Performance Analysis of Carrier-less Modulation Schemes for Wireless Nanosensor Networks

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***Abstract*—Wireless Nano-scale Sensor Networks (WNSNs) are very simple and energy restricted networks that operate over terahertz band ranging from 0.1-10 THz, which faces significant molecular absorption noise and attenuation. Given these challenges, reliability, energy efficiency, and simplicity constitute the main criteria in designing communication protocols for WNSNs. Due to its simplicity and energy efficiency, carrier-less pulse based modulation is considered the best candidate for WNSNs. In this paper, we compare the performance of four different carrier-less modulations, PAM, OOK, PPM, and BPSK, in the context of WNSNs operating within the terahertz band. Our study shows that although BPSK is relatively more complex in terms of decoding logic at the receiver, it provides the highest reliability and energy efficiency among all the contenders. PAM has the worst performance in terms of reliability as well as energy efficiency. OOK and PPM have simpler decoding logic, but perform worse than BPSK in both reliability and energy efficiency.**

Keywords: WNSN; Modulation schema; Pulse based modulation; Nanoscale communication.

I. INTRODUCTION

With recent advancements in nanotechnology, researchers are now seriously contemplating the possibility of wireless nano-scale sensor networks (WNSNs) [3]. WNSNs introduce the possibility to sense and control important physical processes at the molecule level which is not possible with conventional sensor networks and can be used to enhance the performance of many chemical and biological processes [3], [25], [26].

In [25] we have demonstrated that how a network of nanomotes can be used to monitor and control chemical reactors with the ultimate goal of increasing the performance of the synthesis i.e. the ratio of desired product in the output. In this application and many others such as biomedical WNSNs, the reliability of communication between naomotes plays a key role in the ultimate performance of the system [28].

It has been shown that nano antenna made from graphene can radiate in the terahertz band ranging from 0.1-10 THz [13] which is also the resonance frequency of many molecules. Due to the size and energy constraints of nanosensors and also high molecular absorption noise and attenuation in the terahertz channel, designing simple, reliable and energy efficient communication protocols is one of the active ongoing research area in WNSNs [2], [24], [27], [29].

In addition, modulation and coding schema has a key role in designing energy efficient and reliable communication protocols. Due to restrictions of nanosensors, the best modulation option for WNSNs is carrier-less pulse based modulation (PBM) as it is technologically very challenging for a nano-transceiver to generate a high-power carrier frequency in the terahertz band [12]. The only proposed modulation scheme for WNSNs is TS-OOK which is an extension of the well-known carrier-less On-Off Keying method that employs a full pulse to represent '1' and no transmission for '0'. However, there are other PBM schemes that might be a better basis to develop more appropriate modulation schemes for WNSNs. In this work, we provide a framework to compare the main PBM schemes including PAM, OOK, PPM and BPSK, based on the required criteria for WNSNs. Our contributions can be summarized as follows:

- Using the proposed propagation model for WNSN, we provide an analytical framework to compare the BER performance of the PBM schemes. Based on our numerical analysis, while BPSK provides the highest reliability PAM has the lowest reliability. OOK and PPM have similar reliability performances which is higher than PAM and lower than BPSK.
- We compare the energy efficiency of the PBM schemes. The results show that PAM and BPSK have the lowest and highest efficiency, respectively while OOK and PAM have the same energy efficiency that is lower than BPSK and higher than PAM.
- We analyze the complexity of the required transceivers for the PMB schemes. The analysis shows that while BPSK is relatively more complex due to using coherent receivers, other schemes are much simpler.
- In order to evaluate the proposed BER analysis framework, we simulate a WNSN that is operating in a wireless channel with standard air composition. Our extensive simulations confirm the numerical analysis.

The rest of the paper is structured as follows. In section II, the concept and constraints of WNSNs are reviewed. In Section III, we describe the system model and general specification of main pulse based modulation schemes. In Section IV, the performance of different modulation schemes are numerically evaluated, followed by simulation of a real

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WNSN channel in Section V. We will review the related works in Section VI followed by conclusion in Section VII.

II. WIRELESS NANO SENSOR NETWORKS

Nanosensors are tiny devices made from novel nanomaterials capable of sensing new types of physical, chemical and biological phenomenon at the molecular level [23]. The recently proposed nano-scale transceivers which are made from carbon nanotube or Graphene [13] can be used to form a WNSN among these tiny motes to extend their capabilities in performing more complex tasks and also to transmit data to the macro-scale. Figure 1 illustrates a general schematic architecture for online microscopic environmental monitoring using the WNSNs. The data collected by nanomotes will be transmitted to a nearby micro or macroscale sink, then it will be transferred to a remote server via a macroscale gateway connected to the Internet.

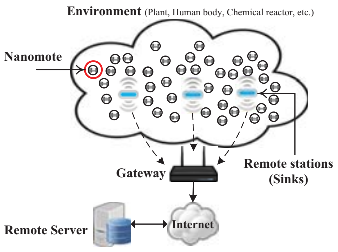

Fig. 1. A schematic architecture for environmental monitoring via WNSN.

Nevertheless, as the nano-scale transceivers work in the terahertz band, wireless nano-scale communication is mainly affected by molecular absorption [11] because the terahertz is also the resonance frequency of many molecules. Indeed, molecular absorption is a new source of noise and attenuation in terahertz channel and has not before seen in the traditional wireless communication. In this section, we overview the propagation model for WNSNs over terahertz band and then review the main restrictions of WNSNs.

A. Characteristics of WNSNs radio channel

This section reviews the modelling of terahertz radio channel based on radiative transfer theory [11]. Radio communication in the terahertz band is affected by the chemical compositions of the channel in two different ways. First, radio signal is attenuated because molecules in the channel absorb energy in certain frequency bands. Second, this absorbed energy is re-radiated by the molecules and create noise in the channel. The task of radiative transfer theory is to model these two effects.

We assume the radio channel is a medium consisting of N different chemical species $S_1, S_2, ..., S_N$. The effect of each chemical species S_i on the radio signal is characterised by its molecular absorption coefficient $K_i(f)$ at frequency f. The molecular absorption coefficients of many chemical species are available in HITRAN database for different frequencies, temperatures and pressures [4].

Let m_i be the mole fraction of chemical species S_i in the medium. The medium absorption coefficient $K(f)$ at frequency f is defined as the weighted sum of the molecular absorption coefficients in the medium:

$$K(f) = \sum_{i=1}^{N} m_i K_i(f) \tag{1}$$

The medium absorption coefficients $K(f)$ determines the attenuation and the molecular absorption noise in the radio channel for different molecules in different frequencies. We first discuss the attenuation effect that is resulted by the molecular absorbtion and spreading. The total attenuation, i.e. attenuation due to spreading and attenuation due to molecular absorption, at frequency f and a distance d from the transmitter is given by [11]:

$$A(f,d) = \left(\frac{4\pi f d}{c}\right)^2 \times e^{(K(f)\times d)} \tag{2}$$

where c is the speed of light in the vacuum. The power spectral density (PSD) of the received signal $P_r(f,d)$ at frequency f and distance d is:

$$P_r(f,d) = \frac{U(f)}{A(f,d)} \tag{3}$$

where $U(f)$ is the PSD of the transmitted signal at frequency f. The average received energy at distance d is:

$$E_r(d) = \int_B P_r(f,d) T_p df \tag{4}$$

where T_p is the duration of the transmitted pulse in second and B is the bandwidth. The PSD of the molecular absorption noise $N_{\text{abs}}(f,d)$ which is due to the re-radiation of absorbed radiation by the molecules in the channel is given by [11]:

$$N_{\text{abs}}(f,d) = k_B T_0 (1 - \exp(-K(f) * d)) \tag{5}$$

where T_0 is the reference temperature 296K and k_B is the Boltzmann constant.

B. Restrictions of WNSNs

Nanosensors are made in nano-scale that is the scale of few hundreds molecules which entails designing ultra simple and efficient hardware, software and protocols for individual nanosensors and also for the entire WNSN. For example, classical layered approaches to the network protocol design is not an appropriate method to develop a network between such simple nanosensors [3] as it requires complex and energy consuming algorithms and procedures.

There are two fundamental ways to power a nanosensor, either nanobatteries or nanoscale energy harvesting interfaces. At nanoscale it is difficult to deploy batteries with significant energy reserve for long network life. It is also practically challenging to replace the battery. Energy harvesting therefore is considered the most viable solution for WNSN. Although the power consumption of nanosensors is considered “ultra-low” for macroscale purposes, it is considered prohibitively high relative to what can be practically harvested on a tiny nanomote. For instance, the power density of recently developed nanomaterial-based energy harvesting circuits ranges from 1mW [22] to 4.5W [30] per cm^{-3}, which may be adequate to generate enough power on a macro device to power an onboard nanosensor, but would generate only about one femto to one pico Watt in a microscopic device with one cubic micrometer volume, due to severe space restrictions.

Given that nano-sensors have extremely limited energy storage capacity, designing simple and energy efficient modulation and coding schema are considered a major challenge. In particular, it is practically difficult to generate high-power carrier frequency in the terahertz band by using such limited power. Hence, WNSNs can take advantages of carrier-less pulse based modulation (PBM) schemes that not only are energetically more efficient, but they also lead to low-complexity transceiver design. In the next section, four main carrier-less modulation schemes will be presented.

III. SYSTEM MODEL

In this section, we assume a single user communication system over terahertz channel in which two nanomotes communicate with each other via a carrier-less pulse based modulation schema.

A. Single Pulse Representation

Unlike the classical narrow-band transmissions where the baseband signal is modulated onto a reference radio frequency, in carrier-less pulse based modulation no radio frequency is present and the transmitter consists of a simple pulse generator. In our analysis, we model the pulses as a Gaussian as:

$$p(t) = \frac{c_0}{\sqrt{2\pi}\tau} e^{-(t-\mu)^2/(2\tau^2)} \tag{6}$$

where τ is the time-scaling factor that determine the pulse width (in second), μ is the location in time for the center of the pulse (in second) and c_0 is a normalization constant to adjust the pulse total energy. The pulse energy, E_p then would be [7]:

$$\bar{E}_p = \int_{-\infty}^{\infty} [p(t)]^2 dt \tag{7}$$

B. Pulse based Modulation schemes

In a PBM system, the information is transmitted using a train of extremely short pulses via a modulation technique. The pulse train to transmit a message of L bits can be mathematically written as:

$$s(t) = \sum_{i=1}^{L} a_i \times p(t - i \times T)$$

where a_i is a constant to adjust the pulse amplitude for i^{th} bit, T is the time between two symbols and $p(t)$ is the pulse shape (Equation 6). In general, a desired modulation technique is supposed to provide the best error performance (lower BER) for a given energy per bit. From WNSNs point of view the complexity of the required hardware is also important. In this paper, we will investigate the performance of four well-known carrier-less pulse based modulation schemes including: PAM, OOK, PPM, and BPSK. First we will briefly overview these modulation schemes and then in the next section, we will conduct the performance analysis.

1) PAM: Pulse Amplitude Modulation (PAM) is a technique where the amplitude of the pulse depends on the transmission symbol to be sent. By varying the amplitude the receiver can distinguish the difference between ‘1’ and ‘0’, and thereby decode the data from the received signal. For the binary PAM, the transmitted signals can be expressed as:

$$s_0 = a_0 \times p(t)\ ,\ s_1 = a_1 \times p(t), \tag{8}$$

where $a_0 < a_1$ [16].

2) OOK: On Off Keying (OOK) is a special case of PAM where the absence or presence of a pulse indicates the digital information of ‘0’ or ‘1’, respectively [7].

$$s_0 = 0\ ,\ s_1 = a_{OOK} \times p(t)\ , \tag{9}$$

To avoid the confusion between the transmission of silence and no transmission, packet preamples are required and constant length packets are usually used.

3) PPM: Pulse Position Modulation (PPM) can be obtained by time shifting the pulse $p(t)$ by an amount τ_i, which can be positive or negative. An arbitrary pulse shape of $p(t)$, can be utilized to modulate the data by using a delay parameter of τ_i as [7]:

$$s_i = a_{PPM} \times p(t - \tau_i)\ , \tag{10}$$

4) BPSK: Binary Phase Shift Keying (BPSK) (also sometimes called PRK, Phase Reversal Keying or Bi-Phase Modulation (BPM) [7]) is the simplest form of Phase Shift Keying (PSK) that uses two phases which are separated by 180 degrees and so can also be termed 2-PSK. It means bits ‘0’ and ‘1’ have opposite phase. Equation(11) shows a binary system based on inversion of the basis pulse $p(t)$ [7]:

$$s_0 = -a_{BPSK} \times p(t)\ ,\ s_1 = a_{BPSK} \times p(t)\ , \tag{11}$$

C. Energy per bit

The average energy per bit for any modulation scheme, $\bar{E}_b$, can be calculated as:

$$\bar{E}_b = \sum_{i=1}^{2} p_{tr_i} \int_{-\infty}^{\infty} [s_i(t)]^2 dt \tag{12}$$

where $s_i(t)$ is the waveform for symbol i and p_{tr_i} is its transmitting probability. For fair comparison, we need to consider equal $\bar{E}_b$ for all modulations, so we decide to choose the modulation parameters as in Table I.

TABLE I
MODULATION PARAMETERS IN THIS PAPER.

PAM	OOK	PPM	BPSK
$a_1 = 1.3, a_0 = 0.6$	$a_{OOK} = \sqrt(2)$	$a_{PPM} = 1$	$a_{BPSK} = 1$

We also assume that $p_{tr_0} = p_{tr_1}$. With this setting, the $\bar{E}_b = E_p$ for all modulations where E_p can be calculated from Equation (7).

IV. PERFORMANCE ANALYSIS

The performance of modulation schemes can be analysed based on different metrics such as the reliability level, energy efficiency, spectrum efficiency (capacity), complexity and performance in multiple access scenarios. Due to the restrictions of WNSN, it needs a simple modulation scheme that can provide high reliability with the lowest power consumption. As a result, in this section we compare four binary modulation schemes that have been described in the section III-B based on three metrics including the Symbol Error Rate (SER), power efficiency and complexity. We will study other performance metrics in future studies.

A. *Reliability Analysis*

The average error probability for any binary modulation, SER, can he expressed as[1] [17], [21] :

$$SER = Q\left(\sqrt{\frac{d_{0,1}^2}{2N}}\right) \tag{13}$$

where $d_{0,1}$ is Euclidean distance between two symbols and the higher $d_{0,1}$, the lower probability of error. N is the variance of the molecular absorption noise that can be calculated from Equation (5) and $Q(x)$ is defined as:

$$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{\frac{-x^2}{2}} dx \tag{14}$$

The Euclidean distance between any two signal waveforms of $s_i(t)$ and $s_j(t)$ can be obtained as [21]:

$$d_{i,j}^2 = \int_{-\infty}^{\infty} [s_i(t) - s_j(t)]^2 dt \tag{15}$$

Using Equation (15) and specification of the modulation schemes in the section III-B, $d_{0,1}$ can be expressed as a function of the average signal energy, E_p, which has been presented in the Table II. As it can be seen, the BPSK has the highest $d_{0,1}$, giving hope it will lead to the lower error.

TABLE II
$d_{0,1}^2$ AS A FUNCTION OF PULSE ENERGY AND SER AS A FUNCTION OF $\frac{E_p}{N}$

Schema	$d_{0,1}^2$	$d_{0,1}^2$ **in this paper**	**SER as a function of** $\frac{E_p}{N}$
PAM	$(a_1 - a_0)^2 \times E_p$	$0.5 \times E_p$	$Q\left(\sqrt{0.125 \times \frac{E_p}{N}}\right)$
OOK	$a_{OOK}^2 \times E_p$	$2 \times E_p$	$Q\left(\sqrt{\frac{E_p}{N}}\right)$
PPM	$(\sqrt{2} \times a_{PPM})^2 E_p$	$2 \times E_p$	$Q\left(\sqrt{\frac{E_p}{N}}\right)$
BPSK	$(2 \times a_{BPSK})^2 \times E_p$	$4 \times E_p$	$Q\left(\sqrt{2 \times \frac{E_p}{N}}\right)$

Figure 2 shows the SER performance of different modulation schemes for 20 different SNR ranging from -15dB to 15dB. For fair comparison, we used equal average energy per bit, $\bar{E_b}$ to calculate the SER. It can be seen that the SER performance of PPM and OOK are similar while BPSK and PAM has the highest and lowest performance, respectively.

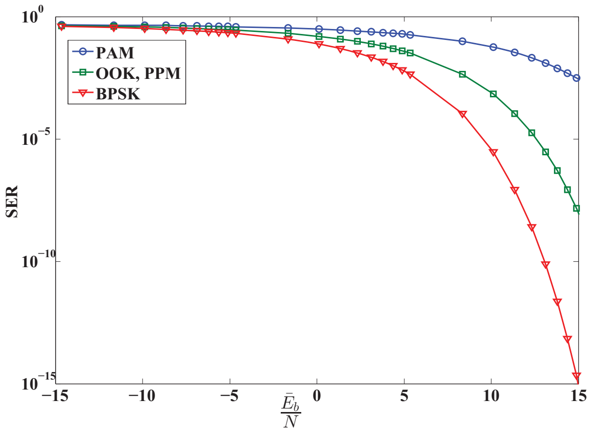

Fig. 2. SER performance of different modulations.

B. *Power efficiency*

Although increasing the signal power of a transmission can increase the Euclidean distance between signals, thus decreasing the SER, a desired modulation is the one that can provide the highest SER performance using the minimum given power budget. The power efficiency of any binary modulation schemes M is expressed as [21]:

$$\epsilon_{P_M} = \frac{d_{0,1_M}^2}{\bar{E_b}} \tag{16}$$

which $d_{0,1_M}^2$ can be calculated from Equation (15) and $\bar{E_b}$ is the average energy per bit that can be calculated via Equation (12). For example, for BPSK modulation as $s_1 = p(t)$ and $s_0 = -p(t)$ then we have:

$$\epsilon_{P_{\{BPSK\}}} = \frac{d_{min_{i,j}}^2}{\bar{E_b}} = \frac{\int_0^T [2 \times p(t)]^2 dt}{\int_0^T p(t)^2 dt} = 4.$$

Recalling Equations (12, (15) and (16) and modulations specification from Section III-B, ϵ_P is 0.5 for PAM, 2 for OOK/PPM and 4 for BPSK which shows the BPSK has the highest efficiency among all schemes.

C. *Complexity*

Complexity is another important issue in designing modulation scheme for WNSNs, which includes the complexity of both transmitter and receiver hardware and software. In this section, we overview the complexity of required transmitter and receiver for each modulation.

1) Transmitter : A pulse generator is one of the most essential parts of a PBM transceiver as its signal shape determines the spectrum efficiency and effectively dictates specific system requirements. According to the literature, pulse generation of the BPSK is more complex than other three schemes [20].

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[1] Note: for a binary scheme, BER and SER would be the same.

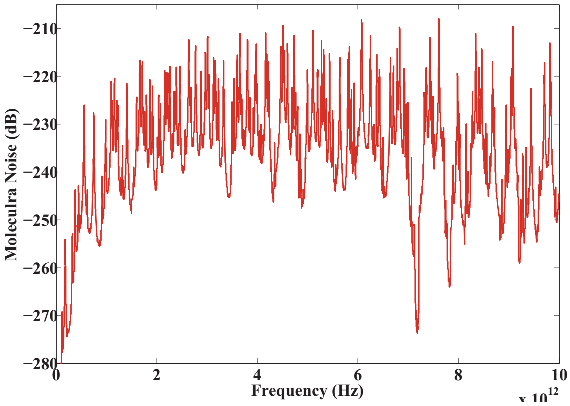

Fig. 3. Molecular absorption noise power in the terahertz channel in a channel with standard air composition in the summer in normal pressure/temperature

2) Receiver: There are two main categories of receivers for PBM, coherent (also sometimes called correlation or Rake) and non-coherent (energy detector). Coherent receivers need to detect the carrier phase of the transmitted information to demodulate the information and that makes it more complex in comparison with non-coherent receivers that only utilizes a match filter to detect the transmitted signal. Non-coherent receivers, such as energy detectors are commonly used to decrease the complexity and cost of the receivers. Due to complexity of coherent receivers, non-coherent receivers are more preferred for WNSNs [18].

While OOK, PAM and PPM can employ non-coherent transceivers to demodulate the transmitted signal, BPSK requires coherent demodulation as the transmitted data is embedded in the polarities of the pulses [15]. However, few non-coherent transceivers has been reported for BPSK [5], [14] which use some techniques to estimate the phase shift for a given sequence of transmission. Although these approaches are simpler than normal coherent demodulators for BPSK but they need to run more complex algorithms in the receiver.

TABLE III
COMPARING PULSE MODULATION FOR BATTER-POWERED NSNS

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

V. SIMULATION

This section aims to simulate and analyse the SER performance of different modulation schemes in a WNSN over terahertz channel. We consider a channel with normal air with composition of Table IV and normal pressure/temperature of 1atm/296K and extract the correspondence molecular absorptions from HITRAN [4] for different frequency ranging from 0.1-10 THz. We implement and simulate different modulation schemes in MATLAB and calculate total path loss from Equation (2) and total noise from Equation (5) for distance equal to $1mm$. Fig. 3 depicts the molecular absorption noise in the described channel. Due to the frequency dependency of the molecular absorption coefficient, the the molecular absorption noise is also frequency sensitive.

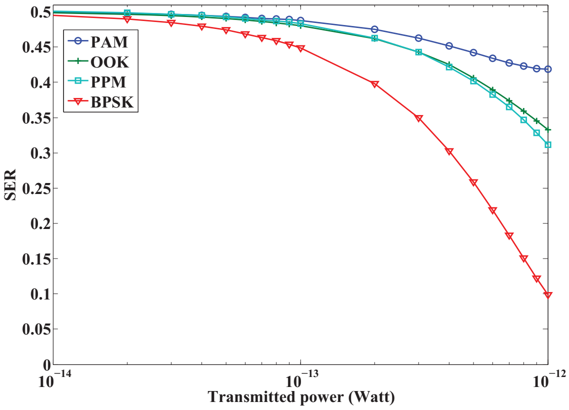

Fig. 4. SER evaluation of different modulation schemes via simulation.

TABLE IV
THE COMPOSITION OF NORMAL AIR

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**

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, Test$_{\text{Data}}$, including one million bits with equal probability for '0' and '1'. For each power level/modulation we transmit the Test$_{\text{Data}}$ over the terahertz channel and measure the SNR in the receiver for each single bit of the message and then calculate the average SER.

In order to calculate the SER via a modulation scheme, SER_M, we first transfer Test$_{Data}$ using the modulation scheme and then demodulate the transmitted message in the receiver. Then, received message is compared against Test$_{Data}$ to calculate the SER. Fig. 4 shows the SER_M for different modulation schemes and as it can be seen, BPSK can provide higher reliability than other modulations and the output of PPM and OOK are approximately similar that is in agree with the numerical analysis in the Section IV-A.

VI. RELATED WORKS

To the best of our knowledge, this is the first attempt to provide an evaluation framework for choosing modulation schemes for WNSNs. However, performance evaluation of pulse based modulation has been well-studied in the literature. Most work studied only the BER performance of the modulation schemes [6], [9]. For instance, in [9] BER evaluation of three schemes including PPM, Biphase Modulation (BM) and a hybrid scheme has been carried out for IR-UWB systems. In [19] BER performance of OOK has been investigated for UWB wireless sensor networks. In [6] the performance of PPM has been evaluated for UWB radio channel in multipath scenario via simulation and numerical analysis. Performance of few UWB modulations has been compared in [1] in terms of spectrum efficiency, SER and noise sensitively under an AWGN channel. Authors in [8] have evaluated BER and spectrum efficiency for few UWB modulations for multi-path and multi-access scenarios. Our work is different from the aforementioned researches as we investigate WNSNs over terahertz channel and consider molecular absorption noise and attenuation that is completely different from conventional AWGN channel.

VII. CONCLUSION

Due to the constraints of WNSNs, designing simple, energy efficient and reliable communication protocols is considered as a major requirement of WNSNs. Carrier-less or pulse based modulation techniques are preferred for WNSNs since they consume less energy and are simpler compared to carrier based schemes. We evaluate four pulse based modulation schemes including PAM, OOK, PPM and BPSK in terms of reliability, energy efficiency and complexity. Our investigation shows that although OOK is the simplest scheme, its reliability performance is lower than BPSK. The BPSK has the highest performance with also highest energy efficiency but it needs more complex transceivers, compared to other schemes. The SER performance and complexity of PPM is similar to OOK but its energy efficiency is better than OOK.

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