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Low-Weight Channel Coding for Interference Mitigation in Electromagnetic Nanonetworks in the Terahertz Band

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***Abstract*—Nanotechnology is providing a new set of tools to the engineering community to design and manufacture integrated devices just a few hundred nanometers in total size. Communication among these nano-devices will boost the range of applications of nanotechnology in several fields, ranging from biomedical research to military technology or environmental science. Within the alternatives for communication, recent developments in nanomaterials point to the Terahertz band (0.1-10 THz) as the frequency range of operation of future electromagnetic nano-transceivers. This frequency band supports very large bit-rates in the short range and enables simple communication mechanisms suited to the limited capabilities of nano-devices, such as pulse-based communications. However, the expectedly very large number of nano-devices and the unfeasibility to coordinate them can make interference a major impairment. In this paper, low-weight channel coding is proposed as a novel mechanism to reduce interference in pulse-based nanonetworks. Rather than utilizing channel codes to detect and correct transmission errors, it is shown that by appropriately choosing the weight of a code, interference is mitigated and the number of transmission errors is reduced. The performance of the proposed scheme is analytically and numerically investigated both in terms of overall interference reduction and achievable information rate, by utilizing a new statistical model for the interference. The results show that this *network-friendly* channel coding scheme can be used to alleviate the interference problem in nanonetworks without compromising the individual user information rate.**

***Index Terms*—Nanonetworks, Terahertz Band, Channel Coding, Interference Mitigation, Pulse-based Communications**

I. Introduction

Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundreds nanometers. At this scale, a nanomachine is defined as the most basic functional unit consisting of nanoscale components which is able to perform very simple tasks. By means of communication, these machines will be able to accomplish more complex missions in a cooperative manner [1]. The resulting *nanonetworks* will boost the range of applications of nanotechnology in the biomedical field (e.g., intrabody networks for health monitoring and drug delivery), in environmental research (e.g., distributed air pollution monitoring), or in military technology (e.g., advanced nanosensor networks for chemical and biological attack prevention), amongst others [2].

For the time being, the communication alternatives for nanomachines are very limited. Focusing on the electromagnetic (EM) paradigm, there are several drawbacks in existing silicon-based manufacturing techniques that make the downscaling of existing EM transceivers unfeasible [10]. 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 [4]. Amongst others, graphene and its derivates, namely, Carbon Nanotubes (CNTs) and Graphene Nanoribbons (GNRs), are expected to become the silicon of the 21st century [8].

From the communication perspective, the EM properties observed in these 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 [7], [16], [12] points to the Terahertz band (0.1 - 10.0 THz) as the expected frequency range of operation of future EM transceivers. In particular, in [7] we determined that a 1 μm long graphene-based nano-antenna can only efficiently radiate in the Terahertz range. This matches the initial predictions for the frequency of operation of graphene-based RF transistors [9].

On its turn, the Terahertz band (0.1 - 10.0 THz) is still one of the least explored frequency ranges of the EM spectrum. In [6], 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 terabits/second for distances below 1 meter. However, the very limited capabilities of individual nanomachines question the reproducibility of these results in a real scenario. For this, new communication schemes that are both suited for very resource-constrained nano-devices and which can still best utilize the Terahertz band have to be developed.

In this direction, we propose in this paper a new communication scheme for nanomachines based on the exchange of very short pulses spread in time. Due to the size and energy constraints of nanomachines, it is technologically not feasible to generate a high-power carrier signal in the Terahertz band in the nanoscale. As a result, classical communication paradigms based on the transmission of continuous signals cannot be used. Alternatively, very short pulses can be generated and efficiently 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 nanoscale imaging [15].

In light of the random nature of nanonetworks and the predictably very large number of nanomachines in the system [3],

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it does not seem feasible to have a network coordinator or to rely on centralized networking protocols to regulate the access to the channel. As a result, interference can become a major impairment for the system. Classical ways to control the interference, e.g., by means of power control mechanisms or sophisticated medium access control protocols, amongst others, need to be revised and tailored for the peculiarities of nanonetworks. Moreover, new ways to control the interference can emerge from the opportunities that pulse-based communications in the Terahertz band offer.

In this paper, we propose the use of channel coding to mitigate the interference in electromagnetic nanonetworks. In particular, we analytically and numerically show that low-weight channel codes can be used not only to detect and correct transmission errors, but also to prevent these errors from occurring in first instance, and, moreover, without compromising the individual user achievable information rate. Our main contributions are:

- We propose a new communication scheme for electromagnetic nanonetworks based on the exchange of femtosecond-long pulses spread in time.
- We develop a new statistical interference model for pulse-based communications in nanonetworks by assuming a spatial Poisson distribution of the nodes.
- We propose the use of low-weight channel codes to reduce the interference in nanonetworks and analytically and numerically evaluate their performance in terms of interference reduction and achievable information rate.

The rest of this paper is organized as follows. In Sec. II, we describe the pulse-based communication scheme that is considered in our analysis and we develop a statistical model of the interference. In Sec. III, we propose low-weight channel coding as a novel approach to mitigate the interference in electromagnetic nanonetworks, and analytically study their performance in terms of interference reduction and achievable information rate. In Sec. IV, numerical results for the overall interference reduction and the information rate achieved when using low-weight channel codes are provided. Finally, we conclude the paper in Sec. V.

II. System Model

In this section, we first describe a new pulse-based communication scheme for nanomachines and then we develop a novel statistical model of interference.

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

Due to the limited capabilities of nanomachines and the peculiarities of the Terahertz band, we introduce 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 nanomachine needs to transmit a binary stream (e.g., the reading from a nanosensor [2]),

- *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) because of the peculiar behavior of molecular absorption noise in the Terahertz band. Indeed, as described in [6], this molecular absorption 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 nanomachine is reduced (nothing is transmitted), and the probability of incorrect symbol detection is also lowered.
- *The time between transmissions is fixed and much longer than the pulse duration.* Due to technological limitations and similarly to Impulse Radio Ultra-Wide-Band (IR-UWB) systems [5], 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.

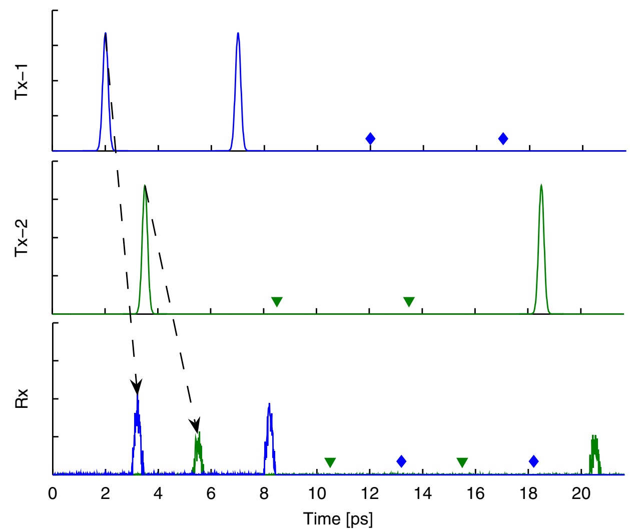

Fig. 1. Time Spread On-Off Keying (TS-OOK) illustration: top) First user transmitting the sequence "1100"; middle) Second user transmitting the sequence "1001"; bottom) Overlapped sequences at the receiver side.

In Fig. 1, we show an example of TS-OOK for the case in which two users are simultaneously transmitting different binary sequences to a third user. The upper plot corresponds to the sequence "1100", which is transmitted by the first user. A logical "1" is represented by a short pulse and a logical "0" is represented by silence. The time between symbols, T_s is much larger than the symbol duration T_p. This transmitted signal is propagated through the channel and corrupted with molecular absorption noise by the time it reaches the receiver (only when pulses are transmitted [6]). Similarly, the second plot shows the sequence transmitted by the second user, "1001". 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 [6]. This signal at the receiver is show in the third subplot.

B. Interference Modeling in TS-OOK

When using TS-OOK, it is intuitive to think that several nanomachines can concurrently use the channel mainly due to the fact that the time between symbols T_s is much longer than the symbol duration T_p. However, by considering a scenario in which nanomachines can start transmitting at any specific time in an uncoordinated manner and taking into account that there might be a very large number of nanomachines in close proximity, collisions between symbols can occur. These collisions result in interference and this imposes a limitation on the information rate at which nanomachines can communicate.

In order to quantitatively evaluate the impact of collisions on the system performance, we first develop a new statistical model for the interference power at the receiver. Our final objective is to have a closed-loop expression for the probability density function (p.d.f.) of the interference power I created at the receiver side, $f_I(i)$, where i refers to interference. Without loss of generality, we position the receiver at the origin of coordinates. The interference created at the receiver side by the nanomachines contained in an area of radius a is given by

$$I_a = \sum_{r \leq a} g(r) \tag{1}$$

where $g(r)$ refers to the power of a given signal at a distance r from its transmitter. From [6], $g(r)$ can be written as

$$g(r) = \int_B S(f) \left(\frac{c}{4\pi f r} \right)^2 e^{-k(f) r} df \tag{2}$$

where B refers to the bandwidth of the transmitted signal, $S(f)$ is the power spectral density (p.s.d.) of the transmitted symbol, f stands for frequency, c refers to the speed of light, and $k(f)$ is the molecular absorption coefficient of the medium. In Fig. 2, $g(r)$ is illustrated as a function of the distance r by using the channel model introduced in [6]. For the distances that are considered in our analysis, between a few hundred of micrometers and up to one meter, $g(r)$ can be approximated by the polynomial

$$g(r) \approx \beta (r)^{-\alpha} \tag{3}$$

where α and β are two constants which depend on the specific channel molecular composition as well as on the power and the shape of the transmitted signal [6]. In particular, for a standard medium composition with 10% of water vapor molecules, $\alpha \approx 2.1$ and $\beta \approx 2 \cdot 10^{-13}$, when using 100 femtosecond-long Gaussian pulses with an energy equal to 1 picoJoule per pulse.

To compute the overall interference created by the nanomachines contained within a disc of radius a, it is necessary to know the spatial distribution of the nodes. In our analysis, we model the positions of the nanomachines as a spatial Poisson point process. Therefore, the probability of finding k nodes in a disc of radius a and area $A(a)$ in m^2 can be written as

$$P[k \text{ in } A(a)] = \frac{(\lambda A(a))^k}{k!} e^{-\lambda A(a)} \tag{4}$$

where λ refers to the Poisson process parameter in nodes/m^2. Then, a collision between symbols will occur when these reach the receiver at the same time. In TS-OOK, by considering also a Poisson distribution of the arrivals in time, the probability of having an arrival during T_s seconds is a uniform random probability distribution with p.d.f. equal to $1/T_s$. Thus, for a given transmission, a collision will occur with probability $2T_p/T_s$ (we assume that a correlation-based energy detector is used at the receiver). We should note that not all types of symbols *harmfully collide*, but only pulses (logical "1"s) create interference. Therefore, we can replace the Poisson parameter λ in (4) by

$$\lambda \rightarrow \lambda' = \lambda_T (2T_p/T_s) p_1 \tag{5}$$

where λ_T refers to the density of active nodes in nodes/m^2, T_p refers to the symbol length, T_s stands for the time between symbols, and p_1 refers to the probability of a nanomachine to transmit a pulse (logical "1") instead of a silence (logical "0").

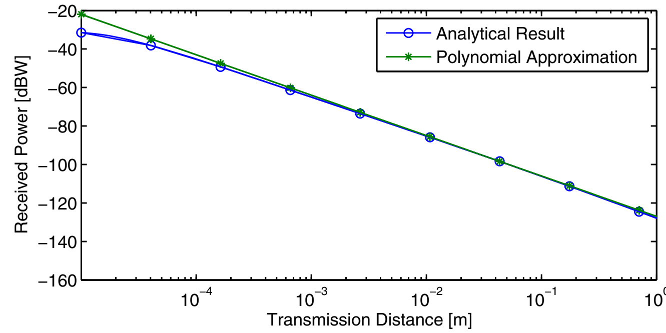

Fig. 2. Received power in dBW as a function of the transmitted distance when transmitting 100-femtosecond-long pulses with an energy equal to 1 pJ, in a medium with 10% of water vapor molecules.

Following a similar procedure as in [13], we will first compute the characteristic function of the interference I_a created by the nodes in a disc of radius a, $\Phi_{I_a}(\omega)$, then calculate its limit when the radius a goes to infinity, $\Phi_I(\omega)$, and finally obtain the p.d.f. of the interference power $f_I(i)$ as the inverse Fourier transform of $\Phi_I(\omega)$.

We define the characteristic function of the interference power I_a as $\Phi_{I_a}(\omega) = E\{exp(\jmath\omega I_a)\}$, which by using conditional expectations and taking into account the spatial Poisson distribution of the nodes, can be evaluated as

$$\begin{aligned}\Phi_{I_a}(\omega) &= E\left\{E\left\{e^{\jmath\omega I_a} | k \text{ in } A(a)\right\}\right\} \\ &= \sum_{k=0}^{\infty} \frac{\left(\lambda' \pi a^2\right)^k}{k!} e^{-\lambda' \pi a^2} E\left\{e^{i\omega I_a} | k \text{ in } A(a)\right\}\end{aligned} \tag{6}$$

where "k in $A(a)$" refers to the event of having k active nodes in a disk of radius a, and the expectation is over the random variable I_a. To compute this last term, we can proceed as follows. Under the Poisson assumption, when having k nodes in a disc of radius a, their locations follow independent and identically distributed uniform distributions. If R is the distance to the origin of a point that is uniformly distributed in $A(a)$, then the p.d.f. of R is

$$f_R(r) = \begin{cases} (2r)/a^2 & \text{r} \leq \text{a} \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

Now, taking into account that the characteristic function of the sum of a number of independent random variables is the product of the individual characteristic functions, we can write

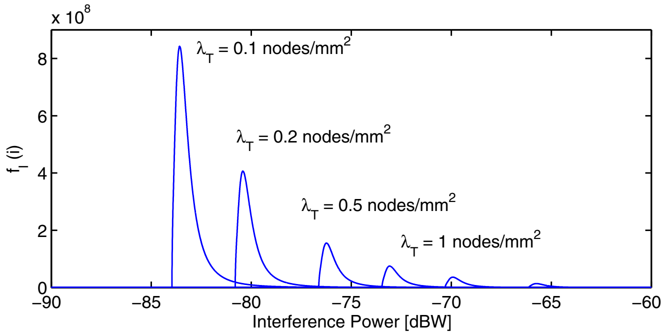

Fig. 3. Probability density function of the interference power for different transmitting nodes densities λ_T, when $T_s/T_p = 100$ and $p_1 = 0.5$.

$$E\left\{e^{\jmath\omega I_a}|k \text{ in } A(a)\right\} = \left(\int_0^a \frac{2r}{a^2} e^{\jmath\omega g(r)} dr\right)^k. \quad (8)$$

By combining (8) in (6), summing the series, and computing the limit when $a \to \infty$, the characteristic function of the interference power becomes

$$\Phi_I(\omega) = exp\left(\jmath\lambda'\pi\omega\left(\int_0^\infty [1/g(t)]^2 e^{\jmath\omega t} dt\right)\right) \quad (9)$$

where λ' refers to spatial Poisson point process parameter as defined in (5) in nodes/m^2 and $g(t)$ stands for the received power at the origin for a signal transmitted at a distance t as defined in (3).

Finally, for the specific case in which $g(t)$ can be approximated as a polynomial of the form $\beta t^{-\gamma}$, with $0 < \gamma = 2/\alpha < 1$, the integral in (9) may be evaluated to obtain:

$$\Phi_I(\omega) = exp\left(-\lambda'\pi\beta\Gamma(1-\gamma)e^{-\pi\gamma/2}\omega^\gamma\right) \quad (10)$$

where $\Gamma(\cdot)$ stands for the gamma function. For $0 < \gamma < 1$, the p.d.f. of I can now be obtained by taking the inverse Fourier transform, and results in

$$f_I(i) = \frac{1}{\pi i}\sum_{k=1}^{\infty}\frac{\Gamma(\gamma k+1)}{k!}\left(\frac{\pi\lambda'\beta\Gamma(1-\gamma)}{i^\gamma}\right)^k \sin k\pi(1-\gamma) \quad (11)$$

where λ' refers to the spatial Poisson point parameter given by (5), $\gamma \approx 0.95$ and $\beta \approx 2 \cdot 10^{-13}$ as shown before.

In Fig. 3, the p.d.f. of the interference power, $f_I(i)$ given by (11), is illustrated for different values of λ'. In particular, λ' is obtained from (5), with $T_s/T_p = 100$, $p_1 = 0.5$ and for λ_T ranging between 0.1 nodes/mm^2 and 10 nodes/mm^2.[1] For example, the interference created by a Poisson field of nanomachines with $\lambda_T = 0.1$ nodes/mm^2 which are operating under the previous conditions, has an average power of approximately -83 dBW. When the node density is increased to $\lambda_T = 1$ nodes/mm^2, this value reaches -73 dBW. By comparing these results with the received power as a function of the transmitted distance shown in Fig. 2, it is clear that interference will limit the performance of electromagnetic nanonetworks. Therefore, there is a need for new ways to mitigate the interference in the nanonetworking paradigm.

[1]We are considering devices whose total size is in the order of 10 μm^2 and which are transmitting pulses with an energy approximately equal to 1 pJ [2].

III. Channel Coding for Interference Mitigation

As a novel way to mitigate interference in nanonetworks, we propose the utilization of low-weight channel coding schemes. In this section, we first describe this new concept and then analytically study its performance in terms of information rate.

A. Interference Mitigation Capabilities of Low-Weight Codes

In existing communication systems, channel codes are used to allow the receiver of a message to detect and correct transmission errors. These transmission errors occur due to several reasons such as noise, multi-path or interference created by other nodes transmitting at the same time. The origin and type of transmission errors can be taken into account when choosing the coding scheme to be used. Going one step ahead, we propose to design channel codes to reduce the chances of having these errors in first instance. Our aim is not to develop new types of error correcting codes, but to analytically and numerically show how by controlling the weight of a code, i.e., the average number of bits equal to "1" in a codeword, the interference power can be reduced without compromising the achievable information rate or even improving it.

Existing channel codes generally make use of all the possible codewords independently of their weight. However, we show next that it is sometimes desirable to limit the values that the weight of the codewords can take. In this direction, ration coding techniques were proposed in [14] to reduce the electronic noise in chip interconnects. Rather than utilizing coding schemes to detect and correct data errors, by keeping the weight of the codewords constant, it is shown that the electronic noise can be reduced. In a similar direction, in [11], the performance of sparse Low Density Parity Check (LDPC) codes is analyzed in terms of error probability as a function of their weight. In particular, the authors show that for the binary symmetric channel and the parallel Z channel, the block error probability of LDPC codes can be reduced by reducing the code weight. To the best of our knowledge, these are the only papers in which the impact of the code weight in the performance of a communication system is investigated.

In our system model, it is clear from (11) and (5) that the probability of transmitting a pulse (logical "1") is directly related with the power of the interference. By controlling the weight of the transmitted codewords, the probability distribution of "1"s and "0"s can be modified. Ultimately, by using constant low-weight channel codes, we can reduce the interference of the system. This reduction in interference comes with the price of longer messages, as usually in order to uniquely code a message with a lower weight, it will be necessary to use a larger number of bits. To illustrate this effect, we proceed as follows. In our analysis, the length of an unencoded message is constant and equal to n bits. For a given n, the total number of possible n-bit words is given by 2^n. The length of an encoded message is $m \geq n$ bits, and its weight, which is defined as the number of bits equal to "1", is denoted by u. For a given m, the total number of possible codewords with a weight equal to u is given by:

$$\mathcal{W}(m,u) = \frac{m!}{(m-u)!u!}. \quad (12)$$

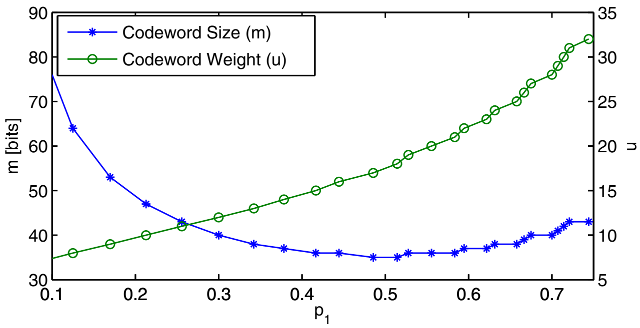

Fig. 4. Codeword size m and constant code weight w as a function of the target probability of transmitting a logical "1".

Therefore, in order to be able to encode all the possible source messages into fix weight codewords, the following condition must be satisfied:

$$\mathcal{W}(m, u) \geq 2^n \tag{13}$$

For example, for $n = 32$ bits, a total of $m = 35$ bits are needed to generate 2^{32} codewords with exact weight equal to $u = 17$. Note that this is just the minimum number of additional bits needed. When combined with other channel coding schemes aimed at the detection and correction of errors, additional bits will be necessary. Moreover, we acknowledge that generating such codes can be computationally demanding, and this is why rather than advocating for advanced channel coding schemes, we motivate the use of channel codes to diminish the number of potential transmission errors.

Then, under the assumption of a constant weight code, the probability of transmitting a pulse (logical "1"), p_1, and the probability of being silent (logical "0"), are given by:

$$p_1 = \frac{u}{m}; \quad p_0 = \frac{m-u}{m} \tag{14}$$

where m stands for the number of bits in the encoded message and u stands for its weight. In Fig. 4, the necessary codeword length in bits and the codeword weight necessary to achieve a specific probability of transmitting a pulse when encoding 32-bit messages is shown. For example, in order to achieve a probability of pulse transmission $p_1 = 0.3$, the encoded message size is $m = 42$ bits with exact weight $u = 12$.

Therefore, it is clear that by reducing the weight of the code, we can reduce the overall interference in the network. However, due to the fact that additional bits are being transmitted, it is intuitive to think that the amount of useful information that can be transmitted per unit of time is reduced. For this, in the next section we investigate the compromise between code weight reduction and useful information transmitted per unit of time by means of the individual user information rate.

B. Information Rate

In order to evaluate the performance of low-weight channel codes, we use the individual user information rate as a metric. For a pulse-based communication system such as TS-OOK, the useful information rate in bits/second is given by:

$$I(X,Y) = \frac{n}{m}\frac{T_p}{T_s}B\left(H(X) - H(X|Y)\right) \tag{15}$$

where n and m are the unencoded and encoded message lengths respectively, T_p is the symbol duration, T_s is the time between symbols, B stands to the bandwidth, 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 our system, the source X can be modeled as a discrete binary random variable, whose entropy $H(X)$ is given by:

$$H(X) = -p_1 \log_2 p_1 - p_0 \log_2 p_0 \tag{16}$$

where p_1 refers to the probability of transmitting a pulse (logical "1") and p_0 stands for the probability of being silent (logical "0"), and are both given by (14).

Similarly, the output of the channel Y can be modeled as a continuous random variable. In particular, the output of the transmitter is attenuated by the channel and corrupted by noise and interference. In our analysis, we consider the channel behavior to be deterministic. Thus, the only random components affecting the received signal are the noise and the interference. Therefore, the equivocation of the channel $H(X|Y)$ can be written as,

$$H(X|Y) = \int_y \sum_{l=0}^{1} p_Y(Y|X=l)\, p_l \cdot \log_2\left(\frac{\sum_{q=0}^{1} p_Y(Y|X=q)\, p_q}{p_Y(Y|X=l)\, p_l}\right) dy. \tag{17}$$

Finally, the probability of the channel output Y given the input $X = l$, $p_Y(Y|X=l)$, is given by,

$$p_Y(Y|X=l) = f_I(i) * f_{N_o}(n_o|X=l) \tag{18}$$

where $f_I(i)$ stands for the p.d.f. of the interference power given by (11), $f_{N_o}(n_o|x = x_l)$ is the p.d.f. of the noise conditioned to the fact that x_l has been transmitted, and $*$ denotes convolution. As introduced in [6], the noise in electromagnetic nanonetworks is mainly governed by molecular absorption noise and can generally be modeled as colored Gaussian noise.

Analytically solving the individual user information rate equation given by (15) is not feasible. Instead of this, we numerically investigate the compromise between interference mitigation and information rate in the following section.

IV. Numerical Results

In this section we provide numerical results for the performance of constant low-weight channel codes in terms of interference power mitigation and information rate. For the computation of the channel path-loss and noise, the models introduced in [6] are used. In an attempt to keep these numbers realistic, the energy of the transmitted 100-femtosecond-long Gaussian pulses is limited to 1 picoJoule in our analysis.

A. Interference Power

In Fig. 5, the maximum interference power obtained from the model given by (11) as a function of the probability of transmitting a pulse p_1 given by (14) is shown for different transmitting node densities λ_T in nodes/mm^2. For a specific node density, by increasing the probability of transmitting a pulse p_1, the interference power increases too. Thus, by

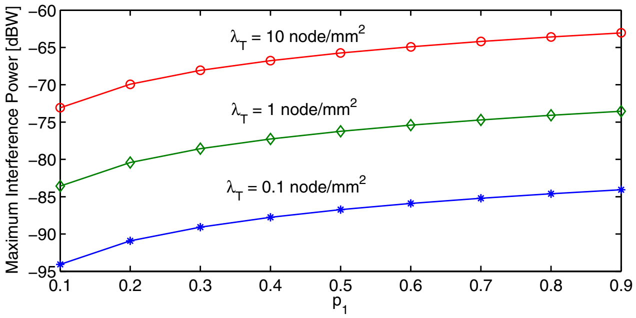

Fig. 5. Maximum interference power as a function of the probability of transmitting a pulse p_1 for different node densities λ_T. ($T_p/T_s = 0.01$)

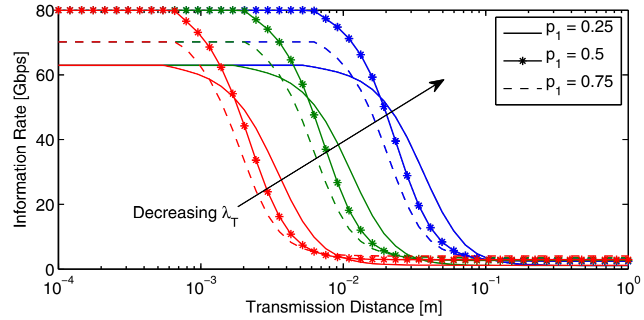

Fig. 6. Information rate as a function of the transmission distance for different node densities and different probabilities of pulse transmission ($T_p/T_s = 0.01$, $\lambda_T = 0.1, 1, 10$ nodes/mm^2).

using constant low-weight codes with lower values of p_1, the interference can be reduced. This effect is the similar for the different nodes densities considered in our analysis. In order to reduce the weight of a code, it is necessary to use longer codewords, which reduces the amount of useful information transmitted per unit of time. However, because the interference is lower, the equivocation of the channel as given by (17) is expectedly lower too, and the information rate is not severely compromised. This effect is numerically analyzed next.

B. Information Rate

The information rate given by (15) as a function of the transmission distance is shown in Fig. 6 for different node densities λ_T in nodes/mm^2 and for different probabilities of transmitting a pulse p_1 given by (14). For a specific node density, the impact of the probability of transmitting a pulse p_1 on the information rate strongly depends on the transmission distance (or, equivalently, the transmission power). We can mainly distinguish three different regions. For very short transmission distances, i.e., below 1 mm, interference is almost negligible (and so is noise), and thus, the equivocation of the channel is practically zero. Therefore, the maximum information rate is achieved when utilizing channel codes with $p_1 = 0.5$, which maximize the source entropy as given by (16). As the power of interference and the noise becomes comparable to the power of the received signal, the information rate decreases abruptly. However, by reducing the code weight and thus reducing the interference power, a relevant improvement can be achieved. Even if this requires the utilization of longer codewords, the overall useful information rate (15) is larger than when utilizing for example a code with $p_1 = 0.5$. Finally, further increasing the transmission distance will just result in the impossibility of communicating.

V. Conclusions

In this paper, we propose the utilization of low-weight channel codes to mitigate the interference in pulse-based electromagnetic nanonetworks in the Terahertz band. For this, we first statistically model the impulsive interference generated by a Poisson field of nanomachines which operate under a new pulse-based communication scheme named TS-OOK, and provide a closed-loop expression for the probability density function of the interference. Then, we analytically and numerically evaluate the impact of the code weight on the total interference power and the information rate. The results show how, by using low-weight channel codes, the overall interference can be reduced while keeping constant or even increasing the achievable information rate in an interference-limited scenario.

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References

[1] I. F. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A new communication paradigm," *Computer Networks (Elsevier) Journal*, vol. 52, no. 12, pp. 2260–2279, August 2008.

[2] I. F. Akyildiz and J. M. Jornet, "Electromagnetic wireless nanosensor networks," *Nano Communication Networks (Elsevier) Journal*, vol. 1, no. 1, pp. 3–19, March 2010.

[3] ——, "The Internet of Nano-Things," *IEEE Wireless Communications Magazine*, vol. 17, no. 6, pp. 58–63, December 2010.

[4] P. Avouris, "Carbon nanotube electronics and photonics," *Physics Today*, vol. 62, no. 1, pp. 34–40, January 2009.

[5] *IEEE 802.15.4a: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs). Amendment 1: Add Alternate PHYs.*, IEEE Standard for Information Technology, Telecommunications and Information Exchange between Systems Std.

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

[7] ——, "Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band," in *Proc. of 4th European Conference on Antennas and Propagation, EUCAP*, April 2010, pp. 1–5.

[8] P. Kim, "Toward carbon based electronics," in *IEEE Device Research Conference*, June 2008.

[9] Y. M. Lin, C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H. Y. Chiu, A. Grill, and P. Avouris, "100-GHz Transistors from Wafer-Scale Epitaxial Graphene," *Science*, vol. 327, no. 5966, p. 662, February 2010.

[10] S. Luryi, J. Xu, and A. Zaslavsky, *Future Trends in Microelectronics*. John Wiley & Sons - IEEE Press, 2007, ch. Scaling Limits of Silicon CMOS and Non-silicon opportunities, pp. 203–211.

[11] E. Ratzer and D. MacKay, "Sparse low-density parity-check codes for channels with cross-talk," in *Proc. of IEEE Information Theory Workshop*, March 2003, pp. 127–130.

[12] M. Rosenau da Costa, O. V. Kibis, and M. E. Portnoi, "Carbon nanotubes as a basis for terahertz emitters and detectors," *Microelectronics Journal*, vol. 40, no. 4-5, pp. 776–778, April 2009.

[13] E. Sousa, "Performance of a spread spectrum packet radio network link in a poisson field of interferers," *IEEE Transactions on Information Theory*, vol. 38, no. 6, pp. 1743 –1754, November 1992.

[14] J. Tabor, "Noise reduction using low weight and constant weight coding techniques," MIT, Cambridge, MA, USA, Tech. Rep., 1990.

[15] D. Woolard, P. Zhao, C. Rutherglen, Z. Yu, P. Burke, S. Brueck, and A. Stintz, "Nanoscale imaging technology for thz-frequency transmission microscopy," *International Journal of High Speed Electronics and Systems*, vol. 18, no. 1, pp. 205–222, 2008.

[16] G. Zhou, M. Yang, X. Xiao, and Y. Li, "Electronic transport in a quantum wire under external terahertz electromagnetic irradiation," *Physical Review B*, vol. 68, no. 15, p. 155309, October 2003.