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Pulse Based Modulation Techniques for Wireless Nanosensor Networks

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Abstract:- Wireless nanosensor networks (WNSNs) which consists of numerous nanosensors, offer a number of promising applications in diverse fields like biomedical, environment, industrial, military etc. The extremely small size and the envisaged application environments in which WNSNs are expected to operate give rise to many issues for reliable wireless communication at nanoscale, which require re-design of the existing macroscale communication protocols. The promising virtues of carrier-less pulse-based modulation techniques, mainly energy efficiency, high reliability etc., make it appropriate for designing WNSNs communication protocols. The performance of four different carrier-less modulations for WNSNs, such as PAM, OOK, PPM and BPSK will be compared in this paper. In terms of Bit Error Rate (BER), complexity, energy efficiency and capacity these modulation schemes have different characteristics and exhibit different performance levels. Our study shows that if lower complexity is essential, the best option is to look out for OOK or PPM. PAM has poor performance in terms of energy efficiency and reliability. BPSK will be the first choice if higher power efficiency and robustness against error are the major issues to be considered.

Keywords:*-WNSN;BER; Pulse based modulation; Complexity; Energy Efficiency*.

I. INTRODUCTION

Due to recent developments in the nanotechnology, wireless nanoscale sensor networks (WNSNs) will be able to reach unprecedented locations, collect and share information at the molecular level, empower bottom up control of many industrial processes in domains like chemical, agricultural, environmental domains. However, the operating range of WNSNs is at macro level they cannot be realized with conventional sensor networks and wireless communication at nanoscale also faces some unique challenges. For example, WNSNs operate over very high frequencies like the Terahertz band (0.1-10 THz) using small antennas, which leads to the molecular absorption.

A Pulse Based Communication (PBC) system [1] works by exchanging short pulses between transmitters and receivers to show different symbols in the channel and also having the advantages like low equipment cost, high data rate, low power consumption , and noise immunity. These advantages of PBCs make them an appropriate candidate for designing WNSNs communication protocols. Different PBCs schemes like OOK, PAM, PPM and BPSK [2] can be adopted for WNSNs. These modulation schemes possessing varied characteristics display different performance levels in terms of energy efficiency, Bit Error Rate (BER). If lower complexity is required the best option is OOK. BPSK is the best candidate if robustness against error and higher power efficiency are required.

II. WIRELESS NANO SENSOR NETWORKS

Wireless Nanosensor Networks as in Fig.1 generally consists of four elements namely: Nano nodes, Nano router, Nano-micro interface and gateway.

A. Nano nodes

They are small devices with limited computational, and storage capabilities. They are spread into a target area for sensing and collecting the information from the area. Nanonodes also influence the performance of the WNSN because more the number of nanonodes more is the data for computation.

B. Nano router

The information coming from the nano nodes are aggregated and processed by the nano router and then they direct this information to nano-micro interface through nano-link. By sending short controlling messages nano router also controls the behavior of the system.

C. Nano-micro interface

These are the most complex hybrid devices which are the able to use classical communication paradigm to communicate with conventional communication networks and also can communicate in the Nano scale using Terahertz Band. These devices are used to aggregate the information coming from Nano router and convey this information to the micro scale and vice versa.

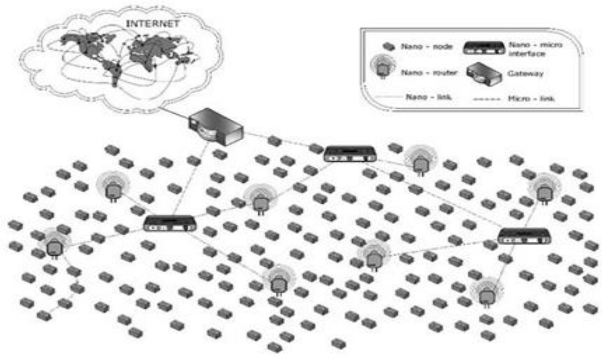

Fig 1:- Nano-micro interface

D. Gateways

Gateways enable the control of entire system over the internet remotely by collecting the information from the Nano networks and provide these information to the remotely placed monitor through internet.

The above elements can be static or dynamic based on the application. For instance, in the industrial arena we can assume that the topology of WNSN is static while in the health-care scenario the network topology can be dynamic. A limiting factor of THz band communication channel is molecular absorption, which are frequency selective [6]. The large molecular absorption loss along with the large free space path loss (FSPL) limits the maximum communication distances to a few meters.

- *Characteristics of WNSNs radio channel*

The most important propagation phenomenon in the THz band is molecular absorption, which is the distinguishing feature of the higher frequency bands. Absorption of energy also causes transmission induced noise. Molecular absorption is caused by the resonance frequencies of the molecules in the atmosphere. It causes random discrete frequency domain loss. However, because of the large numbers of molecules in a unit volume of the atmosphere, the molecular absorption loss is deterministic in practice. The molecular absorption is ultimately caused by the transmitted EM wave shifting the molecules in the medium to higher energy states. The energy, equivalent to the difference between the higher and the lower energy state of a molecule, determines the absorption energy that is drawn from the EM wave. This has a direct impact on the absorption frequency because the absorbed energy is E = h f , where h is the Planck constant and f is frequency. This process can be described stochastically by using the absorption coefficient $K_a(f)$. This quantity describes the average effective area of the molecules per unit volume. Let $K^i_{la}(f)$ is the absorption coefficient of the ith absorbing species then the total summed absorption coefficient is denoted as $K_{la}(f)$, i.e.,

$$K_{la}(f) = \sum_i K^i_{la}(f) \tag{1}$$

Molecular absorption noise is caused by the temperature of the absorbing atmosphere/ medium, causing the medium to be an effective black body radiator, or a grey body radiator in non-homogenously absorbing medium (in frequency domain). The molecular absorption noise is therefore known as a background noise and it is independent of the transmitted signals. the molecular absorption noise can be approximated as

$$N_{sn}(T_{A,} d, f) = k_B T_A W F_a (1 - e^{-K_a(f)d}) \tag{2}$$

Where W is the bandwidth of the system and F_a is a molecular absorption noise acceptance factor of the receiver (an aperture term for the noise). In the general case, $k_B T$ should be replaced by the Planck law.

Accordingly, loss to the received signal due to molecular and particle scattering is

$$A_{mol}(f)A_{sca}(f) = e^{(K_a(f)+K_s(f))r)} \equiv e^{K_e(f)r} = A_{ext}(f) \tag{3}$$

Where, $A_{ext}(f)$ is the total extinction loss with an extinction coefficient k_e(f).

If absorption loss and scattering loss are included then the total received LOS power at the receiver, can be calculated with

$$P_r = \int_W P_{Tx}(f) \frac{c^2 e^{-k_e(f)r}}{(4\pi f r)^2} \, df \tag{4}$$

Where P_{Tx}(f) is the PSD of the transmitted signal in W/Hz and W is a bandwidth over which the power is calculated.

- *Restrictions of WNSNS*

A single nanosensor in WNSNs is constrained by the limited capability, due to nanoscale components, particularly the extremely small nanobatteries. Hence, energy efficiency has been a critical issue for WNSNs. The energy-harvesting system in the nanoscale is still under researching and not mature, especially the current energy-harvesting rate is not sufficient to provide reliable data transmission. hence, energy optimization in WNSNs needs further investigation and improvement. WNSNs can take advantages of carrier-less pulse based modulation (PBM) schemes because it is difficult to generate high power carrier frequency in terahertz band due to limited energy storage capacity of nanosensors. PBM schemes are energetically more efficient and hence lead to low-complexity transceiver design. Four main carrier-less modulation schemes will be presented in the next section.

III. SYSTEM MODEL

A. *Single Pulse Representation*

Here, we assume two nanomotes communicate with each other through the proposed pulse based modulation scheme [4]. Transmitted pulse is considered as Gaussian pulse which is given below:

$$P(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(1/2)((t-\mu)/\sigma)^2} \tag{5}$$

Where μ is the centre of the pulse and σ relates to the width of the pulse.

- *The pulse energy, E then would be*

$$E = \int_{-\infty}^{\infty} [p(t)]^2 dt \tag{6}$$

B. *Pulse based Modulation schemes*

The transmitted binary baseband pulse modulated information signal x(t) can be presented as [5]

$$x(t) = d_j w_{tr}(t) \tag{7}$$

Where $w_{tr}(t)$ represents the pulse waveform, j represents the bit transmitted (“0” or “1”).

A. *PAM*

In case of pulse amplitude modulation, d_j is having two different amplitudes to represent the symbol to be transmitted

B. On-off keying

The second modulation scheme is binary on-off keying (OOK). Wherein,

$$d_j = \begin{cases} -1, & j = 0 \\ 1, & j = 1 \end{cases} \tag{8}$$

C. BPSK

BPSK modulation alternates the polarities of the pulses in response to the information to be transmitted. i.e.

$$d_j = \begin{cases} 0, & j = 0 \\ 1, & j = 1 \end{cases} \tag{9}$$

D. PPM

With pulse position modulation (PPM), the chosen bit to be transmitted influences the position of the pulse. That means that while bit "0" is represented by a pulse originating at the time instant 0, bit "1" is shifted in time by the amount of δ from 0. The signal can be represented as follows:

$$x(t) = w_{tr}(t-\delta d_j) \tag{10}$$

Where d_j assumes the following values, depending on the bit chosen to be transmitted,

$$d_j = \begin{cases} 0, & j = 0 \\ 1, & j = 1 \end{cases} \tag{11}$$

C. Energy per bit (E_b)

The average energy per bit for any modulation scheme, E_b can be calculated as:

$$E_b = \sum_{i=1}^{2} p_i \int_{-\infty}^{\infty} [x_i(t)]^2 dt \tag{12}$$

Where $x_i(t)$ and p_i are the waveform and transmitting probability of the i[th] symbol. The modulation parameters are considered as in TABLE I to make equal E_b for all modulations.

PAM	OOK	PPM	BPSK
$d_1 = 1.3$, $d_0 = 0.6$	$d_{OOK} = \sqrt{2}$	$d_{PPM} = 1$	$d_{BPSK} = 1$

Table 1. Modulation Parameters

It is assumed that $p_0 = p_1$. Hence, for all modulations Energy per bit (E_b) will be same as the Pulse Energy(E).

IV. PERFORMANCE ANALYSIS

To analyze the performance of modulation schemes various metrics are used like complexity, energy efficiency, reliability level, spectrum efficiency (capacity), etc. However, considering the restrictions of WNSN, the proposed modulation schemes should be able to provide high reliability with less least power consumption. Here, four modulation schemes proposed in the previous section are compared in terms of the complexity power efficiency and Symbol Error Rate (SER).

A. Reliability Analysis

For any binary modulation, the SER can be calculated using the distance between two symbols as

$$SER = Q\left(\sqrt{\frac{d}{2N_0}}\right) \tag{13}$$

This distance is different for each modulation scheme, i.e,

$$d_{PPM} = \sqrt{2\gamma_b}\,; \quad d_{PSK} = 2\sqrt{\gamma_b}\,;$$
$$d_{OOK} = \sqrt{2\gamma_b}\,; \quad d_{PAM} < \sqrt{2\gamma_b}\,; \tag{14}$$

Wherein, $\gamma_b = E_{RX}/N_0 = N_sE$ is the average bit energy in the receiver and E is its average pulse energy. As per the Table II, which indicates 'd' interms of pulse energy, shows that BPSK provides lower error because of the highest value of 'd'.For simplicity, let us assume Ns = 1 with a normalized pulse energy.

Scheme	Distance 'd ' interms of pulse Energy 'E'	SER interms of *E/N*
PAM	0.5 x E	$Q\left(\sqrt{0.125 \, x \frac{E}{N}}\right)$
OOK	2 x E	$Q\left(\sqrt{\frac{E}{N}}\right)$
PPM	2 x E	$Q\left(\sqrt{\frac{E}{N}}\right)$
BPSK	4 x E	$Q\left(\sqrt{2 \, x \frac{E}{N}}\right)$

Table 2. Distance 'd' as a function of Energy 'E' and SER as a function of E/N

In Figure 2 for 20 different SNR ranging from -15dB to 15dB, SER performance of different modulation schemes are shown. Equal average energy per bit is considered. It shows that BPSK has the highest SER performance and PAM has the lowest performance. However, PPM and OOK are having the same SER performance indication.

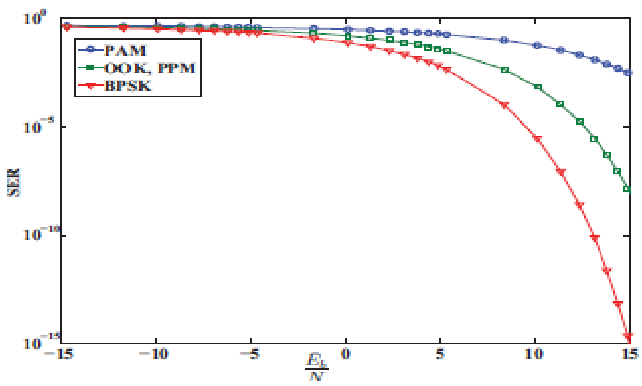

Fig 2:- SER performance of various modulations schemes

B. Power efficiency

It is preferable to use the modulation scheme which can provide better SER performance with minimum power requirement. However, for better SER, it is required to increase

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the signal power of transmission to increase the Euclidean distance between signals. For any binary pulse modulation scheme the power efficiency of is expressed as

$$\eta = d/E_b \quad (15)$$

For example, for BPSK modulation, two symbols are x(t) and −x(t) then we have:

$$\eta = \frac{d}{E_b} = \frac{\int_0^T [2 \times x(t)]^2\, dt}{\int_0^T x(t)^2\, dt} = 4 \quad (16)$$

Similarly, power efficiency for PAM, OOK & PPM are calculated as 0.5, 2,2 respectively. It shows that among all schemes BPSK has the highest efficiency.

C. Complexity

Hardware and software of the transmitter and receiver are required to be simple to avoid the complexity while designing modulation scheme for WNSNs. For each modulation complexity is discussed here.

- Transmitter : Complexity of the transmitter [3] depends on the pulse generator because its spectrum efficiency is determined by the signal shape and effectively dictates specific system requirements. It shows, BPSK system is having more complexity than other three schemes .
- Receiver:, coherent and non-coherent receivers [7] are the two different categories of receivers. To demodulate the information, coherent receivers are required to detect the carrier phase of the transmitted information, whereas, non-coherent receivers require only a match filter. Hence, WNSNs prefer only non-coherent receivers. It shows that to demodulate the transmitted signal non-coherent transceivers are used by OOK, PAM and PPM schemes and coherent demodulation is used by BPSK because of its bipolar nature.

V. SIMULATION

In WNSN, simulation and analysis of SER performance is shown here for different modulation schemes over the terahertz channel. it is explained in the previous sections that the molecular absorption noise is frequency sensitive because of the molecular absorption coefficient is frequency dependent. Here, we considered a channel with normal air having normal pressure/temperature of 1atm/296K and composition as in Table III. From HITRAN, molecular absorptions is extracted for frequencies from 0.1-10. We then simulate different modulation schemes in MATLAB and calculate the total path loss and total noise for distance equal to 1mm. The molecular absorption noise is indicated in fig.3.

Species	N_2	O_2	H_2O	CO_2	Others (CH_4, CO, O_3, N_2O)
Ratio (%)	77.39	20.71	1.86	0.032	0.000218

Table 3. The composition of Normal Air

Twenty different power levels are considered ranging from 10-1000 fW (10−14 − 10−12) that have been equally spaced in this range. We randomly generate a stream of digital data, TestData, including one million bits with equal probability for ‘0’ and ‘1’. Over the terahertz channel, we transmit the TestData for each power level/modulation and in the receiver we measure the SNR for each single bit of the message and calculated the SER. For SER, using the modulation scheme, TestData is transferred first and is demodulated in the receiver. Receiver output is compared with the Testdata for calculation of SER. SER for different modulation schemes is shown in Fig.4. It shows that better reliability will be provided by BPSK and OOK and PPM performance is approximately similar as indicated in Section IV-A.

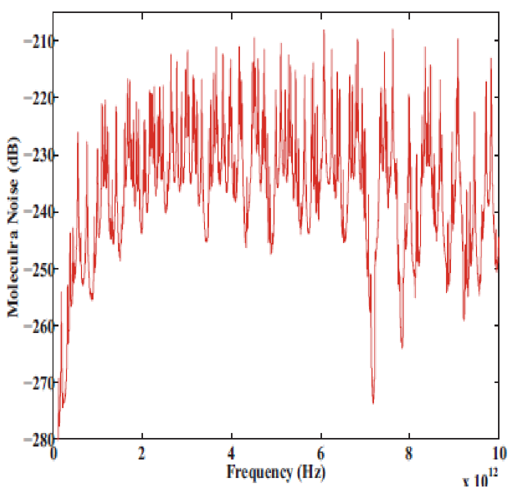

Fig 3:- Molecular noise (in dB) vs frequency in terahertz band in a channel with standard air composition at normal pressure/temperature

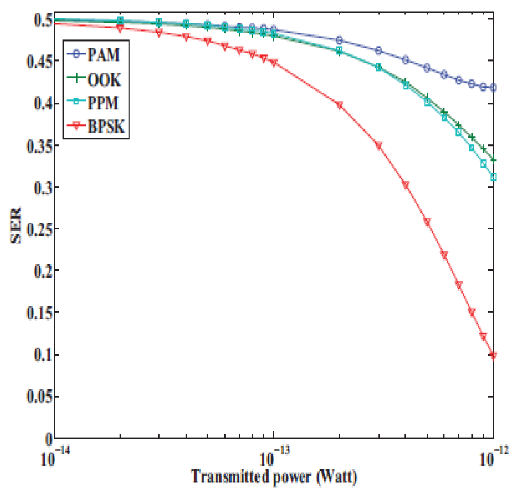

Fig 4:- Ser Evaluation For Different Modulation Schemes

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- Summary of the total work in this paper is given in the below (TABLE IV):

- Analytical framework for comparison of SER performance of different Pulse based modulation schemes is provided. It shows that BPSK has the highest SER performance and PAM has the lowest performance. However, PPM and OOK are having the same SER performance indication. It clearly shows that BPSK has the highest reliability.
- Energy efficiency is compared for different PBM schemes. It shows that among all schemes BPSK has the highest efficiency.
- complexity of the required transceivers are analyzed for different PMB schemes. It shows that because of the coherent receivers BPSK is relatively more complex compared to other schemes.
- Finally, we simulate a WNSN in a wireless channel with standard air composition and evaluated proposed BER analysis framework. Results are observed in similar to the the numerical analysis.

Scheme	Reliability	Power Efficiency	Complexity of Transceivers
PAM	Lowest	0.5	Simple
OOK	Good	2	Simple
PPM	Good	2	Simple
BPSK	Best	4 (Best)	Complex

Table 4. Comparing Pulse Modulation for Battery Powered NSNs

VI. CONCLUSION

It is required to design a simple, energy efficient and reliable communication protocols due to the energy and other constraints in Wireless Nanosensor Networks,. Since carrier-less or pulse based modulation techniques consume less energy and are less complex compared to carrier based schemes, they are preferred for WNSNs. Different pulse based modulation schemes like PAM, OOK, PPM and BPSK are evaluated in terms of different parameters like reliability, energy efficiency and complexity and our investigation shows that reliability performance of OOK is lower than that of BPSK although it is simple. The energy efficiency of PPM is better than OOK even though the SER performance and complexity of both are similar. BPSK has the highest performance with highest energy efficiency but at the expense of more complex transceivers, compared to other schemes.

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