 dB	Astop=40 dB	S12=-30 dB
IIP3=26 dBm	ILoss=1 dB	NF=5 dB
		IIP3=13

TABLE 3
CIRCUIT BLOCK PARAMETERS OF RECEIVER

Filter	LNA	Mixer	Filter	Amplifier 1	Amplifier 2
Fcenter=2.4 GHz	S21=20 dB	Con gain=-8 dB	Fcenter=70 MHz	S21=20 dB	S21=20 dB
BWpass=20 MHz	S11=-15 dB	S21=-35 dB	BWpass=10 MHz	S11=-20 dB	S11=-20 dB
BWstop=40 MHz	S22=-20 dB	S31=-35 dB	BWstop=40 MHz	S22=-20 dB	S22=-20 dB
Astop=40 dB	S12=-35 dB	S32=-35 dB	Astop=40 dB	S12=-35 dB	S12=-35 dB
ILoss=1 dB	NF=1.1 dB	IIP3=26 dBm	ILoss=2 dB	NF=3	NF=3
	IIP3=10 dBm			IIP3=20	IIP3=20

Adjacent Channel Power Ratio (ACPR) or Alternate Channel Power Ratio (AltCPR) respectively.Fig. 11 shows the reduction of side lobes in AQ-DBPSK. Compared to DBPSK the side lobes are reduced by about 10dBm.Fig. 12 shows the adjacent and alternate channel power measurements.

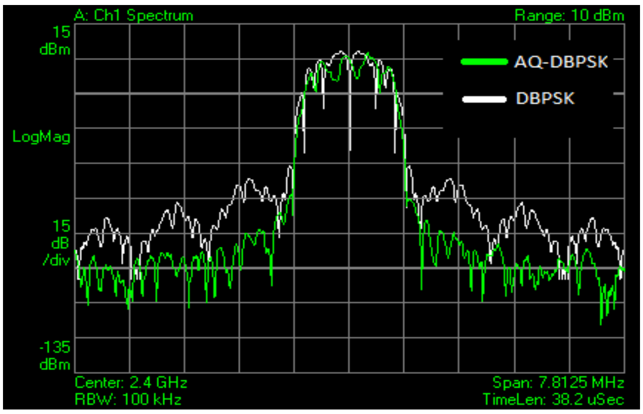

Fig.11Comparison of Transmitoutput spectrum for DBPSK and AQ-DBPSK.

The measured carrier power is 8.05 dBm, the ACPR is measured as –79.79 dBc (upper) and -79.41 dBc (lower). The AltCPR is –88.73 dBc (upper) and -88.99 dBc (lower). The difference between reference and received constellations is a measure of modulation accuracy termed as Error vector magnitude (EVM). For the proposed transmitter the EVM is 6.9 % which is acceptable for wireless sensor applications.

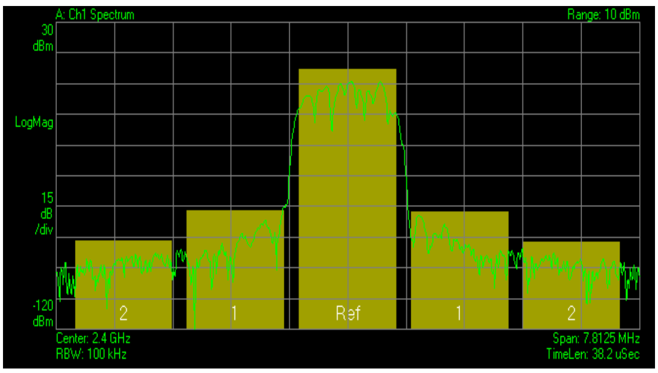

Fig.12 Adjacent and Alternate Channel power Measurements

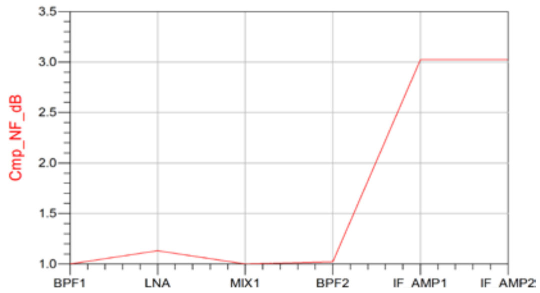

Fig.13 Noise Figure for Individual Components

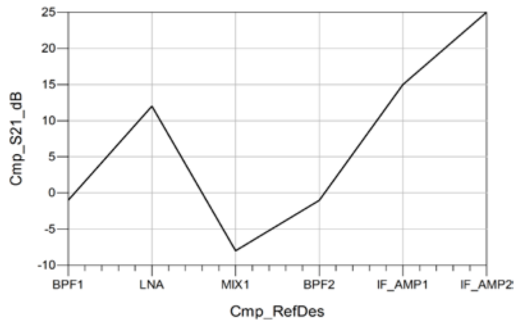

Fig.14 Gain of Receiver at Different Components

Fig. 13 and 14 presents the contribution of noise figure and gain respectively at the block level. The simulation results show a cascaded gain of 38 dB and a cascaded noise figure of 9.4dB. Fig. 15 shows the input digital waveform is and the demodulator output after compensating for delay. The original data is recovered without distortion. The Sensitivity performance of the system in AWGN channel was simulated and is shown in Fig.16. The receiver sensitivity for the specified BER was -83dBm conforming to the required specifications.Table 4 shows an overview of the commonly used transceivers in sensor node platforms. There is a tradeoff between the data rate and sensitivity. Lower data rate transceivers provide for bettersensitivity like the CC1000 which provides a data rate of 76.8 kbps with a sensitivity of -110dBm.Our AQ-DBPSK transceiver provides for higher data rates at 1Mbps compromising on sensitivity.

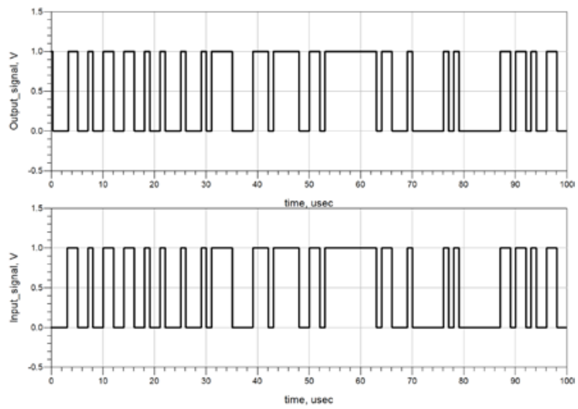

Fig.15 Input Digital Signal and Output Recovered Signal.

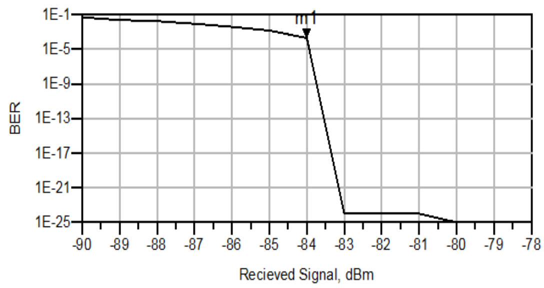

Fig.16 Sensitivity performance

TABLE 4
TRANSCEIVERS USED IN SENSOR NODE PLATFORMS

Transceiver	Band (MHz)	RF transmit power (dBm)	Max.Data rate(kbps)	Sensitivity(dBm)	Modulation
TR1000 (RFM) [21]	916.5	0	115.2	-106	OOK/ASK
CC1000(CHIPCON)[22]	300-1000	-20 to10	76.8	-110	FSK
CC2420 (CHIPCON)[22]	2400	-24 to 0	250	-94	OQPSK
nRF2401 [23]	2400	-20 to 0	1000	-80	GFSK
Ref [24]	2400	0	100	-90	BFSK
Our Work	2400	0	1000	-83	AQ-DBPSK

7Conclusions

Wireless sensor communication networks require modulation schemes with high energy efficiency and efficient utilization of transmitter power, particularly in indoor environments. These capabilities extend the lifespan of the transceiver batteries thus improving the lifetime of the node. The AQ-DBPSK scheme realizes these requirements by limiting the phase transitions between all adjacent symbols to ±90º. This contributes to the increase in transmitter power efficiency. In this research work, a transceiver architecture using AQ-DBPSK is presented. The spectral power of the AQ-DBPSK signal is calculated using Vector Signal Analyzer (VSA 89600) and found to be 8.99 dBm. The presented transceiver uses a heterodyne model for transmitter and receiver. Simulation results for the transceiver chain shows that the system gives EVM of 6.9%, and with a sensitivity of -83 dBm, it conforms to the proposed specifications. Our efforts in this work towards understanding transceiver architectures for wireless sensor communication networks will be very supportive to wireless network planners and for indoor location technologies and cognitive computing methods which are expected to proliferate across very wide variety of consumer devices over the next years.

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