where $i(k)$ is the in-phase channel integrator output, $q(k)$ is quadrature phase channel integrator output. $n_i(k)$, $n_i(k-2)$, $n_q(k)$, $n_q(k-2)$ are the in-phase and quadrature components of band pass noise signal which are uncorrelated zero mean Gaussian random variable with variance $\sigma_n^{\,2}$. The integrator outputs enter the Differential Decoder (DD) which contain $2T_b$ delay elements and a multiplier. The differential decoding in the in-phase channel is as follows :

$$\beta_1^{\,i} = i_1 \ , \ \beta_2^{\,i} = i_2 \ , \ \beta_k^{\,i} = i_k \times i_{k\text{-}2} \qquad for\ k \geq 3 \quad (7)$$

where $\beta_k^{\,i}$ are bits at output of DD. Similarly for the quadrature channel:

$$\beta_1^{\,q} = q_1 \ , \ \beta_2^{\,q} = q_2 \ , \ \beta_k^{\,q} = q_k \times q_{k\text{-}2} \quad for\ k \geq 3 \ \ (8)$$

where $\beta_k^{\,q}$ are bits at output of DD.

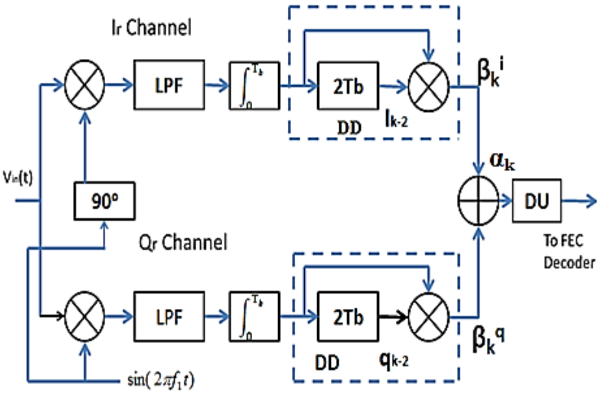

Fig.5. Block Diagram of AQ-DBPSK demodulator

The statistic α_k is formed by summing the output signals of the DD:

$$\alpha_k = \beta_k^{\,i} + \beta_k^{\,q} \qquad (9)$$

The Decision Unit (DU) forms a binary output signal using the sign and value of α_k. If $\alpha_k>0$, the DU decides that $g_1(t)$ was transmitted. On the other hand, if $\alpha_k< 0$, then $g_2(t)$ was transmitted.

The probability of error, P_b for AQ-DBPSK [4] in AWGN channel is given in equation (10) where E_b is energy per bit and N_0 is one sided noise power spectral density.

$$P_b = 0.5\exp(-E_b / N_o) \qquad (10)$$

The BER curve for simulated AQ-DBPSK modulation is shown in Fig.6 and is compared with DBPSK and BPSK. The E_b / N_o required for achieving a BER of 10^{-3} is 6.2dB. This is 0.4dB less as compared to BPSK which requires 6.6dB and 1.8dB less as compared to DBPSK which requires nearly 8 dB.

4.1 BER Comparison

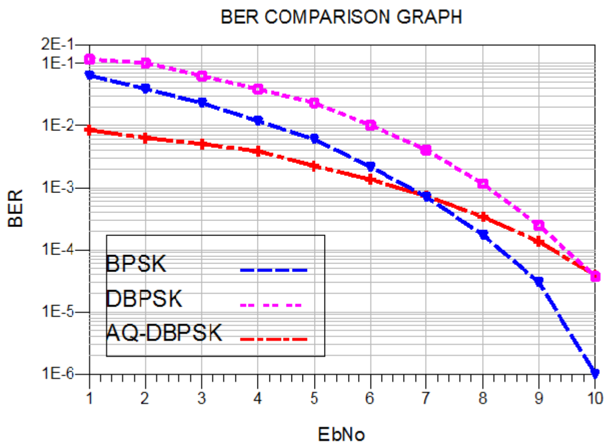

Fig. 6. BER comparison graph

Though BPSK shows better bit error rate performance for SNR > 7dB, the phase ambiguity problem and complex synchronization are major drawbacks. The DBPSK scheme excludes the phase ambiguity and need for phase acquisition and tracking but it has lower energy efficiency than BPSK. In AQ-DBPSK, though the BER is higher compared to BPSK, for higher SNR values, the reduction of phase shift between adjacent signals from 180° to ±90° reduces the side-lobe regeneration. This leads to better utilization of transmitter power compared to BPSK and DBPSK. For indoor applications, the AQ-DBPSK modulation performance in Rayleigh fading channel was also simulated as shown in Fig.7.

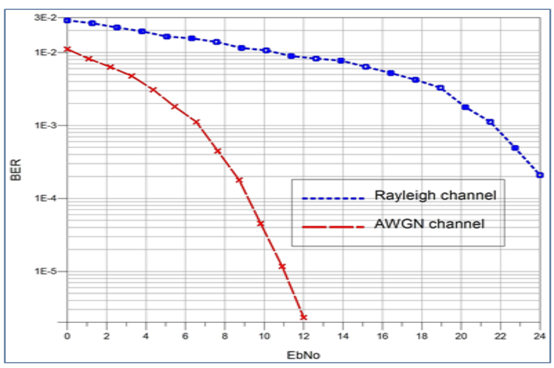

Fig.7. BER performance of AQ-DBPSK in AWGN and Rayleigh Fading Channel

To achieve the same BER of 10^{-3}, the Eb/No 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.

5 Performance using Pulse Shaping filters

As shown in Fig.8, the Phase Shift Keying (PSK) spectrum consists of a main lobe representing the middle of the spectrum and various side lobes located on either side of the main lobe. Using a pulse shaping filter at the baseband provides frequency limitation by generating band limited channel [16]. It also reduces the Inter Symbol Interference (ISI) from multiple signal reflections. So, selection of a proper pulse-shaping filter with an appropriate value of excess bandwidth would limit bandwidth of the channel with a moderate value of ISI. Though theoretically, the sinc filter is an ideal pulse shaping filter, it is non-causal with slowly decaying tails. So it cannot be implemented precisely. The raised cosine filters are practical to implement and is in wide use. These filters exhibit zero impulse response at the zero crossing points. Thus, if the transmitted signal is correctly sampled at the receiver, the original symbols can be recovered. The root raised cosine filter is used in series pairs, so that the total filtering effect is that of the raised cosine filter. This configuration sets up a matched filter, maximizing signal to noise ratio while minimizing ISI. Raised cosine filters have configurable excess bandwidth, so that tradeoffs can be made between spectral efficiency, simplicity and energyefficiency.

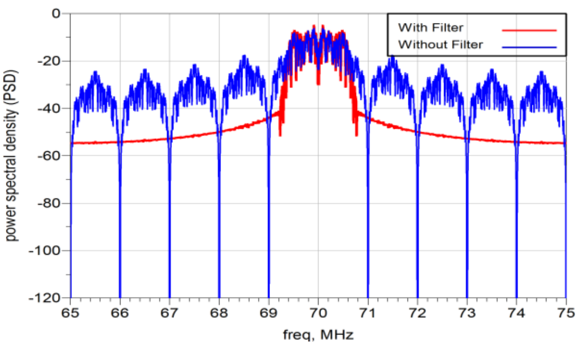

Fig.8. Power spectral density of BPSK signal

The Agilent Vector Signal Generator (VSG) was used to generate the BPSK and DBPSK signals. The results were measured at 70 MHz intermediate frequency and 1 MHz data rate. The results were analyzed using Agilent Vector Signal Analyzer (VSA). Various communication metrics such as magnitude error, phase error, bandwidth efficiency and BER for different values of excess bandwidth is plotted for both raised cosine and root-raised cosine filtering. In this paper, the normalized value of excess bandwidth is considered. This graphical comparison would provide selection criteria for the pulse-shaping filter excess bandwidth with respect to the different performance metrics.

5.1 Phase Error and Magnitude Error

Magnitude and phase errors are indicators of the quality of the amplitude and phase of the modulated signal. Fig.9 and Fig.10 show the phase error and magnitude error curve for the BPSK, DBPSK and AQ-DBPSK systems. For all these modulation schemes, the phase error and magnitude error curve fall rapidly in the range of excess bandwidth between 0.1 to 0.2. The curve falls very slowly between 0.2 to 0.5. For, excess bandwidth having 0.5 to 1.0, the value is almost constant. AQ-DBPSK with RRC filter provides the lowest phase error with excess bandwidth value between 0.2 to 0.5 whereas, with RC filter it provides lowest phase error with excess bandwidth = 0.35.

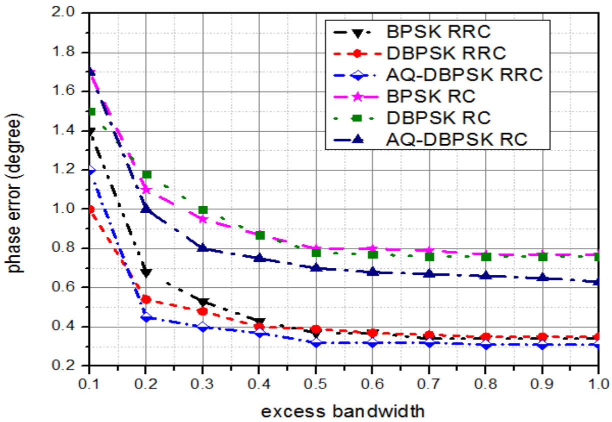

Fig. 9. Phase error curve for different modulation schemes

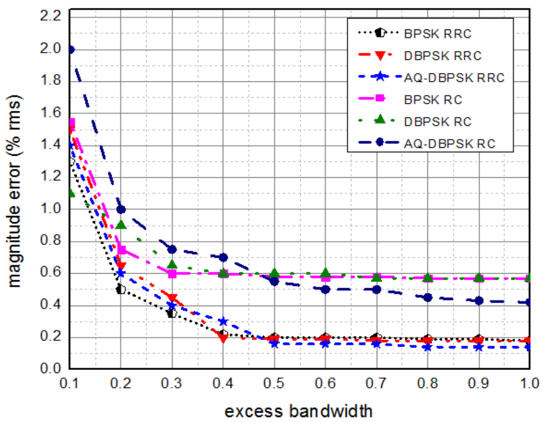

Fig.10.Magnitude error curve for different modulation schemes

In regard to magnitude error the AQ-DBPSK provides lowest magnitude error with excess bandwidth = 0.5 with RRC filter. Considering, magnitude error parameter, AQ-DBPSK format with RRC filter having excess bandwidth = 0.5 and with RC filter having excess bandwidth = 0.6 to 0.7 provide the lowest magnitude error.

5.2 Bit error rate measurement for different excess bandwidth

The variation of BER with excess bandwidth has been presented in Fig.11. The BER curve in Fig.12. shows that for AQ-DBPSK modulation, RRC filter with excess bandwidth =0.5 and RC filter with excess bandwidth=0.6 provide the lowest value of BER. For DBPSK modulation RRC filter provide minimum value of BER for excess bandwidth between 0.5 and 0.6.

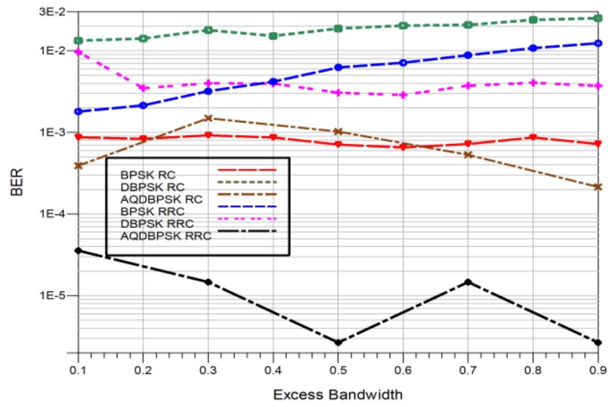

Fig. 11. BER curve for different Excess bandwidth

5.3 Bandwidth Efficiency Measurement

The power spectral density of the AQ-DBPSK modulator output was measured using Vector Signal Analyzer (VSA). The occupied bandwidth or Overall Bandwidth (OBW) is the bandwidth which contains 99% power. From this, the Bandwidth efficiency is calculated using equation (11).

$$Band\ width\ efficiency = \frac{data\ rate(bps)}{OBW\ (Hz)} \qquad (11)$$

The output power spectral density of the BPSK, DBPSK, AQ-DBPSK modulators were displayed using VSA. Then the value of OBW for various values of excess bandwidth for each modulation technique was tabulated as shown in Table 1. The bandwidth efficiency for each modulation scheme was calculated from the measured OBW for a data rate of 1Mbps and plotted against excess bandwidth as shown in Fig.12.

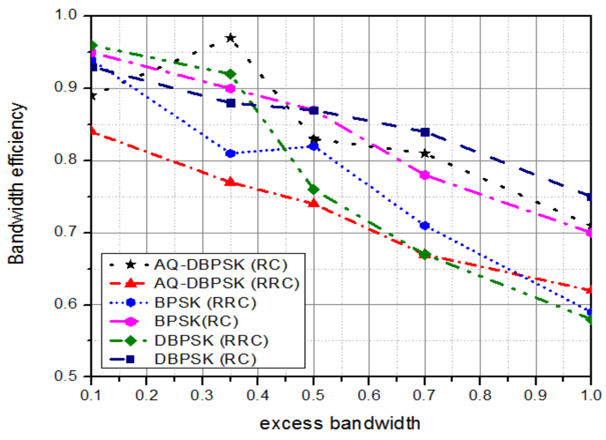

Fig. 12. Bandwidth efficiency for different excess bandwidth

As expected with increase in excess bandwidth, the bandwidth efficiency reduces. Since the other performance metrics remain stable for excess bandwidth greater than 0.5 to 1.0, the selection of bandwidth efficiency is made by comparing its value up to 0.5. DBPSK and BPSK with RC filtering shows high bandwiddth efficiency.

Table.1 Measured OBW And Calculated Bandwidth Efficiency With Different Excess Bandwidth

Excess Bandwidth	**AQ-DBPSK**			
	Raised-Cosine Filter		**Root-Raised Cosine Filter**	
	OBW (MHz)	**BW Efficiency (bps/Hz)**	**OBW (MHz)**	**BW Efficiency (bps/Hz)**
0.10	1.12	0.89	1.18	0.84
0.35	1.03	0.97	1.29	0.77
0.5	1.20	0.83	1.35	0.74
0.7	1.22	0.81	1.49	0.67
1.0	1.30	0.71	1.61	0.62
	DBPSK			
0.10	1.07	0.93	1.04	0.96
0.35	1.13	0.88	1.08	0.92
0.5	1.14	0.87	1.30	0.76
0.7	1.19	0.84	1.48	0.67
1.0	1.32	0.75	1.72	0.58
	BPSK			
0.10	1.05	0.95	1.06	0.94
0.35	1.10	0.90	1.22	0.81
0.5	1.14	0.87	1.21	0.82
0.7	1.28	0.78	1.4	0.71
1.0	1.41	0.70	1.68	0.59

The AQ-DBPSK spectral efficiency is poorer compared to DBPSK and BPSK. In AQ-DBPSK, the data is carried in alternate bit periods. So, the use of the narrow pulse shaping filters result in increase in ISI because more symbols can contribute. So this tightens the requirements on clock accuracy. Also it results in more peak carrier power due to higher overshoots.

The critical analysis of the results as discussed above is summarized in Table 2. The best choice of modulation format along with the proper pulse shaping filter and its excess bandwidth for each performance metric is given. It is apparent that the ultimate selection of the type of modulation and pulse shaping filter with proper excess bandwidth is made by appropriate trade off among the performance metrics.

Table.2 Performance Comparison of BPSK, DBPSK, AQ-DBPSK Modulation in Regard to Pulse Shaping Filters

Performance metric	Choice
Magnitude error	DBPSK, BPSK, AQ-DBPSK with RRC filter (excess bandwidth=0.5)
Phase error	DBPSK or AQDBPSK with RRC filter (excess bandwidth=0.5)
Band width efficiency	DBPSK, BPSK with RC filter (excess bandwidth = 0.4)
Bit error rate	AQ-DBPSK with RRC filter(excess bandwidth = 0.5)

6. Conclusions

In WSC based wireless networks, energy efficiency is of paramount importance in extending the lifetime of the node. This paper analyzes the performance of AQ-DBPSK modulation scheme under AWGN channel and Rayleigh fading conditions. The BER performance is shown to be superior to BPSK and DBPSK schemes. This makes it a good choice for energy efficient communication systems. Also since pulse shaping circuits influence the behavior of a modulation scheme, we have presented the analysis of different performance metrics such as magnitude and phase error, Bandwidth efficiency and BER of the BPSK, DBPSK and AQ-DBPSK techniques. The graphical representation of the results and its critical analysis could be used by system designers for choosing a proper modulation format with suitable pulse shaping filter. For wireless communication system designers, looking to maximize power and bandwidth efficiency, this work is beneficial from the system design point of view.

Acknowledgment

Authors are very much appreciative to the Department of Science and Technology (DST), Government of India for providing financial backing in accomplishing this research work.

References:

[1] Ian.F.Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, Erdal Cayirci, “A survey on sensor networks,” *IEEE Communications magzine*, Vol. 40, 102–114, August. 2002.

[2] F. Costa, H. Ochiai, “Energy optimization for reliable point-to-point communication in energy-constrained networks,” in *Proc. IEEE 2010 Vehicular Technology Conference*, VTC Spring, 1–5, May 2010.

[3] J.M. Rabaey, J. Ammer, T. Karalar, S. Li, B. Otis, M. Sheets, T. Tuan, "Pico Radio for wireless sensor networks: the next challenge in ultra-low power design," in *Proc.IEEE International Solid-State Circuits Conference: (ISSCC) Dig. Tech. Papers*, 200-201, 2002.

[4] Yefim S. Poberezhskiy, “Novel Modulation Techniques and Circuits for Transceivers in Body Sensor Networks,” *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, Vol.2, No.1, 96-108, March 2012.

[5] Y.S.Poberezhskiy, “Modulation and Spreading techniques for burst transmission,” in *Proc. IEEE Aerospace Conf. BigSky MT*, 1-11, March 2007.

[6] T.K. Sarkar, Zhong Ji; Kyungjung Kim; A. Medouri, M. Salazar-Palma, ”A Survey of various propagation models for mobile communication,” in *IEEE Antennas and propagation Magzine*, Vol.45, No.3, 51-82, June 2003.

[7] K.A.Qaraqe et al.,”Statistical wireless channel propagation characteristics in underground mines at 900 MHz: A comparative analysis

with indoor channel," *Ad hoc networks*, 2011, doi:10.1016/j.adhoc.2011.01.015.

[8] R. Ganesh, K. Pahlavan, "Statistical characteristics of a partitioned indoor radio channel," in *Proc. IEEE international conf. on communication*, 1252-1256, 1992.

[9] W.K. Tam, V.N. Tran, "Propagation modelling for indoor wireless communication," in *IEEE Electronics and communication engineering Journal*, 221-228, October 1995.

[10] T. Rama Rao, D. Balachander, "RF Propagation Investigations at 915/2400MHz in indoor corridor environments for Wireless Sensor Communications", *Progress in Electromagnetics Research B*, Vol. 47, 359-381, 2013.

[11] John G. Proakis, Masoud Salehi, "*Digital Communication"*, McGraw-Hill,5th Edition, 2007.

[12] B.Sklar "*Digital communication, fundamentals and applications"*, 2nd ed. Upper Saddle River, NJ: Prentice Hall PTR, pp.167-240, 2001.

[13] Kaur Harjot Jain, Bindiya Verma, Amit., "Comparative performance analysis of M-ary PSK modulation schemes using Simulink" *International Journal of electronics and communication technology*, Vol.2, No. 3, 204-209, September 2003.

[14] Chauhan Vikas, Arora, Manoj, Chauhan,R.S., "Comparative BER performance of PSK based modulation techniques under multipath fading," *Advances in Applied Science Research*, 521-527, 2011.

[15] Razavi, B., "*RF Microelectronics"*, Prentice Hall, Upper Saddle River, NJ,1998.

[16] Theodore S. Rappaport, "*Wireless Communications Principles and Practice"*, Pearson, Second Edition, 2002