An Energy Efficient Modulation Scheme for Body-Centric Nano-Communications in the THz band

Apostolos K. Vavouris*, Foteini D. Dervisi*, Vasilis K. Papanikolaou*, and George K. Karagiannidis*
*Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece
e-mails: {vavouris, foteinidd, vpapanikk, geokarag}@auth.gr

***Abstract*—In body-centric communications, energy efficiency is the most critical parameter, while the maximum achievable data rate is not of primary concern. In this paper we present a novel modulation scheme, which can be efficiently used in body-centric terahertz (THz) nanonetworks. This scheme is a combination of the time-spread On-Off keying (TS–OOK) and the pulse position modulation (PPM). The new modulation scheme presents lower energy consumption levels at a small cost to the achievable data rate. Furthermore, another important aspect is that, due to the nature of noise in THz communications, the proposed modulation is affected in a much smaller way by the noise. Finally, we present analytical and simulation results in order to compare the new scheme with TS–OOK.**

***Index Terms*—Terahertz Band, Nanosensors, Nanonetworks, Femtosecond Pulses, Body-Centric Communications**

I. Introduction

Recent advancements in nanotechnology allowed us to envision the everyday use of nanomachines. A plethora of applications can benefit from the use of nanodevices, ranging from flexible electronics to medical technologies [1]. Particularly, in medicine, nanotechnology offers a novel way of performing diagnostic analysis in a non-invasive way with the in-vivo use of these nanodevices [2]. Nanosensing can be used to detect chemical compounds in extremely low concentrations in the human body and other nanodevices can be used to perform drug delivery services [3], [4]. However, the aforementioned scenarios require a horde of nanomachines to cover sufficiently large areas, thus creating a nanonetwork inside the human body. It is, also, obvious that the nanonetwork must have the ability to communicate with nodes outside the human body.

Advances in the field of nanomaterials has allowed the use of graphene and its derivatives for developing transceivers, which can be used in nano-networks. Moreover, the operational frequency of nanoantennas, constructed from these materials appears to be in a region 0.1THz – 10THz of the electromagnetic spectrum, called the *terahertz gap*. THz radiation is non-ionizing and, as such, it is accepted to be safe for the human body [1].

In body-centric communications, usually the achievable data rate is not of primary concern. Even though THz communications have shown to achieve very high data rates, for these specific applications energy efficiency is more crucial. In the pioneering work of Jornet *et al.* [5]–[7], the authors proposed the use of Time–Spread On Off Keying (TS–OOK), where “1” and “0” are represented as a pulse and silence, respectively. Following that, a link budget analysis was also presented in [8]. It has been shown that noise deteriorates farther the pulses compared to the silences, because of the molecular absorption noise that exists in this frequency band. In order to achieve higher system capacity, it is obvious that the use of pulses should be restrained, in order to limit the effect of the molecular absorption noise.

In this paper, we propose the use of a novel modulation, which emphasizes on energy efficiency rather than the maximum data rate, thus, making it ideal for use in in-vivo applications. The new scheme is a combination of the time-spread On-Off keying (TS–OOK), which has already been proposed for these applications, and the pulse position modulation (PPM). It uses only one pulse per symbol, which significantly decreases the energy consumption of the nanodevice. Furthermore, the proposed modulation scheme is scalable i.e., the degree of modulation can be chosen to adjust to each application, where the need to conserve energy is even more crucial. We show that with a very small cost to the achievable data rate (compared to the TS–OOK), we can obtain significant energy savings. Thus, a trade-off between energy efficiency and data rate is established. Finally, the new scheme is designed to minimize the effect of the noise in THz systems without adding more complexity to the system.

The rest of the paper is organized as follows

- In section II, we define the concept of the novel modulation scheme we are proposing.
- In section III, a comparison regarding energy consumption and data rate is drawn between the new scheme and TS–OOK.
- Finally, some conclusions are presented in section IV.

II. The proposed modulation

Due to the size of the nanodevices proposed, their batteries cannot have a large capacity. Also, the frequencies that are used belong in the terahertz band, so it is challenging to use conventional modulation schemes, that are based on amplitude and/or phase modulation. As mentioned above, in this paper, we propose a new modulation scheme, which is based on TS–OOK and PPM. In contrary to TS–OOK, which sends bits one by one, the basic idea of the proposed scheme is to transmit the bits as a sequence. Each sequence is represented by a

978-1-5386-4788-2/18/$31.00 ©2018 IEEE

certain number of silences and a very short pulse (in the order of one hundred femtoseconds [5]). So, in order to transmit M codewords of length equal to N bits, we correspond every sequence of bits to a certain number of silences through a bijective function and only one pulse in the end of the symbol transmission. This also resembles a PPM, with the difference that the duration of each symbol is not constant, but diverges according to the transmitted symbol, in order to spare time and increase the achieved data rate.

Another important aspect to take into account is the nature of noise in THz communications. The main contribution comes from the *molecular absorption noise*, which is generated from the molecules that re-emit part of the absorbed from the transmission radiation. As such, the molecular absorption noise is considered to affect only the *pulses* and not the *silences*. Other sources, such as the electronic thermal noise or the noise created by surrounding nanomachines are considered negligible in the current analysis, due to their relatively small magnitude. What makes this noise different from conventional communication channels is that it *self-induced*, which means it is induced by the transmissions of the users sharing the medium [9]. In [6], they derived a model for the power spectral density (psd) of the noise that is based on the Beer-Lambert Law. The model was adjusted in [10]–[12] to fit the in-vivo scenario. The molecular absorption becomes negligible when no molecules are irradiated, i.e., when no user is transmitting. In the proposed modulation, we manage to send more bits of information, by using more silences and less pulses, thus, effectively minimizing the effect of the molecular absorption noise, which leads to an increase to the signal-to-noise ratio. In this way, the probability of detecting a symbol incorrectly is lower and less energy is consumed to transmit a sequence of symbols.

After the receiver senses the transmitter's preamble signal, it counts the number of silences between the one hundred femtosecond long pulse of the previous signal and that of the current signal, and corresponds them to a sequence of bits via the bijective function, which enables the mapping procedure. Finally, the time slot offered for each silence or pulse is much longer than the duration of each pulse. In this way, the possibility of overriding, i.e. the possibility of a pulse sent by a transmitter coinciding with a silence sent by another transmitter, is diminished. The signal of a single symbol transmitted by a user can be written as

$$s(t) = Ap(t - t_{previous} - kT_s), \tag{1}$$

where A is the amplitude of the pulse, $p(t)$ is a one hundred femtosecond long pulse, $t_{previous}$ is the end time of the last time slot used by the previous signal, k is a constant that varies according to the order of the modulation and T_s is the period of the time slot.

The signal received by a user is deteriorated by the channel impulse response $h(t)$ (which is affected by the medium conditions and by the distance between the transmitter and the receiver as well as by the molecular absorption noise ($w(t)$) [12]. So the received signal is

$$\tilde{s}(t) = Ap(t - t_{previous} - kT_s) * h(t) + w(t). \tag{2}$$

By observing the equations (1) and (2), which portray the transmitted and received signals, it becomes clear than the reduction of $w(t)$ makes the received signal $\tilde{s}(t)$ resemble to the transmitted signal $s(t)$ more than in the case of TS–OOK. So, by sending less pulses and more silences, we can achieve a better channel behavior concerning the error probability, but as a downside we need more time to transmit each symbol.

III. Energy consumption and data rate

Since we have introduced the concept of our proposed modulation scheme, we need to examine how it compares with the TS–OOK, in terms of energy efficiency and data rate. The standard TS–OOK scheme has a modulation order of 2, since it uses only two symbols. However, in order to fairly compare the two modulations, we need to expand the TS–OOK to a higher modulation degree M. Thus, we present the following analysis, where we have generalized the concept of TS–OOK to incorporate this issue. Note that, this increase in modulation degree is given by incorporating more time slots in the TS–OOK, instead of more spacial dimensions in the symbols.

A. Energy consumption

The energy consumption of an M-degree TS–OOK scheme is derived in the following lemma. This analysis is normalized for pulse energy $E_{pulse} = 1$.

Lemma 1. *The average energy required to transmit a symbol by using TS–OOK is given by*

$$E(M) = \frac{M}{2}, \tag{3}$$

where M is the order of modulation.

Proof: We calculate the probabilities of transmitting a pulse for each modulation order - e.g. for order 2 we have four cases (00, 01, 10, 11): one case with no pulses, two cases with one pulse and one case with two pulses - and we present the first 6 rows of the calculated data on the table that is given at the top of the next page.

It can be easily observed that Table I is a Pascal's triangle, from which we can obtain the equation (3) by summing the products of each element of each row with the number of pulses and then dividing them by the number of different cases in order to find the mean value – e.g. for modulation order two ($M = 2$) we sum one signal with no pulses, two signals with one pulse and one signal with two pulses, which gives a result of four and then we divide it by the number of different cases which is equal to four, having a final result of one.

$$E(M) = \frac{(M + \frac{M(M-1)}{1!} + \frac{M(M-1)(M-2)}{2!} + ...)}{2^M} = \\ = \frac{M}{2}. \tag{4}$$

	0 pulses	1 pulse	2 pulses	3 pulses	4 pulses	5 pulses	6 pulses
1 bps	1	1	-	-	-	-	-
2 bps	1	2	1	-	-	-	-
3 bps	1	3	3	1	-	-	-
4 bps	1	4	6	4	1	-	-
5 bps	1	5	10	10	5	1	-
6 bps	1	6	15	20	15	6	1

TABLE I
PASCAL'S TRIANGLE FOR BITS AND PULSES.

■

In the proposed modulation the average energy is always 1, due to the fact that we transmit only one pulse for each symbol. Thus, for $M > 2$ the recommended modulation is much more energy efficient, which is vital for applications where the available energy is limited.

Fig. 1 presents a comparison of the two modulations, regarding the mean energy consumption.

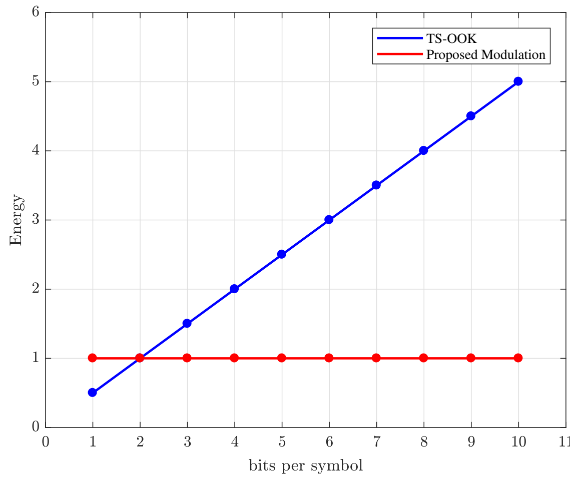


Fig. 1. Average Energy Consumption.

B. Data Rate

The data rate of the new modulation is derived in the following lemma.

Lemma 2. *The mean data rate of the new modulation scheme can be written as*

$$u(M,t) = \frac{2M}{t(2^M+1)}. \tag{5}$$

Proof: The mean time required to transmit a bit by using the proposed scheme is calculated by summing the time needed to transmit each symbol and then dividing it by the number of cases multiplied by the number of bits in a symbol, which in short is given by

$$f(M,t) = \frac{t\sum_{i=1}^{2^M} i}{M2^M} = \frac{t(2^{M-1}(2^M+1))}{M2^M}$$

or

$$f(M,t) = \frac{t(2^M+1)}{2M}, \tag{6}$$

where M is the modulation order (bits per symbol) and t is the time required for each time slot.

Finally, in order to evaluate the data rate we inverse the fraction, which results to

$$u(M,t) = \frac{1}{f(M,t)} = \frac{2M}{t(2^M+1)}.$$

■

Figs. 2 and 3 compare the proposed modulation and TS–OOK. For illustrative purposes, we use five picoseconds for each time slot, so $t = 5$ psec [7]. Hence we have

$$f(M, 5\times10^{-12}) = \frac{5\times10^{-12}(2^M+1)}{2M} \tag{7}$$

and

$$u(M, 5\times10^{-12}) = \frac{2M}{5\times10^{-12}(2^M+1)} \tag{8}$$

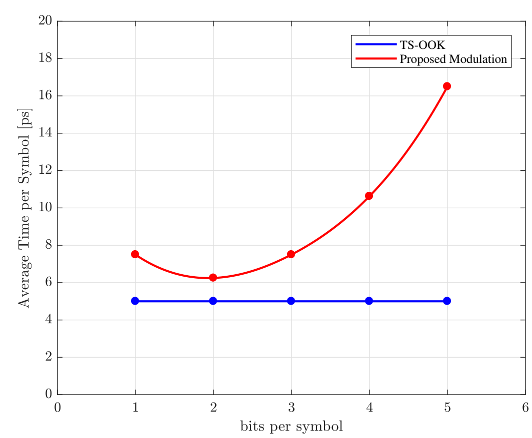


Fig. 2. Average Time per symbol.

In Figs. 2 and 3 we can observe that, in the case of the new scheme, the mean time for the transmission of each bit is increased with the order of the modulation (number of bits transmitted per symbol), compared to the TS–OOK modulation, where the time required for the transmission of each bit is constant. However, as it can be observed in the energy diagram (Fig. 1) we need much less energy to transmit these bits.

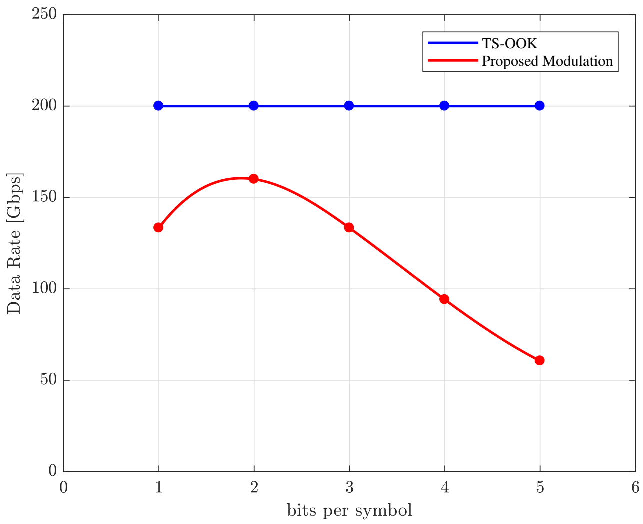
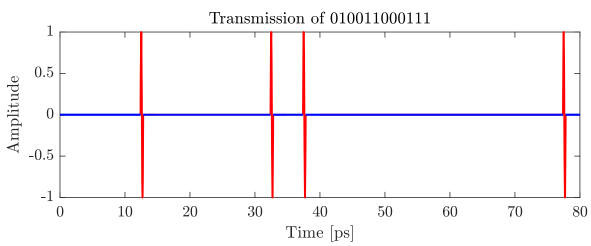


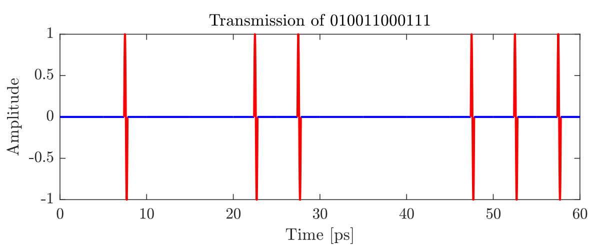
Fig. 3. Transmission Data Rate.

C. Simulation Results

Fig. 4(a) and 4(b) display an example which serves to show the difference between the signals sent by the new modulation and TS–OOK for the transmission of the same bit stream. In this example, we use modulation of order three.



(a) Proposed Modulation



(b) TS-OOK

Fig. 4. Modulation examples.

This example portrays the trade-off between low energy and high speed rate. We observe that the proposed modulation needs 80 picoseconds and 4 energy bursts(pulses), while TS–OOK needs 60 picoseconds and 6 energy bursts.

IV. Conclusion

We have proposed a novel modulation scheme, which can be efficiently used in body-centric nano-networks that operate in the THz band. The new modulation can achieve higher energy efficiency, compared to TS–OOK. It can also achieve a better error rate as a consequence of the diminished molecular absorbtion noise. However, slightly more time is needed to transmit the same bits, thus leading to lower data rate, compared to TS–OOK. This is not a primary issue, as the type of applications that are to be used with body-centric nano-networks do not require that high of a data rate. Moreover, the modulation degree of the proposed scheme can be chosen to be low in order to avoid heavily deteriorating the data rate, effectively turning this issue in a trade-off between energy efficiency and data rate. Finally, further analysis must be performed in order to produce the exact single and multi-user capacity analysis.

References

[1] V. K. Papanikolaou and G. K. Karagiannidis, "Channel Modeling of in-vivo THz Nanonetworks: State-of-the-art and Research Challenges," in *7th EAI International Conference on Wireless Mobile Communication and Healthcare (MobiHealth 2017)*, 2017.

[2] Q. H. Abbasi, A. A. Nasir, K. Yang, K. Qaraqe, and A. Alomainy, "Cooperative in-vivo nano-network communication at terahertz frequencies," *IEEE Access*, 2017.

[3] J. Safari and Z. Zarnegar, "Advanced drug delivery systems: Nanotechnology of health design a review," *Journal of Saudi Chemical Society*, vol. 18, no. 2, pp. 85–99, 2014.

[4] S. S. Suri, H. Fenniri, and B. Singh, "Nanotechnology-based drug delivery systems," *Journal of occupational medicine and toxicology*, vol. 2, no. 1, p. 16, 2007.

[5] J. M. Jornet and I. F. Akyildiz, "Channel capacity of electromagnetic nanonetworks in the terahertz band," in *2010 IEEE International Conference on Communications (ICC)*. IEEE, 2010, pp. 1–6.

[6] ——, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3211–3221, 2011.

[7] ——, "Information capacity of pulse-based wireless nanosensor networks," in *2011 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*. IEEE, 2011, pp. 80–88.

[8] H. Elayan, R. Shubair, J. M. Jornet, and P. Johari, "Terahertz channel model and link budget analysis for intrabody nanoscale communication," *IEEE Trans. Nanobiosci.*, vol. 16, pp. 491–503, 2017.

[9] J. Kokkoniemi, J. Lehtomäki, and M. Juntti, "A discussion on molecular absorption noise in the terahertz band," *Nano Communication Networks*, vol. 8, pp. 35–45, 2016.

[10] K. Yang, A. Pellegrini, M. O. Munoz, A. Brizzi, A. Alomainy, and Y. Hao, "Numerical analysis and characterization of thz propagation channel for body-centric nano-communications," *IEEE Trans. THz Sci. Technol.*, vol. 5, no. 3, pp. 419–426, 2015.

[11] G. Piro, K. Yang, G. Boggia, N. Chopra, L. A. Grieco, and A. Alomainy, "Terahertz communications in human tissues at the nanoscale for healthcare applications," *IEEE Trans. Nanotechnol.*, vol. 14, no. 3, pp. 404–406, 2015.

[12] R. Zhang, K. Yang, A. Alomainy, Q. H. Abbasi, K. Qaraqe, and R. M. Shubair, "Modelling of the terahertz communication channel for in-vivo nano-networks in the presence of noise," in *2016 16th Mediterranean Microwave Symposium (MMS)*. IEEE, 2016, pp. 1–4.