Performance of Energy Efficient Source Coding and Interference Reduction in Wireless Sensor Network Systems

Md. Rezaul Hoque Khan, Roberto Passerone
Dipartimento di Ingegneria e Scienze dell'Informazione
University of Trento, Via Sommarive 14, I-38100 POVO (TN), ITALY
E-mail: [khan, roberto.passerone]@disi.unitn.it

Abstract

In this paper, our focus is on energy efficient coding schemes for wireless sensor networks. A source coding and modulation technique for reducing multiple access interference (MAI) as well as for reducing power consumption in MC-CDMA wireless sensor network systems is presented. In all our analysis we consider perfect power control mechanism. Source symbols are represented by a special coding, termed Minimum Energy coding (ME coding), which exploits redundant bits for saving power when transmitted via RF links with On-Off-Keying. This ME coding is applied to MC-CDMA sensor network systems in order to reduce MAI as well as to reduce power consumption. The proposed method is aptly suitable for wireless sensor video node in application of video coding.

1. Introduction

Wireless sensor networks hold the promise for a wide range of new applications. A sensor web can be used to collect information regarding environment, climate, it can be deployed in a battlefield for intelligence gathering and for scientific investigations on other planets. Because the nodes in wireless sensor network are powered by battery, energy efficiency has been a focus when devising of transmission for wireless sensor networks. Energy efficient source coding and modulation scheme means longer lifetime of the system. Furthermore, since the networks can be deployed in inaccessible or hostile environments, replacing the batteries that power the individual nodes is undesirable, if not impossible. Our main goal is to reduce the transmission power usage in the wireless sensor networks.

Since sensor nodes need to last several years on a single battery, energy saving is a top priority in wireless sensor network research. Low power designs try to reduce total power consumption. Recently, energy efficient calculation algorithms and circuit design techniques have been studied, and other authors have proposed scaling circuit voltage and frequency according to application requirements [1-3]. In [4], a low power, low complexity direct-sequence spread-spectrum (DSSS) modem is proposed, which reuses timing recovery circuitry. Nodes in a sensor network communicate with each other through wireless media and multiple access can be a serious problem due to the high node density. MC-CDMA is a promising multiple access scheme for sensor and ad hoc networks due to its interference averaging properties [5]. The performance of MC-CDMA systems is limited by multiple access interference (MAI). In sensor networks, this means that nearby nodes can overwhelm the received signal of the desired user. The minimum energy (ME) coding combined with DS-CDMA is proposed to address both power savings and MAI problems in [6]. ME coding reduces the number of high bits (i.e. the "1" bits) by inserting redundant bits, which result in an increased codeword length (bandwidth) with less high bits. Power saving can be achieved by using On-Off-Keying (OOK) because only the high bits are transmitted through the channel. As most bits in a codeword are zero, the MAI is also significantly reduced, allowing nearby users to co-exist and enhancing the bit error rate (BER) performance. To our knowledge, a performance study of MC-CDMA sensor network systems was yet to be reported.

In this paper, a ME MC-CDMA coding is proposed in order to further reduce the receive power and BER. A complete analysis of this minimum energy (ME) coding scheme is performed. We have considered a channel with frequency-selective fading that obeys the Rayleigh distribution. For the calculation of multiple access interference (MAI) we have used the Gaussian approximation [7]. The transmitter block of the generalized system is elaborated in Figure 1.

978-0-7695-3114-4/08 $25.00 © 2008 IEEE
DOI 10.1109/UKSIM.2008.82

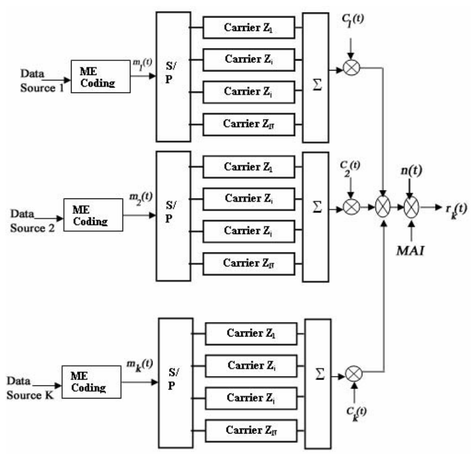

Figure 1: Transmitter of ME MC-CDMA wireless sensor network system

The remainder of this paper is organized as follows. Section 2 provides a brief motivation background on aspects of ME MC-CDMA wireless sensor networks systems pertinent to the subject of the paper. Section 3 provides related research in this field. Section 4 illustrates Minimum Energy Coding (ME-Coding). Section 5 introduces the following three sections by presenting an analytical model for ME MC-CDMA Sensor systems Model. Later sections present simulations and discussion with few areas for future research.

2. Motivation

Many energy constrained applications demand an energy efficient design to minimize power consumption and to extend operation lifetime. Having an energy-efficient underlying transmission and communication mechanism is critical to improve the overall effectiveness. In terms of power consumption, operation of a wireless sensor node can be divided into three parts: sensing, processing, and transmission. Among those three operations, it is known that the most power-consuming task is data transmission. Approximately, 80% of power consumed in each sensor node is used for data transmission [8]. So, energy efficient channel coding becomes the focus for WSN coding paradigm.

In [9], an extensive research has been conducted on power consumption by data compression and data transmission in wireless communication. In their experiments, the Compaq Personal Server, which is research version of the Compaq iPAQ, was used for data collection instead of wireless sensor nodes, so their experimental results may not be totally applicable for WSNs. However, it still gives significant insights of power consumption in data processing and transmission.

3. Related work

A simple and energy efficient source coded On/Off Keying modulation and near optimal error detection scheme for wireless applications is presented in [10]. This authors come up with an energy efficient coded modulation scheme that consumes comparatively less power both at system and circuit level. A simple On/Off keying (OOK) digital modulation scheme is used for this purpose.

In [11], source coding and channel coding algorithms minimizing the battery power needed for RF transmission are presented. The authors first formulate the minimum energy-coding problem for RF transmission. They derive the energy-optimal source-coding algorithm from the source statistics. Finally, they combine this energy-optimal source-coding algorithm with Hamming Codes for energy efficient error recovery. Overall, it takes a first step towards a novel energy saving wireless communication protocol.

C. Chien et al. present a direct sequence spread-spectrum modem architecture that provides robust communications for wireless sensor networks while dissipating very low power [12]. An On-Off keying based minimum-energy coding scheme with coherent receiver has been shown to provide better performance than BPSK [13]. This paper presents a closed-form expression of the BER performance of that scheme over an AWGN channel with either a coherent receiver or a non-coherent receiver. Wang *et al.* [14] showed BPSK is a preferred energy efficient scheme for low-data rate applications. A simple digital modulation technique such as OOK is totally ignored due to its low error performance. ME-coding was originally proposed by Erin and Asada [15]. In an effort to take advantage of OOK's feature (i.e., having to transmit only high bits), they map the source data bits into codewords that have fewer high bits in them and codewords with fewer high bits are assigned to messages with higher probabilities.

4. Minimum Energy Coding (ME-Coding)

For low data-rate wireless applications, the simplest form of digital modulation technique like On/Off keying (OOK) can also be considered. In OOK, the base band signal modulates a carrier wave at a higher frequency f_c and transmits it as RF waves. That is, a carrier signal is transmitted when a bit-1 is to be sent and no signal is transmitted when a bit-0 is to be sent. Figure 1 shows OOK transmitted signals for a sequence of bits. Hence, the transmitter expends energy only when transmitting a signal for bit-1. Thus, for a system that uses OOK modulation technique, the obvious way to reduce the energy consumed would be to reduce the number of bit-1's transmitted compared to the bit-0's. Since we have no control over the information source, the only way to reduce the high bits (bit-1s) would be to map a set of information bit sequence to a constant length codeword (ME Code) which has fewer bit-1's in it. This is originally based on the idea proposed by Erin and Asada [16]. They have formulated the power optimization problem for wireless communication applications with message source of known statistics. They bring about the reduction in energy consumption in two steps. Firstly, use a set of codes that have a smaller number of high bits. Secondly, they assign these set of codes to the messages in such a way that codes with fewer ones are assigned to messages of higher probabilities. They have also taken one step towards improving the performance of these codes by simple concatenation process. Their approach of ME Coding cannot be applied to sources with unknown statistics. We keep the basic idea of ME-Coding (source-bits mapped to code-bits) for source with unknown statistics (unknown probabilities of occurrence of symbols) and use a very simple near optimal detection process to improve the performance of ME-coding, thus proposing a new approach towards ME-coding.

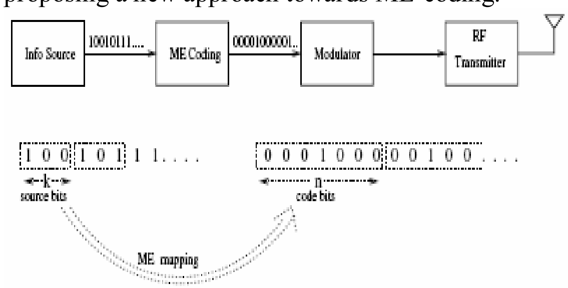

Figure 2: Block Diagram of ME Mapping Scheme

5. Analytical Model for ME MC-CDMA Wireless Sensor Network Systems Model

In our present work, we have designed an energy efficient analytical model for ME MC-CDMA wireless sensor networks systems. We have taken a system with K number of users, L number of multipath, N number of subcarriers and G is the processing gain. The chip length T_c is given by $T_c = T_b/G$ where T_b is the bit interval duration.

In the following sections, we will analyze the system performance with respect to SINR and BER.

5.1 Transmitted Signal Model

At the transmitter side, the configuration of an Energy-Efficient MC-CDMA system combined with the ME source coding. Data sources, k through K, are coded with the ME coding having sufficient redundant bits. The coded data stream having a bit duration of T_b is serial-to-parallel converted to N parallel substreams. The new bit duration of each substream or the symbol duration is $T_s=NT_b$. After serial-to-parallel conversion, the n-th substream modulates a subcarrier frequency f_n using On-Off-Keying (OOK) for n=1,2,……N. Then, the N subcarrier-modulated substreams are added in order to form the complex modulated signal. Finally, each channel of signal is spreaded with a unique pseudorandom (PN) sequence. The PN sequence, however, applies only to high bits of source code; for low bits, no spread signals are produced. Therefore, the transmitted signal of user can be expressed as:

$$S_k(t) = \sqrt{2P_k}\, m_{kn}(t-\tau_k) C_k(t-\tau_k) \cos(\omega_n t + \theta_k) \tag{1}$$

where P_k is the power of the transmitted signal, ω_c is the common carrier frequency, θ_k is a phase shift offset, m_k (t) and C_k (t) are the data and spreading signals for the k-th receiver respectively and τ_k is a random transmission delay calculated with respect to reference transmitted signal, accounting for the lack of synchronization among the users.

The data signal m_k (t) can be expressed as follows [17]

$$\mathrm{m_k}(t) = \sum_{j=-\infty}^{\infty} m_j^{(k)} \prod_t (jT, (J+1)T) \tag{2}$$

and the signature sequence signal

$$\mathrm{c_k}(t) = \sum_{j=-\infty}^{\infty} c_j^{(k)} \prod_t (jT_c, (J+1)T_c) \tag{3}$$

where $m_j^{(k)} \in \{-1,1\}$, $\prod_t (t_1, t_2)$ is the unit rectangular pulse on $[t_1, t_2)$, and $c_j^{(k)} \in \{-1,1\}$ with $c_j^{(k)} = c_{j+N}^{(k)}$. Because we are using ME coding to code the data, $P_r(m_j^k = 0) >> P_r(m_j^k = 1)$.

We assume the total number of asynchronous users is K and each sensor node has N subcarriers. Furthermore, it is assumed that the chip rate and the bit rate of message signals are fixed so that the processing gain G, is fixed by the ratio of the chip rate and the bit rate. Under these assumptions, when K signals obeying the form of "(1)" are transmitted over the frequency-selective fading channels, the received signal including the other-user interference, fading and the background noise at the base Node can be modeled as

$$r_k(t) = \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{l=1}^{L} \sqrt{2P_k} m_k(t-\tau_k) C_k(t-\tau_k) \cos(\omega_c t + \theta_k) + n(t) \quad (4)$$

where n(t) represents the additive white Gaussian noise (AWGN) with zero mean and double-sided power spectral density of $N_0/2$.

5.2 Decision Statistic

Let us assume that the desired user is the first user. Let the correlation between the signals of the k-th sensor node with carrier n and signals of the V-th sensor node with carrier v be given. With no loss of generality, it can be assumed also that $\tau_{11}= 0$ and $\theta_{11} = 0$. Furthermore, there is no loss in generality in assuming that $\tau_k \in [0, T\}$ and $\theta_k \in [-\pi, \pi\}$ since we are only interested in time delays modulo T and phase delays modulo 2π. Then the output of the matched filter for the k-th sensor node using n-th subcarrier is

$$Z_{kn} = \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{l=1}^{L}\sqrt{2P_k} m_k(t-\tau_k) c_1(t) C_k(t-\tau_k)\cos(\omega_n t+\theta_k)$$

$$\cos(\omega_n t) + \sqrt{2P_1} m_1(t)\cos^2(\omega_n t) + n(t)\cos(\omega_n t) \quad (5)$$

$$= \sum_{l=1}^{L}\sqrt{\frac{P_k}{2}} I_1^k(\tau_k, \theta_k, m_k)$$
$$+ \sum_{l=1}^{L}\sum_{k=2}^{K}\sqrt{\frac{P_k}{2}} I_2^k(\tau_k, \theta_k, m_k)$$
$$+ \sum_{\substack{n=1\\ n\neq v}}^{N}\sum_{l=1}^{L}\sqrt{\frac{P_k}{2}} I_3^k(\tau_k, \theta_k, m_k)$$
$$+ \sum_{k=2}^{K}\sum_{\substack{n=1\\ n\neq v}}^{N}\sum_{l=1}^{L}\sqrt{\frac{P_k}{2}} I_4^k(\tau_k, \theta_k, m_k)$$
$$+ \sqrt{\frac{P_1}{2}} m_0^1 T_b + \eta \quad (6)$$
$$= I + D + R \quad (7)$$

Where, $m_k = (m_{-1}^{(k)}, m_0^{(k)})$

$$\eta = \int_0^T n(t) c_k(t)\cos(\omega_c t) dt$$

$$I_1^k(\tau_k, \theta_k, m_k) = \cos\theta_k [m_{-1}^{(k)} R_1^{(k)}(\tau_k) + m_0^{(k)} \hat{R}_1^k(\tau_k)]$$

$$R_1^k(\tau_k) = \int_0^{\tau} c_k(t-\tau) c_1(t) dt$$

And $\hat{R}_1^k(\tau_k) = \int_{\tau}^{T} c_k(t-\tau) c_1(t) dt \quad$ for $0 \leq \tau \leq T$

The first sum of terms in Z_{kn} is referred to as multiple access noise and the last term η in Z_{kn} is a Gaussian random variable due to integration of the Gaussian channel noise.

Noise Term R:
AWGN can be calculated as

$$R = \frac{\alpha_1^2 N_0 T_b}{4}$$

Desired Term D:
Signal power can be found by following

$$D = \frac{1}{T}\int_0^T \left(\sqrt{\frac{P_1}{2}} m_0^1 T_b\right)^2 dt \; = \frac{\alpha_1 P_1}{2} T_b^2 \quad \text{if } m_0^1 \in \{0,1\}$$

Where α_1 is the percentage of high bits for $m_1(t)$ during the transmission duration of T seconds.

Interference Term I:
The MAI can be calculated as

$$I = \sum_{l=1}^{L} \frac{\alpha_1 \alpha_K p_K}{2} \sigma^2_{I_1^{(K)}}$$
$$+ \sum_{l=1}^{L}\sum_{k=2}^{K} \frac{\alpha_1 \alpha_K p_K}{2} \sigma^2_{I_2^{(K)}}$$
$$+ \sum_{\substack{n=1\\ n\neq v}}^{N}\sum_{l=1}^{L} \frac{\alpha_1 \alpha_K p_K}{2} \sigma^2_{I_3^{(K)}}$$
$$+ \sum_{k=2}^{K}\sum_{\substack{n=1\\ n\neq v}}^{N}\sum_{l=1}^{L} \frac{\alpha_1 \alpha_K p_K}{2} \sigma^2_{I_4^{(K)}} \quad (8)$$

5.3 Analysis of SINR and BER

In any multiple access system, one of the fundamental design parameter is the signal-to-interference noise ratio (SINR) at the receiver, which measures the ratio between the useful power and the amount of interference generated by all the other sources sharing the same resource plus the noise. Therefore, the expression of SINR in the energy efficient MC-CDMA system can be found as

$$SINR_{ME} = \left(T_b^2 P\right) / \left(\frac{\alpha_1^2 N_0 T_b}{2} + \sum_{l=1}^{L} \frac{\alpha_K p_K}{2} \sigma^2_{I_1^{(K)}} + \sum_{l=1}^{L} \sum_{k=2}^{K} \frac{\alpha_K p_K}{2} \sigma^2_{I_2^{(K)}} + \sum_{\substack{n=1 \\ n \neq v}}^{N} \sum_{l=1}^{L} \frac{\alpha_K p_K}{2} \sigma^2_{I_3^{(K)}} + \sum_{k=2}^{K} \sum_{\substack{n=1 \\ n \neq v}}^{N} \sum_{l=1}^{L} \frac{\alpha_K p_K}{2} \sigma^2_{I_4^{(K)}} \right) \quad (9)$$

We take a similar simplistic approach as that of [18], in that MAI is assumed sufficiently well represented by an equivalent Gaussian random process. We assume perfect power control condition so that all transmitters' signals arrive at the receiver of transmitter 1 with the same power and the probability of transmitting high bits for each transmitter is the same, i.e., $m_1 = m_2 = = m_k$. Under these conditions we can show that equation "(8)" can further be simplified as

$$SINR_{ME} = \frac{\alpha_1}{\frac{1}{3G}\{(L + (K-1)L + (K-1)NL)\} + \frac{N_0}{2E_b}} = \frac{\alpha_1}{\frac{1}{3G}(LK + KNL - NL) + \frac{N_0}{2E_b}} \quad (10)$$

BER is expressed by the well-known relation

$$BER = Q\left(\sqrt{SINR}\right) \quad (11)$$

6. Simulation Results

Following the analytical formulation presented in section 5, we evaluate the performance of the ME MC-CDMA wireless sensor network system. We present the impact of noise and multipath propagation with SINR and BER characteristics. We use equation "(10)" and "(11)" to calculate SINR and BER respectively and measure the performance parameters by the number of simultaneous users.

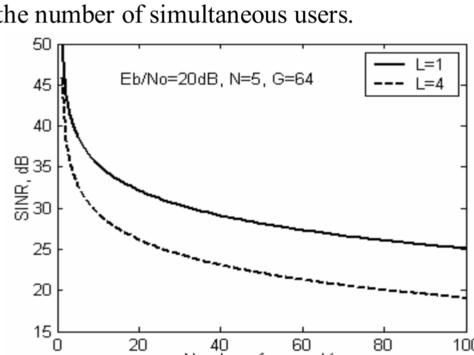

Figure 3: SINR versus the number of users with E_b/N_0=20dB, N=5, G=64, L=1, and 4.

From Figure 3, it is observed that keeping all other parameters constant, if the number of simultaneously active users is increased, the SINR decreases. As the number of users increases, the interference among the users increases, which in turn increases the MAI power and consequently, the SINR decreases. It is also observed that, if all other variables are kept constant, the SINR decreases with the increase of the number of fading paths L, i.e., with the increase of the number of signal propagation paths.

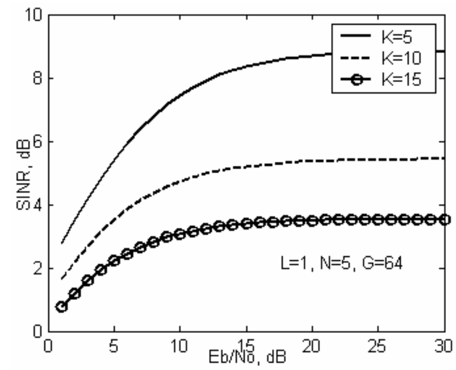

Figure 4: SINR for MC-CDMA system with E_b/N_0 using L=1, G=64, N=5.

The variation of SINR with E_b/N_0 using L=1, G=64, N=5, K=5, 10 and 15 is shown in Figure 4. From that it is seen that keeping all other parameters constant, if the ratio E_b/N_0 is increased, the SINR increases almost linearly up to a certain value. After that, the SINR becomes almost independent of E_b/N_0. This can be explained as follows. For lower values of E_b/N_0, the interference power caused by multiple users is negligible compared to the noise power. Consequently, for lower values of E_b/N_0, SINR is linearly related with E_b/N_0. Beyond that, the noise power becomes less significant compared to that of MAI. Hence the SINR becomes almost independent of E_b/N_0.

Next we compare the BER performance of asynchronous reception of ME MC-CDMA system in Figure 5.

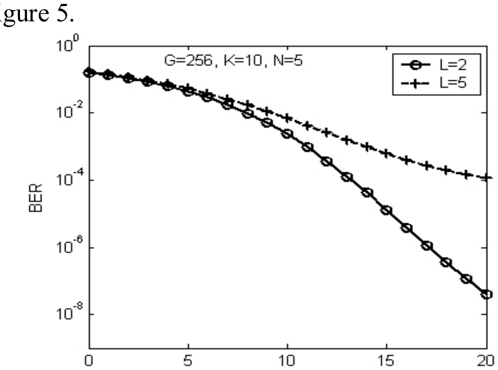

Figure 5: BER versus SINR for ME MC-CDMA system

This figure can be interpreted as follows: 1) At small SINR, where the impulsive, colored noise and fading effects dominate the multiple access interference (MAI) from other users, the system performance mainly depends on the diversity order achieved. 2) At large SINR where MAI dominates, due to the orthogonality between carriers and the narrow-band signaling on each carrier, the MAI caused by intercarrier interference is less than that caused by interpath interference.

7. Discussions

A signal model is obtained for the new source coding and transmission process, and the SINR and BER are analyzed. When each channel uses the ME coding combined with a spreading code and OOK, fewer high bits are transmitted and thereby the probability of multiple channels sending signals at the same time is lowered. This implies that the MAI is reduced. This way, an energy efficient MC-CDMA wireless sensor network system can greatly reduce the multiple access interference. In all our analysis we consider perfect power control conditions. The effect of imperfect power control conditions is part of our future research.

8. References

[1]. Y. Wang and A. P. Chandrakasan, "Energy-efficient dsps for wireless sensor networks," *IEEE Signal Processing Magazine*, pp. 68–78, July 2002.

[2]. A. Sinha, A. Wang, and A. Chandrakasan, "Energy scalable system design," *IEEE Trans. Very Large Scale Integration Systems*, vol. 10, no. 2, pp. 135–145, Apr. 2002.

[3]. C. Schurgers, O. Aberthorne, and M. B. Srivastava, "Modulation scaling for energy aware communication systems," *Proc., IEEE ISLPED*, pp. 96–99, Aug. 2001.

[4]. C. Chien, I. Elgorriaga, and C. McConaghy, "Low power direct-sequence spread-spectrum modem architecture for distributed wireless sensor networks," in *Proc., IEEE ISLPED*, Aug. 2001, pp. 251–254.

[5]. S. Toumpis and A. J. Goldsmith, "Capacity regions for wireless ad hoc networks," *IEEE Trans. on Wireless Communications*, vol. 24, no. 5, pp. 736–48, May 2003.

[6]. C. H. Liu and H. H. Asada, "A source coding and modulation method for power saving and interference reduction in DSCDMA sensor network systems," in *Proc., American Control Conf.*, May 2002, vol. 4, pp. 3003–3008.T. S. Rappaport*, "Wireless Communications: Principle & Practice,*" Prentice Hall PTR, New Jersey, 1996.

[7]. Naoto Kimura and Shahram Latifi , "A Survey on Data Compression in Wireless Sensor Networks" Proceedings of the *International Conference on Information Technology: Coding and Computing (ITCC'05)*

[8]. Kenneth Barr and Krste Asanovic, "Energy Aware Lossless Data Compression," In *First International Conference on Mobile Systems, Applications, and Services*, May 2003.

[9]. Y. Prakash and S. K. Gupta, "Energy efficient source coding and modulation for wireless applications," in *Proc., IEEE WCNC*, Mar. 2003, vol. 1, pp. 212–217.

[10]. C. Erin and H. H. Asada, "Energy optimal codes for wireless commutations," in *Proc., IEEE Conf. on Decision and Control*, Dec. 1999, vol. 5, pp. 4446–4453.

[11]. C. Chien, I. Elgorriaga, and C. McConaghy, "Low power direct-sequence spread-spectrum modem architecture for distributed wireless sensor networks," in *Proc., IEEE ISLPED*, Aug. 2001, pp. 251–254.

[12]. Qinghui Tang , etal., "BER performance analysis of an on-off keying based minimum energy coding for energy constrained wireless sensor applications", ICC 2005, *IEEE International Conference on communication,* Vol 4, 16-20 May 2005 Page(s):2734 – 2738

[13]. A. Wang, S. Cho, C. Sodini, and A. Chandrakasan, "Energy efficient modulation and MAC for asymmetric RF microsensor systems," in *Proceedings of the 2001 international symposium on Low power electronics and design*. ACM Press, 2001, pp. 106–111.

[14]. A. C. Erin and H. H. Asada, "Energy optimal codes for wireless communications," in *Proc. IEEE 38th Conf. Decision and Control (CDC03)*, Phoenix, AZ, USA, Dec. 1999.

[15]. A.C.Erin and H.H.Asada, Energy Optimal Codes for Wireless Communications*, IEEE Proceedings of the 38th Conference on Decision and Control*, PHX, AZ, Dec 1999.

[16]. C. H. Liu and H. H. Asada, "A source coding and modulation method for power saving and interference reduction in DSCDMA sensor network systems," in *Proc., American Control Conf.*, May 2002, vol. 4, pp. 3003–3008.

[17]. Khan Md. Rezaul Hoque, Luca Debiasi, Francesco G.B. De Natale, *"Performance analysis of MC-CDMA Power Line Communication system"*, in the proceedings of *fourth IEEE and IFIP International Conference on wireless and Optical communications Networks (WOCN2007),* July, 2007.