Information Capacity of Pulse-based Wireless Nanosensor Networks

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***Abstract*—Nanotechnology is enabling the development of sensing devices just a few hundreds of nanometers in size, which are able to measure new types of events in the nanoscale by exploiting the properties of novel nanomaterials. Wireless communication among these nanosensors will boost the range of applications of nanotechnology in the biomedical, environmental and military fields, amongst others. Within the different alternatives for communication in the nanoscale, recent advancements in nanomaterials point to the Terahertz band (0.1 - 10.0 THz) as the frequency range of operation of future electronic nanodevices. This still unlicensed band can theoretically support very large transmission bit-rates in the short range, i.e., for distances below one meter. More importantly, the Terahertz band also enables very simple communication mechanisms suited to the very limited capabilities of nanosensors. In this paper, a new communication paradigm called TS-OOK (Time Spread On-Off Keying) for Electromagnetic Wireless Nanosensor Networks (WNSNs) is presented. This new technique is based on the transmission of femtosecond-long pulses by following an on-off keying modulation spread in time. The performance of this scheme is assessed in terms of information capacity for the single-user case as well as aggregated network capacity for the multi-user case. The results show that by exploiting the peculiarities of the Terahertz band, this scheme provides a very simple but robust communication technique for WNSNs. Moreover, it is shown that, due to the peculiar behavior of the noise in the Terahertz band, the single-user capacity and the aggregated network capacity can exceed those of the AWGN channel classical wireless networks, when the appropriate channel codes are used.**

***Index Terms*—Nanosensors, Nanonetworks, Terahertz Band, Femtosecond Pulses, Network Capacity, Graphene.**

I. INTRODUCTION

Nanotechnology is providing a new set of tools to the engineering community to design and manufacture integrated devices just a few hundred of nanometers in size. One of the early applications of these nano-devices is in the field of nanosensing [24], [14], [6]. Nanosensors are not just tiny sensors, but devices that take advantage of the properties of novel nanomaterials to identify and measure new types of events in the nanoscale, such as chemical compounds in concentrations as low as one part per billion [17], [15], or the presence of virus or harmful bacteria [23], [19].

Communication among nanosensors will expand the capabilities and applications of individual nano-devices both in terms of complexity and range of operation [1], [2]. Wireless Nanosensor Networks (WNSNs) will boost the range of applications of nanotechnology in the biomedical field (e.g., cooperative health monitoring and drug delivery systems in healthcare applications), in environmental research (e.g., distributed air pollution control), and in military technology (e.g., Nuclear, Biological and Chemical defenses).

For the time being, the communication alternatives for nanoscale devices are very limited. Focusing on the electromagnetic (EM) paradigm, there are several drawbacks in the existing silicon-based solutions that hamper their direct application in the nanoscale, such as their size, complexity and energy consumption [12]. Alternatively, the use of novel nanomaterials to build a new generation of electronic components is envisioned to solve part of the main shortcomings of current implementations [3]. Amongst others, carbon-based materials, such as graphene, are expected to become the silicon of the 21st century [10].

From the communication perspective, the electrical and optical properties observed in nanomaterials will decide on the specific bandwidth for emission of EM radiation, the time lag of the emission, or the magnitude of the emitted power for a given input energy, amongst others. Ongoing research on the characterization of the EM properties of graphene [9], [25], [16] points to the Terahertz band (0.1 - 10.0 THz) as the expected frequency range of operation of EM nano-transceivers. In particular, in [9] we determined that a 1 μm long graphene-based nano-antenna can only efficiently radiate in the Terahertz range. Interestingly enough, this matches the initial predictions for the frequency of operation of graphene-based RF transistors [22], [11].

On its turn, the Terahertz band (0.1 - 10.0 THz) is one of the least explored frequency ranges of the EM spectrum. In [8], we developed a propagation model for short range Terahertz communications and showed how the Terahertz band can theoretically support very large bit-rates, up to several hundreds of Terabit/second for distances below 1 meter. However, it is not likely that nanosensors will require these very large transmission bit-rates. Alternatively, and probably more importantly, we believe that having a very large bandwidth enables new simple communication and medium sharing mechanisms suited for the expectedly very limited capabilities of nanosensors, as we present next.

In this paper, we introduce a new communication paradigm called TS-OOK (Time Spread On-Off Keying) for WNSNs. This new technique is based on the asynchronous transmission of femtosecond-long pulses among nanosensors by following an on-off keying modulation spread in time. We assess the performance of the TS-OOK in terms of information capacity for a single-user case and the aggregated network capacity for the multi-user case. The capacity or maximum information rate collects into a single metric the ability for a communication mechanism to successfully transmit over a channel by taking into account the propagation effects, the noise sources, and the information source statistics. The ultimate goal of this paper is to show the validity of TS-OOK despite its simplicity, and to define new guidelines for the design of future coding schemes. For this, new models of noise and interference in the Terahertz band are developed. Moreover, we show that both the single-user capacity and the aggregated network capacity can exceed that of the Additive White Gaussian Noise (AWGN) channel classical wireless networks.

We summarize the main contributions of our work as follows:

- We first begin with a review of the Terahertz channel and emphasize the challenges posed by molecular absorption, which are addressed by TS-OOK.
- We motivate and explain TS-OOK, a the new communication paradigm which is based on the asynchronous exchange of femtosecond-long pulses among nano-devices.
- We statistically model the molecular absorption noise and analytically investigate the information capacity of TS-OOK for the single-user case.
- We statistically model the interference in TS-OOK and analytically investigate the aggregated network capacity for the multi-user case.

The remainder of the paper is organized as follows. In Sec. II, we review the main properties of the Terahertz channel. In Sec. III, we present TS-OOK, the new communication scheme for WNSNs. In Sec. IV, we derive the capacity of TS-OOK for the single-user case analytically. Further, in Sec. V, we analytically derive the capacity of the network for the multi-user case. Finally, we conclude the paper in Sec. VI.

II. Terahertz Channel Behavior

Graphene-based electromagnetic nano-transceivers will operate in the Terahertz band [9], [25], [16], [22], a frequency range that spans the frequencies between 100 GHz and 10.0 THz. In [8] we investigated the properties of the Terahertz band in terms of path-loss, noise, bandwidth and channel capacity which we are presenting briefly next, and which will be used for the capacity analysis in Sec. IV and Sec. V.

The total path-loss for a traveling wave in the Terahertz band is defined as the addition of the spreading loss and the molecular absorption loss [8]. The *spreading loss* accounts for the attenuation due to the expansion of the wave as it propagates through the medium and it depends on the frequency and the transmission distance. The *absorption loss* accounts for the attenuation that a propagating wave suffers because of molecular absorption, i.e., the process by which part of the wave energy is converted into internal kinetic energy to some of the molecules which are found in the channel [5]. This loss depends on the signal frequency, the transmission distance and the concentration and the particular mixture of molecules encountered along the path. As a result, the Terahertz channel is *highly frequency selective*, specially when the concentration of molecules or the transmission distance are increased.

The noise in the Terahertz band is mainly contributed by the *molecular absorption noise* [8]. Vibrating molecules re-radiate part of the energy that they have previously absorbed and this is conventionally modeled as a noise factor [4]. Molecular absorption noise is determined by the number and the particular mixture of molecules found along the path. There are two main differences with the classical AWGN channel in terms of noise. First, this type of noise is *correlated with the transmitted signal*. Indeed, molecular absorption noise is only present when transmitting, i.e., there is no noise unless the molecules are irradiated [5]. Second, this noise is *colored*. Due to the presence of different resonant frequencies and absorption coefficients corresponding to different types of molecules, the power spectral density of the noise is not flat, but has several peaks in frequency. This requires the development of new noise models, as we present in Sec. IV.

The usable bandwidth of the Terahertz channel is also determined by molecular absorption. Within a WNSN, it is unlikely to achieve single-hop transmission distances above a few meters because of the power and energy constraints of nanosensors [2], [20]. For this transmission range, the available bandwidth is almost the entire band, i.e., 10 THz. Because of this, we think of the Terahertz band as an *ultra-broad-band window*. The predicted channel capacity of the Terahertz band is promisingly very large, up to a few hundreds of Terabit/second [8]. However, this value serves only as an upper bound, and would require the development of very complex modulation techniques. Alternatively, and more importantly, this very large bandwidth enables new simple communication schemes suited for WNSN, as we present next.

III. Pulse-based Communication for WNSNs in the Terahertz Band

In light of the peculiarities of the Terahertz band and the limited capabilities of nanosensors, we motivate and propose a new communication scheme for WNSNs called TS-OOK, which is based on the transmission of extremely short pulses. In the rest of the paper, the terms nanosensor, node and user are used interchangeably.

A. Motivation for Femtosecond Pulse-based Communications

Due to the size and energy constraints of simple nanosensors, it is technologically very challenging for a nano-device to generate a high-power carrier frequency in the Terahertz band. As a result, classical communication paradigms based on the transmission of continuous signals might not be used in electromagnetic WNSNs. Alternatively, very short pulses can be generated and radiated from the nanoscale. In particular, femtosecond-long pulses, which have their main frequency components in the Terahertz band, are already being used in several applications such as in nanoscale imaging systems [21]. Because of this, we envision a new communication paradigm in which nano-devices use these very short pulses for communication. Prototypes for such a scheme do not exist up to date, but the state of the art in graphene-based Terahertz electronics [22], [11] motivate the theoretical analysis of the potential of this communication paradigm for WNSNs.

Communication based on the exchange of very short pulses has been successfully used for high-speed communication systems, such as in Impulse-Radio Ultra-Wide-Band (IR-UWB) systems [7] in the last decade. In IR-UWB, picosecond-long pulses are exchanged among users following orthogonal time-hopping sequences which have been distributed by a network coordinator. However, the complexity of these solutions is far from what can be expected from a nanosensor device. For example, it does not seem feasible to generate and distribute orthogonal hopping sequences among nano-devices in WNSNs. Moreover, the requirement of a network coordinator would limit the applications of WNSNs. Therefore, there is a need for novel communication solutions for nano-devices.

B. TS-OOK: Time Spread On-Off Keying

Based on the expected capabilities of an EM nano-transceiver, we propose TS-OOK, a new communication scheme based on the exchange of femtosecond-long pulses, which are transmitted following an on-off keying modulation spread in time. The functioning of this communication scheme is as follows. Assuming that a nano-device needs to transmit a binary stream (e.g., the reading from a nanosensor),

- *A logical "1" is transmitted by using a femtosecond-long pulse and a logical "0" is transmitted as silence, i.e., the nano-device remains silent when a logical zero is transmitted*. An On-Off Keying (OOK) modulation is chosen instead of a binary Pulse Amplitude Modulation (PAM) or Pulse Position Modulation (PPM) because of the peculiar behavior of the molecular absorption noise. As discussed in Sec. II, this type of noise is only present when molecules are excited; if no user is transmitting, molecules remain still and noise becomes negligible. Thus, by being silent, the energy consumption of the nano-device is reduced (nothing is transmitted), and the probability of incorrect symbol detection is lowered. To avoid the confusion between the transmission of silence and no transmission, initialization preambles to announce that a packet is going to be transmitted and constant length packets are used. After the detection of an initialization preamble, the receiver will just count for the symbols in a packet. During this time, silence will be considered a logical "0".
- *The time between transmissions is fixed and much longer than the pulse duration*. Due to technological limitations and similarly to IR-UWB, pulses or silences are not transmitted in a burst, but spread in time. By fixing the time between consecutive transmissions, after the detection of the first transmitted pulse (e.g., after a initialization preamble) a user does not need to continuously sense the channel, but just wait till the next transmission. This feature can be used to save energy if this is the main constraint of the network. Alternatively, during the time between transmissions a user can follow other users' bit streams or transmit its own data. This scheme does not require tight synchronization among the nanosensor devices all the time, but only some nano-devices will be synchronized after detecting an initialization preamble and only for the duration of a packet transmission.

Under this scheme, the signal transmitted by a user u, $s_T^u(t)$ is given by:

$$s_T^u(t) = \sum_{k=1}^{K} A_k^u p(t - kT_s - \tau^u) \quad (1)$$

where K is the number of bits (symbols) per packet, A_k^u refers to the amplitude of the k-th symbol transmitted by the nanosensor u (either 0 or 1), $p(t)$ stands for a pulse with duration T_p, T_s refers to the time between consecutive transmissions, and τ^u is a random initial time. In general, the time between symbols is much longer than the time between pulses. Following the usual notation, we define β as $\beta = T_s/T_p \gg 1$.

The signal received by a nanosensor j can be written as:

$$s_R^j(t) = \sum_{k=1}^{K} A_k^u p(t - kT_s - \tau^u) * h^{u,j}(t) + w_k^{u,j}(t) \quad (2)$$

where $h^{u,j}(t)$ is the Terahertz channel impulse response between the nanosensors u and j, and $w_k^{u,j}(t)$ stands for the molecular absorption noise created between u and j. $h^{u,j}(t)$ depends on the specific medium conditions and distance between the transmitter u and the receiver j. Similarly, the molecular absorption noise $w_k^{u,j}(t)$ depends on the medium conditions and the transmission distance, and it is correlated with the transmitted symbol k. Thus, the capacity of this communication scheme for the single-user case depends on the Terahertz channel impulse response and the molecular absorption noise.

C. Medium Sharing with TS-OOK

Multiple users can share the channel when using TS-OOK. Due to the fact that the time between transmissions T_s is much longer than the pulse duration T_p, several nanosensors can concurrently use the channel without affecting each other. In light of the type of applications envisioned for WNSNs, we think of a scenario in which nano-devices can start transmitting at any specific time without being synchronized or controlled by any type of network central entity. The traffic in WNSNs is predictably low, but it can drastically increase at specific times due to correlated detections in several nanosensors.

In contrast to IR-UWB [7], time-hopping orthogonal sequences are not considered. In TS-OOK, the probability of having a collision between femtosecond-long pulses is very low. Moreover, not all types of collisions are *harmful*. For example, there are no collisions between silences, and collisions between pulses and silences are only harmful from the silence perspective, i.e., the intended receiver for the pulse will not notice any difference if silence is received at the same time. In any case, collisions may occur, creating multi-user interference and thus limiting the capacity of this communication scheme.

In the multi-user case, the signal received by a nanosensor j is given by:

$$s_R^j(t) = \sum_{u=1}^{U} \sum_{k=1}^{K} A_k^u p(t - kT_s - \tau^u) * h^{u,j}(t) + w_k^{u,j}(t) \quad (3)$$

where U is the total number of users in the system, K is the number of bits (symbols) per packet, A_k^u refers to the

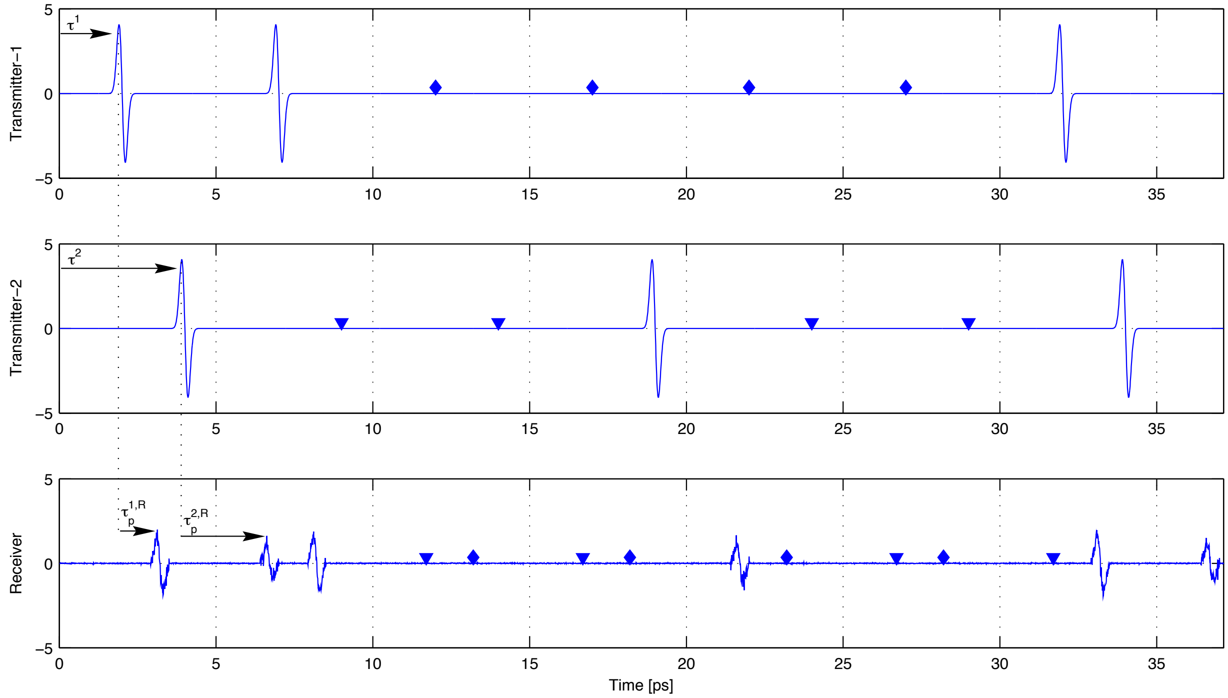


Fig. 1. TS-OOK illustration: top) First nanosensor transmitting the sequence "1100001"; middle) Second nanosensor transmitting the sequence "100101"; bottom) Overlapped sequences at the receiver side.

amplitude of the k-th symbol transmitted by nanosensor u (either 0 or 1), $p(t)$ stands for a pulse with duration T_p, T_s refers to the time between consecutive transmissions, τ^u is a random initial time, $h^{u,j}(t)$ is the channel impulse response between nanosensors u and j, and $w_k^{u,j}(t)$ stands for the molecular absorption noise created by the k-th transmission between nanosensors u and j.

In Fig. 1, we show an example of TS-OOK for the case in which two nanosensors are simultaneously transmitting different binary sequences to a third nanosensor. The upper plot corresponds to the sequence "1100001", which is transmitted by the first nanosensor. A logical one is represented by the first derivative of a Gaussian pulse with T_p=100 fs, and a logical zero is represented by silence. The time between symbols is T_s=5 ps, which is very small for a real case, but more convenient for illustration purposes. This signal is propagated through the channel (thus, distorted and delayed) and corrupted with molecular absorption noise (only when pulses are transmitted). Similarly, the second plot shows the sequence transmitted by the second nanosensor, "1001001". This second user is farther from the receiver than the first user. As a result, the signal at the receiver suffers from higher attenuation, longer delay, and more noise. This can be seen in the third plot, which illustrates the signal at the receiver side.

IV. Single-User Capacity Analysis

In order to investigate the potential of TS-OOK, we compute the maximum achievable information rate or capacity of this new communication technique. The information rate collects into a single metric the ability of a communication scheme to successfully transmit information over a communication channel. Here we develop a statistical model of molecular absorption noise, formulate the capacity of TS-OOK analytically and provide numerical results for the single-user case.

A. A Statistical Model of Molecular Absorption Noise

In order to study the capacity of TS-OOK, it is first necessary to develop a statistical model of molecular absorption noise. For this, we need to recall its nature and peculiar behavior. As described in Sec. II, this type of noise appears as a result of internal vibrations of molecules when they are irradiated by an EM wave carrying energy at very specific frequencies. For a specific resonant frequency v, this noise can be characterized by a Gaussian probability distribution, with mean equal to zero and variance given by the noise power within the band of interest, $\mathcal{N}_v\left(\mu_v=0,\sigma_v^2=\int_B S_{N_v}(f)\,df\right)$, where $S_{N_v}(f)$ refers to the power spectral density (p.s.d.) of the molecular absorption noise created by the resonance v, and B stands for the bandwidth of the transmitted signal.

By considering the different resonances from the same molecule as well as the resonances in different molecules to be independent, we can model the total molecular absorption noise also as additive and Gaussian noise, with mean equal to zero and variance given by the addition of the noise power corresponding to each resonance, $\mathcal{N}\left(\mu=0,\sigma^2=\sum_v\sigma_v^2\right)$. As an alternative to the addition of the power of every single resonance, the total noise power can be obtained by integrating over the entire band the total noise p.s.d., which is given, according to the model introduced in [8], by:

$$N_m=\int_B k_B T_0\left(1-e^{-k(f)d}\right)\frac{P_m(f)}{P_T}df \qquad (4)$$

where k_B refers to the Boltzmann constant, T_0 is the reference temperature, k stands for the medium absorption coefficient, d is the transmission distance, $P_m(f)$ is the power spectral density of the symbol m, P_T refers to the total maximum transmitted power, and the index m refers to the transmitted symbol (zero for silence and one for a pulse).

Note that if silence is transmitted, molecular absorption noise is nonexistent. However, in our analysis, we consider that there is always a background noise, $N_0 \ll N_1$, which, in fact, is related to the relaxation time of the channel, i.e., the time needed for molecules to stop vibrating. Finally, one should also note that this noise is upper bounded by $k_B T_0$ for very large transmission distances or highly adsorptive mediums. However, based on radiative transfer theory [5], this upper bound is only reached when the molecules are excited for a long time compared to the relaxation time of the channel. For a pulse-based scheme, this threshold might be reached only when a user transmits a burst of pulses or when multiple users share the medium.

B. Analytical Study of the Single-User Capacity

The capacity of a communication channel in bit/symbol is given by the well-known Shannon Limit Theorem [18]:

$$\begin{aligned} C_{u-sym} &= \max_X I(X,Y) \\ &= \max_X \{H(X) - H(X|Y)\} \;\; \text{[bit/symbol]} \end{aligned} \tag{5}$$

where X refers to the source of information, Y refers to the output of the channel, $H(X)$ refers to the entropy of the source X, and $H(X|Y)$ stands for the conditional entropy of X given Y, which is a term commonly referred as the equivocation of the channel.

In TS-OOK, the source X can be modeled as a discrete binary random variable. Therefore, the entropy of the source $H(X)$ is given by:

$$H(X) = -\sum_{m=0}^{1} p_X(x_m) \log_2 p_X(x_m) \tag{6}$$

where $p_X(x_m)$ refers to the probability of transmitting the symbol $m = \{0, 1\}$, i.e., the probability to stay silent or to transmit a pulse, respectively.

The output of the channel Y can be modeled as a continuous random variable. In particular, the output of the transmitter is distorted by the channel $h(t)$, and corrupted by the molecular absorption noise $w(t)$. In our analysis, we consider the channel behavior to be deterministic. Thus, the only random component affecting the received signal is the molecular absorption noise. In this case, the equivocation of the channel $H(X|Y)$ is given by:

$$\begin{aligned} H(X|Y) &= \int_y p_Y(y) H(X|Y=y)\, dy \\ &= -\int_y p_Y(y) \sum_{m=0}^{1} p_X(x_m|Y=y) \log_2 (p_X(x_m|Y=y))\, dy \end{aligned} \tag{7}$$

where $p_X(x_m|Y=y)$ stands for the probability of having transmitted x_m given the output y.

By recalling the Mixed Bayes Rule and the Total Probability Theorem [13], the equivocation $H(X|Y)$ can be written in terms of the probability of the channel output Y given the input x_m, $p_Y(Y|X=x_m)$, as:

$$\begin{aligned} H(X|Y) = &\int_y \sum_{m=0}^{1} p_Y(Y|X=x_m) p_X(x_m) \\ &\cdot \log_2 \left(\frac{\sum_{n=0}^{1} p_Y(Y|X=x_n) p_X(x_n)}{p_Y(Y|X=x_m) p_X(x_m)} \right) dy. \end{aligned} \tag{8}$$

Based on the statistical model of molecular absorption noise, the p.d.f. of the output of the system Y given the input $X = x_m$ can be written as:

$$p_Y(Y|X=x_m) = \frac{1}{\sqrt{2\pi N_m}} e^{-\frac{1}{2}\frac{(y-a_m)^2}{N_m}} \tag{9}$$

where N_m stands for the total noise power associated to the transmitted symbol x_m, which is given by (4), and a_m refers to the amplitude of the received symbol, which is obtained by using the Terahertz model that we introduced in [8].

By combining (6), (8), (4) and (9) in (5), the capacity of the channel in bit/symbol can be written as (10). Note that in the classical AWGN channel, noise affects in the same way the transmission of "1"s and "0"s ($N_0 = N_1$). In that particular case, the capacity is obtained by maximizing the entropy of the source $H(X)$ and minimizing the equivocation $H(X|Y)$ independently. However, in the Terahertz channel, molecular absorption noise is only present when a pulse is transmitted and it is almost negligible when the channel is not being accessed. Because of this, the optimal source probability distribution is not necessarily the binary equiprobable distribution, but it depends on the channel conditions.

Finally, the capacity in bit/second is obtained by multiplying the capacity in bit/symbol (10) by the rate at which symbols are transmitted, $R = 1/T_s = 1/(\beta T_p)$, where T_s is the time between symbols, T_p is the pulse length, and β is the ratio between them. If we assume that the $BT_p \approx 1$, where B stands for the channel bandwidth, the capacity is given by:

$$C_u = \frac{B}{\beta} C_{u-sym} \;\; \text{[bit/second]}. \tag{11}$$

If $\beta = 1$, i.e., all the symbols (pulses or silences) are transmitted in a burst, and the maximum capacity per user is achieved. By increasing β, the single-user capacity is reduced, but the requirements on the nano-transceiver are greatly relaxed. Analytically solving the capacity expression given by (10) is not feasible. Instead of this, we numerically investigate the capacity for the single-user case next.

$$\begin{aligned} C_{u-sym} = \max_X \Bigg\{ &-\sum_{m=0}^{1} p_X(x_m) \log_2 p_X(x_m) - \int \sum_{m=0}^{1} \frac{1}{\sqrt{2\pi N_m}} e^{-\frac{1}{2}\frac{(y-a_m)^2}{N_m}} p_X(x_m) \\ &\cdot \log_2 \left(\sum_{n=0}^{1} \frac{p_X(x_n)}{p_X(x_m)} \sqrt{\frac{N_m}{N_n}} e^{-\frac{1}{2}\frac{(y-a_n)^2}{N_m} + \frac{1}{2}\frac{(y-a_m)^2}{N_m}} \right) dy \Bigg\} \;\; \text{[bit/symbol]} \end{aligned} \tag{10}$$

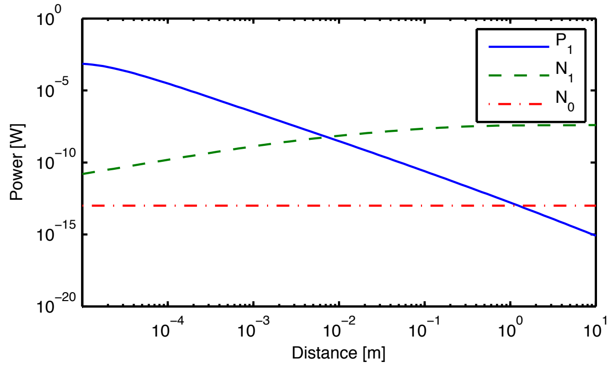


Fig. 2. Received signal power when a pulse is transmitted P_1, noise power when a pulse is transmitted N_1, noise power associated with silence N_0, as functions of distance (energy of the transmitted pulse equal to 1 pJ).

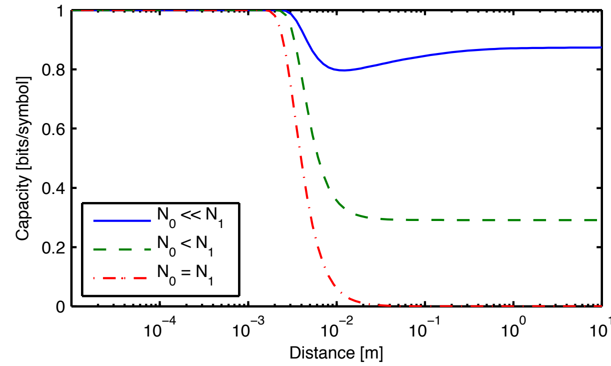


Fig. 3. Single-user capacity as a function of distance in bit/symbol for different noise power N_1 and N_0 ratios.

C. Numerical Study of the Single-User Capacity

In this section, we numerically investigate the capacity of pulse-based communications in the Terahertz band for the single-user case. We use the Terahertz propagation model introduced in [8] for the computation of the total path-loss and molecular absorption noise. The transmitted pulses are modeled as the first-order time-derivative of a 100-femtosecond-long Gaussian pulse. In an intent to keep the numbers realistic, and in light of the state of the art in molecular-electronics [2], we keep the total pulse energy constant and equal to 1 picoJoule. For the transmission distance, path lengths ranging from 10 micrometers to 10 meters are considered.

First of all, it is necessary to visualize the behavior of the Terahertz channel. The received signal power when a pulse has been transmitted, P_1, which is proportional to the square of the amplitude of the received pulse, a_1^2, is shown in Fig. 2 as a function of the transmission distance, d. In the same figure, the noise powers associated with the transmission of pulses, N_1, and silence, N_0, are also represented as a function of d. For distances below a few tens of millimeters, the received signal power when a pulse is transmitted is much larger than the power of the molecular absorption noise that it creates while being propagated, N_1. However, for longer transmission distances, N_1 becomes the dominant factor. Note that the power associated with the transmission of silence is constant with distance and usually much smaller than N_1. This is the main difference with the classical AWGN channel.

The single-user capacity in bit/symbol, C_{u-sym} (10), is shown in Fig. 3 as a function of the transmission distance d, for different relations for the ratio between the noise powers N_1 and N_0. The behavior of the single-user capacity with distance is very peculiar. First of all, for transmission distances below a few millimeters, the capacity is almost constant and equal to 1 bit/symbol, which is the maximum information per symbol that can be transmitted in a binary system. For example, if $\beta = 1000$, and the entire Terahertz band is used, $B = 10$ THz, then the maximum single-user capacity is approximately 10 Gigabit/second. If $\beta = 10$, information rates in the order of 1 Terabit/second are possible.

As the transmission distance is increased, the capacity diminishes up to a certain point, but then it increases again and tends to a constant value. This phenomenon can be explained as follows. When the received signal power associated with the transmission of a pulse, P_1, and the noise power created by the propagation of this pulse, N_1, become comparable in magnitude, the capacity of the system decreases because the equivocation of channel (8) increases, i.e., it is difficult to distinguish between a pulse and just silence because the Gaussian distributions associated to the two symbols, $p_Y(Y|X = x_1)$ and $p_Y(Y|X = x_0)$, are almost overlapped. However, when the transmission distance is further increased, even if the power of the received signal tends to zero, the noise created by the propagating pulse keeps increasing up to a limit. Thus, unless the received signal is very close to zero, it is clear for the receiver that a pulse was transmitted provided that noise is detected. As described in Sec. IV-A, the upper bound for the noise given by (4) is only achieved in a real scenario when the channel is continuously used. Thus, in pulse-based communications, this noise bound will be in fact much lower, the difference between N_0 and N_1 will be smaller, and ultimately the capacity will tend to zero with distance. Note, for the particular case in which $N_0 = N_1$, this channel behaves as the classical AWGN channel.

The asymmetric behavior of the Terahertz channel is also reflected on the optimal source probability distribution X for which the capacity is achieved. For transmission distances below a few tens of millimeters, the optimal source probability distribution corresponds to the binary equiprobable distribution ($p_X(x_0) = p_X(x_1) = 0.5$). However, when the transmission distance is increased, even if both silence and pulses can be easily detected, the optimal probability distribution is no longer the equiprobable one, but one that favors the transmission of silence rather than pulses, because the total noise or equivocation is much lower when zeros are transmitted. In particular, $p_X(x_0)$ approaches 0.55 for distances above 10 mm. This result motivates the development of new channel coding schemes in which more zeros than ones are used.

Up to this point, it has been assumed that only one nanosensor is utilizing the channel. In the following section, the effect of interference in the capacity for every single user as well as in the aggregated network capacity is investigated.

V. Multi-User Capacity Analysis

Here we develop a new statistical model for interference in TS-OOK, formulate the aggregated network capacity analytically and provide numerical results for the multi-user case.

A. A Statistical Model of Interference in TS-OOK

Multi-user interference in TS-OOK occurs when symbols from different nanosensors reach the receiver at the same time, and the amplitude and shape of the received pulses overlap. Without loss of generality, if we focus on the symbols transmitted by the user number 1, the interference, I, at the receiver j during the detection of a symbol from user number 1 is given by:

$$I = \sum_{u=2}^{U} A^u \left(p * h\right)^{u,j} \left(\mathcal{T}_1^u\right) + w^{u,j} \left(\mathcal{T}_1^u\right) \tag{12}$$

where U refers to the total number of users, A^u is the amplitude of the symbol transmitted by user u (either one or zero), $\left(p * h\right)^{u,j}(t)$ stands for the transmitted pulse convoluted with the channel impulse response between users u and j, $\mathcal{T}_1^u$ is the time difference at the receiver side between the transmissions from users 1 and u, and $w^{u,j}(t)$ is the absorption noise created at the receiver by the transmissions from user u.

In order to provide a statistical characterization of the interference, we make the following assumptions:

1. Nanosensors are not controlled by a central entity, but they communicate in an ad-hoc fashion.
2. Transmissions from different users are independent and follow the same source probability distribution X.
3. Transmissions from different users are uniformly distributed in time. This can be achieved by waiting a random time before starting the transmission of a packet.
4. Nanosensors are uniformly distributed in space, thus, the propagation delay between any pair of users is also uniformly distributed in time.
5. Collisions between silence are not harmful. Collisions between pulses and silences are only harmful from the silence perspective.

Under these assumptions, the time difference at the receiver side between the transmissions from users 1 and u, $\mathcal{T}_1^u$, can be modeled as a uniform random variable over $[0, T_s]$. More importantly, we can model the overall interference, I, as a Gaussian random process, $\mathcal{N}_I\left(\mu_I = E[I]; \sigma_I^2 = N_I\right)$, where $E[I]$ and N_I are the mean and variance of the interference, respectively. Indeed, for a single interfering user, the amplitude of the interference depends on the propagation conditions and the distance between this user and the receiver. In addition, this interference can be constructive or destructive, depending on the reflections that pulses may suffer. Then, for a large number of users, we can invoke the Central Limit Theorem [13], and make the Gaussian assumption for I.

Now, the mean of the interference $E[I]$ can be obtained as:

$$\begin{aligned} E[I] &= E\left[\sum_{u=2}^{U} A^u \left(p * h\right)^{u,j} \left(\mathcal{T}_1^u\right) + w^{u,j} \left(\mathcal{T}_1^u\right)\right] \\ &= \sum_{u=2}^{U} \frac{T_p}{T_s} a^{u,j} p_X(x_1) = \sum_{u=2}^{U} \frac{a^{u,j}}{\beta} p_X(x_1) \end{aligned} \tag{13}$$

where U refers to the total number of users, T_p is the pulse length, T_s is the time between symbols, and $a^{u,j}$ is the average amplitude of a pulse at the receiver, j, transmitted by user u.

The variance of the interference is given by:

$$N_I = E\left[I^2\right] - E[I]^2 \tag{14}$$

where

$$\begin{aligned} E\left[I^2\right] &= E\left[\left(\sum_{u=2}^{U} A^u \left(p * h\right)^{u,j} \left(\mathcal{T}_1^u\right) + w^{u,j} \left(\mathcal{T}_1^u\right)\right)^2\right] \\ &= \sum_{u=2}^{U} \left(\frac{\left(a^{u,j}\right)^2 + N^{u,j}}{\beta}\right) p_X(x_1) \\ &\quad + 2 \sum_{u=2<v}^{U} \left(\frac{p_X(x_1)}{\beta}\right)^2 a^{u,j} a^{v,j} \end{aligned} \tag{15}$$

and which results in

$$\begin{aligned} N_I = &\sum_{u=2}^{U} \left(\frac{\left(a^{u,j}\right)^2 + N^{u,j}}{\beta}\right) p_X(x_1) \\ &+ 2 \sum_{u=2<v}^{U} \left(\frac{p_X(x_1)}{\beta}\right)^2 a^{u,j} a^{v,j} - \left(\sum_{u=2}^{U} \frac{a^{u,j}}{\beta} p_X(x_1)\right)^2 \end{aligned} \tag{16}$$

where U is the total number of users, $a^{u,j}$ refers to the amplitude of the pulse transmitted by u at the receiver j, $N^{u,j}$ is the noise power created from the transmission of u to j, and $p_X(x_1)$ is the probability of transmitting a pulse. As a simplifying assumption, we can consider that all the nodes are approximately at the same distance d to the receiver, and then $a^{u,j}$ and $N^{u,j}$ can be replaced by a^d and N^d, which refer to the average amplitude and the average noise power received at a distance d from the transmitter. Thus, in more proper terms, U refers to the total number of interfering users.

B. Analytical Study of the Network Capacity

We define the aggregated network capacity as the maximum aggregated throughput that can be transmitted over the network, i.e.,

$$C_{net} = \max_X \left\{U C_{u-bits}^I\right\} \tag{17}$$

where U refers to the number of interfering users, X refers to the source of information for every single user, and C_{u-bits}^I is the capacity for every single user. Because of multi-user interference, C_{u-bits}^I cannot be computed directly from (11). The optimal source distribution X depends on the number of interfering users in the network, U, and, thus, obtaining the network capacity means to jointly optimize X and U.

In order to determine the C_{u-bits}^I as a function of the number of users U, we need to add the contribution of interference into the probability of the output Y given the input $X = x_m$. Taking into account the previously introduced model for interference, now (9) becomes:

$$p_Y(Y|X = x_m) = \frac{1}{\sqrt{2\pi\left(N_m + N_I\right)}} e^{-\frac{1}{2}\frac{\left(y - E[I] - a_m\right)^2}{N_m + N_I}} \tag{18}$$

where N_m stands for the noise power associated to the symbol m, N_I is variance of the interference, and $E[I]$ is the mean value of the interference. Then, C_{u-bits}^I can be obtained by combining (18), (8) and (6) in (5). Finally, the network capacity is given by (19). Similarly to the single-user case, analytically solving this optimization problem is not feasible. For this, we investigate the network capacity numerically next.

$$C_{net} = \max_X \left\{ U\frac{B}{\beta}\left(-\sum_{m=0}^{1} p_X(x_m)\log_2 p_X(x_m) - \int \sum_{m=0}^{1} \frac{1}{\sqrt{2\pi(N_m+N_I)}} e^{-\frac{1}{2}\frac{(y-E[I]-a_m)^2}{N_m+N_I}} p_X(x_m) \right.\right.$$
$$\left.\left. \cdot \log_2\left(\sum_{n=0}^{1} \frac{p_X(x_n)}{p_X(x_m)} \sqrt{\frac{N_m+N_I}{N_n+N_I}} e^{-\frac{1}{2}\frac{(y-E[I]-a_n)^2}{N_m+N_I}+\frac{1}{2}\frac{(y-E[I]-a_m)^2}{N_m+N_I}} \right) dy \right) \right\} \quad \text{[bit/second]} \qquad (19)$$

C. Numerical Study of the Network Capacity

In this section, we quantitatively study the effects of interference on the capacity of every single user and the aggregated network capacity. The path-loss affecting the received signal power and the interference power, and the power of molecular absorption noise are computed using the Terahertz propagation model introduced in [8]. The energy of a transmitted pulse is kept constant and equal to 1 picoJoule. The ratio between the time between pulses and the pulse duration is kept constant and equal to $\beta = 1000$.

In Fig. 4(a), the capacity for every user C^I_{u-sym} in bit/symbol, obtained from (5), (6) and (8) in (18), is shown as a function of the number of interfering users in the system U and transmission distance d. For a low number of interfering users, the capacity behaves with distance similarly to the single-user case studied in Sec. IV-C. In this case, even for relatively long transmission distances, the capacity does not tend to zero due to the fact that noise is not affecting the transmission of silence (and $N_1 \gg N_0$). As the number of interfering nanosensors is increased, the total interference (which affects silences and pulses) becomes the dominant term in the equivocation of the channel. As a result, the capacity of every user tends to zero.

The aggregated network capacity (19) as a function of the number of interfering users in the system U and the transmission distance d is shown in Fig. 4(b). Different trends for the aggregated network capacity can be observed depending on the transmission distance. In order to understand this behavior, it is important to identify which is the optimal source probability distribution X for which the capacity is being obtained. In Fig. 4(c), the probability to transmit a zero (i.e., to stay silent) corresponding to the source probability distribution X that maximizes both the capacity for every user and the network capacity, is shown as a function of the number of interfering users U and the transmission distance d. In the multi-user scenario, the optimal source distribution clearly prioritizes the transmission of silence, i.e., $p_X(x_0) \gg p_X(x_1)$. This is due to the fact that by transmitting silence, both the molecular absorption noise and specially the interference power are drastically reduced. Indeed, this result is just numerically stating that collisions between silence are never harmful, and, thus, it is more convenient for the entire network to minimize the number of pulses that are sent. Thus, again, this result motivates the development of channel coding schemes suited for nano-devices and which minimize the number of ones. Note that, at the same time, by transmitting less pulses, the total energy consumption for every device is also reduced.

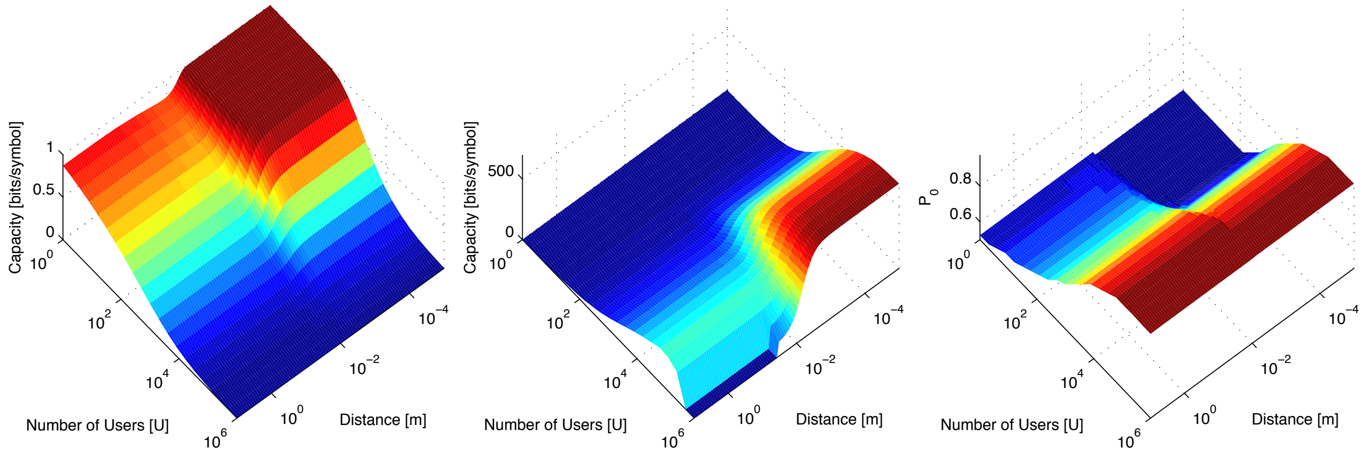
With this result in mind, we can now explain the behavior of the aggregated network capacity for the different transmission distances. First of all, when the transmission distance is short, below a few tens of millimeters, the network capacity increases with the number of users up to a point at which it reaches a constant value. This effect appears because, even when the number of interfering users is drastically increased, provided that the individual probability to transmit silence is much higher than the probability to transmit a pulse, the total noise interference does not increase at the same pace. Thus, the received signal power is sufficiently large to be distinguishable from the reception of silence. When the transmission distance is increased, even by transmitting primarily silence, the power of the received signal when a pulse is transmitted diminishes very fast because of the very high path-loss of the Terahertz band, and it is very difficult for the receiver to discern between pulses and silence. It is interesting to note that, for transmission distances above a few tens of millimeters, there is an optimal number of users for which the network capacity is maximum. The optimal point is again related to the relation between the transmitted and received pulse energy and the total interference power. By changing the energy of the transmitted pulse, we can shift the position of this point. A more complex topology analysis would be required to further analyze this behavior.

VI. Conclusions

Wireless communication among nanosensors will boost the applications of nanotechnology in many fields of our society, ranging from healthcare to homeland security and environmental protection. However, enabling the communication among nano-devices is still an unsolved challenge. We acknowledge that there is still a long way to go before having an integrated nanosensor device, but we believe that hardware-oriented research and communication-focused investigations will benefit from being conducted in parallel from an early stage.

In this paper, we present a new communication paradigm called TS-OOK (Time Spread On-Off Keying) for nano-devices, which is based on the exchange of femtosecond-long pulses by following an on-off keying modulation spread in time. We study the performance of this new paradigm analytically and provide numerical solutions for the single and the multiple user cases. We use analytical models for the path-loss, molecular absorption noise and interference in the Terahertz band, which is the expected frequency range of operation of future graphene-based nano-devices.

The results show that TS-OOK provides a simple but robust communication technique for nano-devices. In addition, we show that the individual capacity of nano-devices and the aggregated capacity of WNSNs can be increased by transmitting more zeros than ones, i.e., more silences than pulses. This is due to the peculiar behavior of molecular absorption noise,



(a) Capacity for every single user

(b) Aggregated capacity

(c) Optimal source distribution

Fig. 4. Numerical analysis of the network capacity of TS-OOK.

whose power increases with the energy of the transmitted signal. Therefore, when the appropriate channel codes are used, the capacity of WNSNs can exceed that of the AWGN channel classical wireless networks.

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