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PHLAME: A Physical Layer Aware MAC Protocol for Electromagnetic Nanonetworks

Joan Capdevila Pujol ‡†, **Josep Miquel Jornet** * and **Josep Sole Pareta** ‡

‡ NaNoNetworking Center in Catalunya (N3Cat)
Universitat Politècnica de Catalunya
Jordi Girona 1-3, 08034, Barcelona, Spain
Email: pareta@ac.upc.edu

* Broadband Wireless Networking Laboratory (BWN Lab)
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, Georgia 30332, USA
Email: {joancp, jmjornet}@ece.gatech.edu

Abstract*—Nanotechnology is enabling the development of integrated devices just a few hundred nanometers in size. Communication among these nano-devices will boost the applications of nanotechnology in the biomedical, environmental and military fields. Within the communication alternatives at the nanoscale, the state of the art in nanomaterial research points to the Terahertz band (0.1-10 THz) as the frequency range of operation of graphene-based electromagnetic (EM) nano-transceivers. This frequency band supports very large transmission bit-rates and enables simple communication mechanisms suited to the limited capabilities of nano-devices. Due to an expectedly very large number of nano-devices sharing the same channel, it is necessary to develop new Medium Access Control (MAC) protocols which will be able to capture the peculiarities of nanonetworks in the Terahertz band. In this paper, PHLAME, a physical layer aware MAC protocol for electromagnetic nanonetworks, is introduced. This protocol is built on top of a novel communication scheme based on the exchange of femtosecond-long pulses spread in time, and exploits the benefits of novel low-weight channel coding schemes. In the PHLAME protocol, the transmitting and receiving nano-devices jointly select the communication parameters that minimize the interference in the nanonetwork and maximize the probability of successfully decoding the received information. The performance of the protocol is analyzed in terms of energy consumption, delay and achievable throughput, by taking also into account the energy limitations of nano-devices. The results show that, despite its simplicity, the PHLAME protocol is able to support densely populated nanonetworks by exploiting the peculiarities of the Terahertz band.

***Index Terms*—Nanonetworks, Terahertz Band, Medium Access Control, Pulse-based Communications, Graphene**

I. INTRODUCTION

Nanotechnology is providing a new set of tools to the engineering community to design and manufacture integrated nano-devices in a scale ranging from one to a few hundred nanometers. The tasks that these devices can individually accomplish are very limited both in terms of complexity and range of operation. By means of communication, nano-devices will be able to achieve more complex tasks in a distributed manner and to cover larger areas [1], [2]. The resulting nanonetworks, i.e., networks of nano-devices, will expand the range of applications of nanotechnology in the biomedical, environmental and military fields, amongst others.

For the time being, the communication alternatives for nano-devices are very limited. Focusing on the electromagnetic (EM) paradigm, the utilization of novel nanomaterials, such as graphene, is enabling the development of miniaturized EM transceivers suited to the target size and energy capabilities of nano-devices [3], [4]. Amongst others, ongoing research on the characterization of the EM properties of graphene [5], [6], [7] points to the Terahertz band (0.1-10.0 THz) as the expected frequency range of operation of future EM nano-transceivers. In particular, in [5] we determined that a 1 μm long graphene-based nano-antenna can only efficiently radiate in the Terahertz range. This matches the predictions for the frequency of operation of graphene-based RF transistors [8].

The Terahertz band (0.1-10.0 THz), on its turn, is one of the least explored frequency ranges [9]. In [10], we developed a propagation model for Terahertz communications and showed how the Terahertz band can theoretically support very large bit-rates, up to several hundreds of terabits per second for distances below one meter. However, it is not likely that nano-devices will require these very large transmission bit-rates in many applications. Alternatively, having a very large bandwidth also enables new simple communication mechanisms suited to the expectedly limited capabilities of nano-devices.

We also introduced a new communication scheme for nano-devices based on the exchange of very short pulses spread in time in [11]. Indeed, due to the size and energy constraints of nano-devices, it is currently not feasible to generate a high-power carrier signal in the nanoscale at Terahertz frequencies [2]. As a result, classical communication paradigms based on the transmission of continuous signals cannot be used. On the other hand, very short pulses can be generated and efficiently radiated in the nanoscale [6]. 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 [12].

In light of the very large number of nano-devices and the

[†] This work was completed during his stay in the Broadband Wireless Networking Lab*.

random nature of nanonetworks [13], there is a need for new Medium Access Control (MAC) protocols. It is not practical to use the classical solutions because they do not capture the peculiarities of nanonetworks. First, the main limitation at the nanoscale is not the available bandwidth, but the energy of nano-devices, which can only be provided by means of energy harvesting systems [14]. Second, classical MAC protocols are not directly applicable in pulse-based communication systems. Only some of the solutions proposed for Impulse Radio Ultra Wide Band (IR-UWB) networks [15] could be considered, but their complexity limit their usefulness.

In this paper, we present PHLAME, a PHysical Layer Aware MAC protocol for Electromagnetic nanonetworks. The PHLAME protocol is based on the joint selection by the transmitter and the receiver of the communication parameters and the channel coding scheme that minimizes the interference in the nanonetwork and maximizes the probability of successfully decoding the received information. To the best of our knowledge, this is the first MAC protocol for EM nanonetworks that captures the peculiarities of the Terahertz band as well as the expected capabilities of future graphene-based nano-devices. Our main contributions are:

- We present Rate Division Time Spread On-Off Keying, RD TS-OOK, a revised version of the communication scheme based on the exchange of femtosecond-long pulses that we first introduced in [11], in order to support different symbol and coding rates.
- We propose a physical-aware MAC protocol for EM nanonetworks, PHLAME, a new channel sharing protocol that adapts the RD TS-OOK coding parameters according to the transmitter and receiver perceived channel quality and available resources.
- We analyze the performance of the proposed protocol by means of energy consumption, delay and achievable throughput, by using accurate models of the Terahertz channel (path-loss and molecular absorption noise) and the interference.

The rest of this paper is organized as follows. In Sec. II, we describe the new pulse-based communication scheme which is considered in our analysis. In Sec. III, we present our new MAC protocol for EM nanonetworks and highlight the novelties of this solution. In Sec. IV, we investigate the performance of the presented protocol in terms of energy consumption, delay and throughput. Finally, we conclude the paper in Sec. V.

II. RATE DIVISION TIME SPREAD ON-OFF KEYING

The Rate Division Time Spread On-Off Keying communication scheme (RD TS-OOK) is a new modulation and channel sharing mechanism for nano-devices based on the asynchronous exchange of femtosecond-long pulses, which are transmitted following an on-off keying modulation spread in time. A simplified version of this mechanism was first introduced in [11].

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),

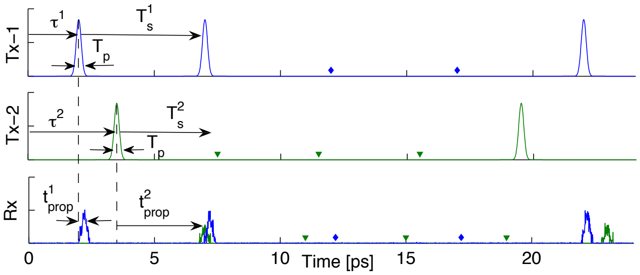

Fig. 1. Rate Division TS-OOK.

- *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, based on the presence or absence of radiation, is chosen instead of a binary Pulse Amplitude Modulation (PAM), based on the change of the signal polarity, because of the peculiar behavior of molecular absorption noise in the Terahertz band. This type of noise is strongly present when molecules are excited [10].
- *The time between symbols T_s is much longer than the pulse duration T_p, and it is fixed for the duration of a packet*. Due to technology limitations and similarly to Impulse Radio Ultra-Wide-Band (IR-UWB) systems [15], the symbols, i.e., the pulses or the silences, are not transmitted in a burst, but spread in time. By determining the time between symbols, i.e., the symbol rate, after the detection of the first transmitted pulses a user does not need to continuously sense the channel.
- *The time between pulses, i.e., the symbol rate, β, is different for different users and different types of packets*. Even if unlikely, very short pulses can collide. If the nano-devices are transmitting at the same rate, a collision in one symbol entails a collision in every symbol until the end of the packets, which are usually referred to as catastrophic collisions. In other pulse-based schemes such as in IR-UWB, orthogonal time hopping sequences are used to avoid this condition [15]. Due to the complexity of generating these sequences in nano-devices, we advocate for the variation of the symbol rate [16].

Several nano-devices can concurrently occupy the channel when using RD TS-OOK mainly due to the fact that the time between symbols T_s is much longer than the symbol duration T_p. The transmission of very short pulses (less than 100 femtoseconds [2]) minimizes the chances of having collisions, and provides almost orthogonal communication channels. Note that under this communication scheme, a collision between packets only occurs when two or more symbols exactly overlap in time. Moreover, by allowing different users to transmit at different rates, a collision in a given symbol does not lead to multiple consecutive collisions in the same packet.

Fig. 1 shows the RD TS-OOK signal transmitted by two users with different initial transmission times τ^1 and τ^2. The upper plot corresponds to the sequence "11001", 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^1 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. Similarly, the second plot shows the sequence transmitted by the second user, "10001", with a different symbol rate T_s^2. In this example, the 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. The signal at the receiver side, $s_R(t)$, is shown in the third plot. In this specific case, the delay introduced by the channel to each signal, t^1_{prop} and t^2_{prop}, is such that the first symbol of the second user overlaps with the second symbol of the first user. As a result of using different rates, consecutive symbols in both users do not overlap.

III. A PHYSICAL LAYER AWARE MAC PROTOCOL FOR NANONETWORKS

We introduce the PHLAME protocol as the first MAC protocol which is tailored to the peculiarities of the Terahertz band and which takes into account realistic limitations of future nanoelectronic devices. The protocol is built on top of RD TS-OOK, and it is split in two stages, namely, the handshaking process and the data transmission process.

A. Handshaking Process

The aim of the handshaking process is twofold. First, it allows a receiver to coordinate multiple simultaneous transmissions. Second, it facilitates the joint selection of both the transmission symbol rate and the channel coding scheme that make the data transmission more reliable. The handshaking process is divided in two substages, the handshaking request and the handshaking acknowledgment.

The *handshaking request* is triggered by any nano-device that has information to be transmitted and which has enough energy to complete the process. A transmitter generates a Transmission Request (TR) packet, which contains the Synchronization Trailer, the Transmitter ID, the Receiver ID, the Packet ID, the transmitting Data Symbol Rate (DSR) and the Error Detecting Code (EDC). The DSR field specifies the symbol rate β that will be used to transmit the data packet. The strength of RD TS-OOK against collisions increases when different users transmit at different rates. In the PHLAME protocol, every transmitting node randomly selects a symbol rate from a set of coprime rates, which minimizes the probability of having catastrophic collisions [16]. The EDC field is used to detect transmission errors as a conventional checksum field.

The TR packet is transmitted using a Common Coding Scheme (CCS), which specifies a predefined symbol rate and channel coding mechanism. By using the same symbol rate, catastrophic collisions might occur. However, the TR packets are very short and the EDC field should suffice to detect simple errors in the majority of cases. Finally, the transmitter waits for a timeout before trying to retransmit the TR packet when no answer is received.

The *handshaking acknowledgment* is triggered by the receiver of the TR packet, which uses the CCS to decode the received bitstreams when listening to the channel. If a TR packet is successfully decoded, the receiver will check whether it can handle an additional incoming bitstream. In our scenario, we consider that due to the energy limitations of nano-devices, after the transmission or active reception of a packet, a device needs to wait for a certain *recovery time* in order to restore its energy by means of energy harvesting systems [14]. This time is much longer than the packet transmission delay and poses a major limitation to the network.

If the handshake is accepted, a Transmission Confirmation (TC) packet is sent to the transmitter using the CCS. The TC packet contains the Synchronization Trailer, the Transmitter ID, the Receiver ID, the Packet ID, the transmitting Data Coding Scheme (DCS) and the Error Detecting Code. The DCS is selected by the receiver in order to guarantee a target Packet Error Rate (PER), which depends on the perceived channel quality and can be estimated from the pulse intensity or the perceived noise. In particular, the DCS determines two parameter values. First, it specifies the channel code weight, i.e., the average number of logical "1"s in the encoded data. By reducing the code weight, interference can be mitigated without affecting the achievable information rate, as we showed in [11]. Second, the DCS specifies the order of the repetition code that will be used to protect the information. Since RD TS-OOK reduces possible transmissions errors by avoiding catastrophic symbol collisions , a simple repetition code is enough to successfully decode the information in the majority of cases.

B. Data Transmission Process

At this point, the data is transmitted at the symbol rate specified by the transmitter in the DSR field, and encoded with the weight and repetition code specified by the receiver in the DCS field. The DP contains a Synchronization Trailer, the Transmitter ID, the Receiver ID, and the useful Data. The Error Detecting Code has been removed from the packet since by using different symbol rates, catastrophic collisions are highly unlikely, and randomly positioned errors can be fixed by means of the chosen channel coding scheme. If the DP is not detected at the receiver before a time-out, T_{out}^{DP}, the receiver assumes that the handshaking process failed.

IV. PERFORMANCE ANALYSIS

In this section, we analyze the performance of the PHLAME protocol in terms of energy consumption, packet latency and normalized throughput.

A. System Model

The following assumptions are considered in our analysis:

- The path-loss and noise in the Terahertz band are computed by using the models introduced in [10]. A standard medium with 10% of water vapor is considered.
- The interference is modeled as in [11], by assuming a Poisson field of interferers. The density of active nodes is a parameter value in our analysis.
- The transmitter encodes logical "1"s by using the first time-derivative of 100 femtosecond long Gaussian pulses. The energy of a pulse is limited to 100 pJ.
- A non-coherent receiver architecture is considered, with an integration time T_i equal to ten times the symbol duration T_p [17].

- The recovery time for a nano-device after transmission or active reception of a DP is three orders of magnitude longer than the data packet duration [14].
- The receiver can simultaneously track a fixed number of incoming packets, K. We model this as a finite length queueing system with K servers and without waiting lane (a packet that cannot be served is discarded) [18].
- The RD TS-OOK symbol rates are randomly chosen by each node from a pool of pairwise coprime rate codes in the order of 1000 (e.g., 1009, 1013, 1019).
- The TR and TC packets in the PHLAME protocol are 16 Bytes. DPs are 125 Kbytes. The packet length is arbitrarily chosen, but it seems appropriate to use relatively large DPs because RD TS-OOK does not cannibalize the channel and transmission errors are expectedly sparse.
- The target Packet Error Rate is equal to 10^{-3}. The possible bit coding schemes are limited to a non repetition code with weight equal to 0.5 (the number of logical "1"s and "0"s is the same), a 3-repetition code with weight equal to 0.4 (only 40% of the bits are logical "1"s), a 5-repetition code with weight equal to 0.3, a 7-repetition code with weight equal to 0.2 and a 9-repetition code with weight equal to 0.1. We understand by a n-repetition code a coding scheme that replicates n times each symbol, either pulses or silences.

B. Energy Consumption

The energy consumption is contributed by the consumption at the transmitter and at the receiver. Currently, the energy consumption of graphene-based nano-electronics is still unknown. Because of this, we focus on the energy that would be spent only in the communication part. These results should be scaled by the overall efficiency of a graphene-based nano-transceiver.

1) Transmitter Energy Consumption: This is mainly governed by the numbers of handshaking attempts and the length and code weight used for the transmission of the DP. Three possible cases can happen when starting a new packet transmission. First, the handshaking can fail because the TR packet collides with other packets, or because the receiver either cannot allocate one more transmission or it is in its energy recovery stage. Second, the handshaking can be aborted because the TC packet collides at the transmitter. The third case corresponds to the situation in which the handshaking succeeds, and the nodes go into the Data Transmission phase.

To estimate the energy consumption at the transmitter, we consider the energy involved in the transmission, E_{TX}, reception, E_{RX}, and time-out, $E_{t/o}$, for each one of the aforementioned cases. These partial energies are given by:

$$\begin{aligned} E_1 &= E_{TX}^{TR} + E_{t/o}^{H} \\ E_2 &= E_{TX}^{TR} + E_{RX}^{TC} \\ E_3 &= E_{TX}^{TR} + E_{RX}^{TC} + E_{TX}^{DP}. \end{aligned} \tag{1}$$

Each type of packet used by the PHLAME protocol has a different number of bits and is encoded using different channel coding schemes. Moreover, the data packets' structure depends on the selected DSR and DCS. When more robust codes are needed, the repetition code order is increased and its weight is reduced. This makes packets longer but not necessarily much more energy consuming, because only the transmission of pulses consumes energy, and this decreases with the code weight. At the same time, transmitting with lower weight codes can also reduce the overall interference and ultimately the number of retransmissions [11].

Then, each case for the energy consumption described above occurs with a certain probability, which can be calculated as:

$$\begin{aligned} p_1 &= 1 - p_a^{Rx} p_s^{TR} \\ p_2 &= p_a^{Rx} p_s^{TR} \left(1 - p_s^{TC}\right) \\ p_3 &= p_a^{Rx} p_s^{TR} p_s^{TC} \end{aligned} \tag{2}$$

where p_a refers to the probability of acceptance at the receiver, and p_s refers to the probability of successful reception. The p_a is computed by taking into account the maximum number of simultaneous incoming packets that the receiver can handle K and its energy status. The p_s is computed from the probability of symbol error for the Terahertz channel with the type of pulses that are considered, and by taking into account the error correcting capabilities of the channel codes in use.

Then, the consumed energy in the transmitter depends on the number of retransmissions required to complete the handshaking. Since the probability of successful handshaking is exactly p_3, the energy consumed at the transmitter is:

$$E_{transmitter} = \frac{1}{p_3} \left(p_1 E_1 + p_2 E_2 + p_3 E_3\right). \tag{3}$$

By combining (1) and (2) into (3), we reach the following closed-form expression:

$$\begin{aligned} E_{transmitter} =& \frac{1}{p_a^{Rx} p_s^{TR} p_s^{TC}} \Big(\left(1 - p_a^{Rx} p_s^{TR}\right) \left(E_{TX}^{TR} + E_{t/o}^{H}\right) \\ &+ p_a^{Rx} p_s^{TR} \left(1 - p_s^{TC}\right) \left(E_{TX}^{TR} + E_{RX}^{TC}\right) \Big) \\ &+ E_{TX}^{TR} + E_{RX}^{TC} + E_{TX}^{D} P. \end{aligned} \tag{4}$$

2) Receiver Energy Consumption: The energy at the receiver is governed by the number of handshaking attempts as well as the DP transmission. The handshaking fails when the receiving node is unable to decode the TR packet, when it cannot handle another transmission or when the TC packet collides. Similarly as before, by expressing the energies and the probabilities for each case, the energy consumption at the receiving node can be written as:

$$\begin{aligned} E_{receiver} =& \frac{1}{p_a^{Rx} p_s^{TR} p_s^{TC}} \Big(\left(1 - p_a^{Rx} p_s^{TR}\right) E_{RX}^{TR} \\ &+ p_a^{Rx} p_s^{TR} \left(1 - p_s^{TC}\right) \left(E_{RX}^{TR} + E_{TX}^{TC} + E_{t/o}^{D} P\right) \Big) \\ &+ E_{RX}^{TR} + E_{TX}^{TC} + E_{RX}^{D} P. \end{aligned} \tag{5}$$

Finally, the total energy consumption per useful bit of information is obtained by adding (4) and (5) and dividing it by the length of the DP.

In Fig. 2 (left), the total energy consumption per bit as a function of the node density is shown for different maximum number of simultaneously handled packets at the receiver, k. When the node density is increased, the interference in the network increases, which has a twofold impact on the

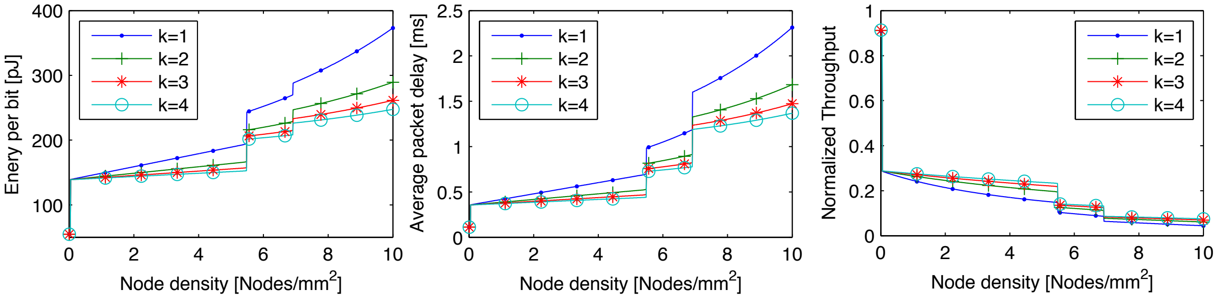

Fig. 2. Energy per bit consumption, average packet delay and normalized throughput as functions of the node density for different maximum number of simultaneous packets that can be handled by the receiver.

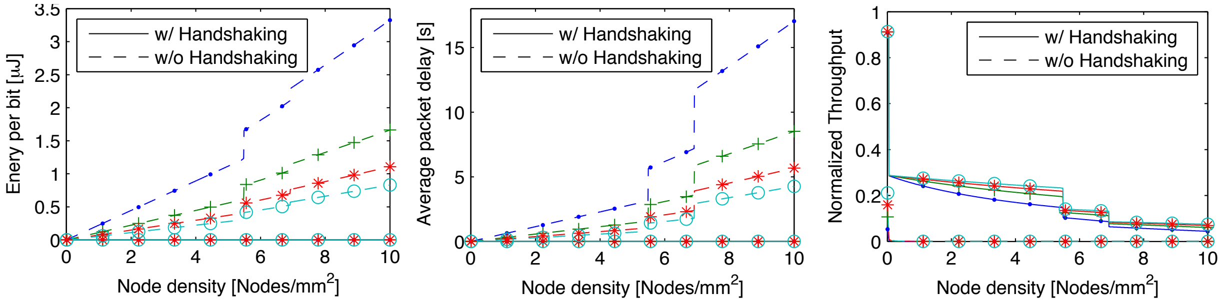

Fig. 3. Comparison between PHLAME and similar protocol without handshaking stage in terms of the energy per bit consumption, average packet delay and normalized throughput as functions of the node density for different maximum number of simultaneous packets that can be handled by the receiver.

energy consumption. First, a higher interference turns into an increased number of handshaking attempts. Second, once the handshake has been completed, the DP is transmitted using higher order repetition codes which are necessary to guarantee the target PER. The steps in the energy curves correspond to the transitions in the coding scheme from non repetition code to 3-repetition, 5-repetition, and so on. At the same time, note that by allowing the receiver to handle more than one packet simultaneously, the energy decreases.

In Fig. 3 (left), we show the energy consumption per useful bit of information in a nanonetwork operating under RD TS-OOK, but in which rather than using the PHLAME protocol, the DPs are directly transmitted without any type of handshaking. There are almost three orders of magnitude of difference between the PHLAME protocol and the protocol without handshake. This result depends on the packet length and the offered load parameters. For a very dense network, as the one we are considering, a handshake avoids having to retransmit the entire DP several times. We acknowledge that a more complete analysis on the impact of the packet size in the system has to be conducted.

Finally, we would like to emphasize the energy reduction achieved by using low-weight coding schemes. In Fig. 4, the energy consumption per bit of the PHLAME protocol is compared to that of the case in which only the repetition code order is variable and the code weight remains at 0.5. The results show that especially for very dense networks, lowering the code weight can reduce the overall energy consumption by more than half. This is due to the fact that the interference is mitigated when using lower weight codes, and this minimizes both the number of handshake attempts and the probability of symbol errors and energy consumed in the DP.

C. Packet Latency

To study the packet latency we should take into account that the different types of packets in the PHLAME protocol have different lengths and are encoded using different parameters. In particular, we consider that packets have the following average durations:

$$\begin{aligned} T^{TR} &= B^{TR}\beta_{min}T_i \\ T^{TC} &= B^{TC}\beta_{min}T_i \\ T^{DP} &= B^{DP}N_r\frac{\beta_{max}-\beta_{min}}{2}T_i \end{aligned} \tag{6}$$

where T^{TR}, T^{TC} and T^{DP} stands for the packet duration of TR, TC and DP packets, respectively, β_{min} and β_{max} are the minimum and maximum symbol rates that the nano-devices can select, T_i refers to the integration time and N_r is the required number of symbols per bit to achieve the target PER.

Following a similar procedure as before, we can write the closed-form expression for the average packet delay as:

$$\begin{aligned} T_{PCK} = &\frac{1}{p_a^{Rx}p_s^{TR}p_s^{TC}}\left(\left(1-p_a^{Rx}p_s^{TR}\right)\left(T^{TR}+T_{t/o}^{H}\right)\right. \\ &\left.+\,p_a^{Rx}p_s^{TR}\left(1-p_s^{TC}\right)\left(T^{TR}+T_{t/o}^{DP}\right)\right) \\ &+T^{TR}+T^{TC}+T^{DP}. \end{aligned} \tag{7}$$

In Fig. 2 (center), the average packet delay given by (7) is shown as a function of the node density. The impact of the capabilities of the receiving node in terms of maximum number of packets that a nano-device can handle is illustrated. When the node density is increased, the interference is increased, and consequently the number of handshaking attempts increases. This turns into longer packet transmission delays. However, the major increase comes from the change

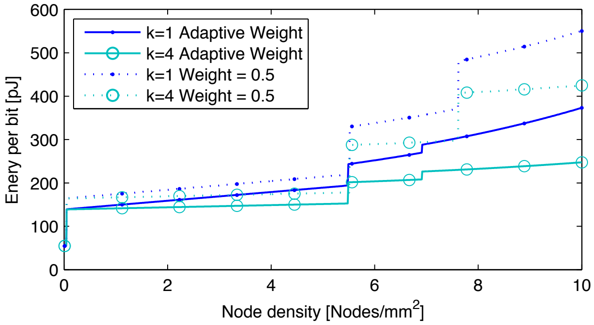

Fig. 4. Energy per bit consumption as a function of the node density for different code weights.

in the repetition code order that is necessary to achieve the target packet error rate. Similarly as before, by allowing the receiver to handle more than one packet simultaneously, the overall delay is clearly reduced. Finally, note that a simple handshaking process can reduce the time delay by almost three orders of magnitude, as shown in Fig. 3 (center), where the delay in the PHLAME protocol is compared to that of utilizing RD TS-OOK without handshaking process.

D. Normalized Throughput

We define the normalized throughput as the maximum information rate that the MAC layer can support divided by the maximum data rate that a node can transmit in a single user scenario. For this, we divide the user bit-rate that the PHLAME protocol can provide by the maximum achievable bit-rate imposed by RD TS-OOK. This is given by,

$$Tput = \frac{R_b^{PHLAME}\ [bps]}{R_b^{max}\ [bps]} = \frac{\frac{L_D}{T_{PCK}}}{\frac{1}{N_r \frac{\beta_{max}-\beta_{min}}{2} T_i}} \tag{8}$$

where L_D stands for the payload length in the data packet, T_{PCK} is the packet latency found in (7), N_r refers to the coding rate used, T_i is the observation time and β_{max}, β_{min} are the maximum and minimum symbol data rate, respectively.

The normalized throughput is shown in Fig. 2 as a function of the node density. Similarly as before, the changes in the coding scheme as the interference increases, create the steps in the throughput curves. As expected, the normalized throughput of the PHLAME protocol is much larger than that of a similar protocol without the handshaking stage (Fig. 3). The main reason for this result comes from the fact that the handshake does not only inform the receiver about a new incoming transmission, but first, it asks for its permission based on its local status, and, second, determines the best communication parameters and coding scheme.

V. CONCLUSIONS

In this paper, we present a physical layer aware MAC protocol for electromagnetic nanonetworks, PHLAME. This protocol is tailored to a novel communication scheme based on the exchange of femtosecond-long pulses spread in time. Our solution allows the transmitter and the receiver to jointly select in an adaptive fashion several communication parameters such as the symbol rate or encoding scheme and channel code weight, by means of a handshaking process. We analyze the performance of the proposed protocol in terms of energy consumption per useful bit of information, average packet delay and normalized achievable throughput. The results show that, despite its simplicity, the PHLAME protocol is able to support densely populated nanonetworks by exploiting the peculiarities of the Terahertz band, the expected capabilities of future electronic graphene-based nano-devices, and the benefits of low weight coding schemes. Future work includes the investigation of the impact of the packet size on the overall network performance, and the validation of these results by means of a network simulation tool.

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