Nano Communication Networks 3 (2012) 74–81

Contents lists available at SciVerse ScienceDirect

Nano Communication Networks

journal homepage: www.elsevier.com/locate/nanocomnet

PHLAME: A Physical Layer Aware MAC protocol for Electromagnetic nanonetworks in the Terahertz Band

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ARTICLE INFO

Article history:
Received 18 January 2012
Accepted 20 January 2012
Available online 31 January 2012

Keywords:
Nanonetworks
Terahertz Band communication
Medium Access Control
Pulse-based communication
Graphene

ABSTRACT

Nanonetworks will enable advanced applications of nanotechnology in the biomedical, industrial, environmental and military fields, by allowing integrated nano-devices to communicate and to share information. Due to the expectedly very high density of nano-devices in nanonetworks, novel Medium Access Control (MAC) protocols are needed to regulate the access to the channel and to coordinate concurrent transmissions among nano-devices. In this paper, a new PHysical Layer Aware MAC protocol for Electromagnetic nanonetworks in the Terahertz Band (PHLAME) is presented. This protocol is built on top of a novel pulse-based communication scheme for nanonetworks and exploits the benefits of novel low-weight channel coding schemes. In PHLAME, the transmitting and receiving nano-devices jointly select the optimal communication scheme parameters and the channel coding scheme which maximize the probability of successfully decoding the received information while minimizing the generated multi-user interference. 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 PHLAME, by exploiting the properties of the Terahertz Band and being aware of the nano-devices' limitations, is able to support very densely populated nanonetworks with nano-devices transmitting at tens of Gigabit/second.

1. Introduction

Nanotechnology is providing a new set of tools to the engineering community to design and manufacture novel electronic components, just a few cubic nanometers in size, which can perform only very specific tasks, such as computing, data storing, sensing and actuation. The integration of several of these nano-components into a single entity will enable the development of more advanced nano-devices. By means of communication, these nano-devices will be able to achieve complex tasks in a distributed manner [1–4]. The resulting *nanonetworks will enable more advanced applications* of nanotechnology in the biomedical, environmental, industrial and military fields, such as intrabody health monitoring and drug delivery systems, or wireless nanosensor networks for biological and chemical attack prevention at the nanoscale, amongst others.

For the time being, the communication options for nano-devices are very limited. The miniaturization of a conventional metallic antenna to meet the size requirements of the nano-devices would impose the use of very high operating frequencies (several hundreds of Terahertz), thus limiting the feasibility of nanonetworks. Alternatively, nanomaterials enable the development of plasmonic nano-antennas which can operate at much

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1 This work was completed during his stay in the Broadband Wireless Networking (BWN) Laboratory.

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doi:10.1016/j.nancom.2012.01.006

lower frequencies. Amongst others, ongoing research on the characterization of the EM properties of graphene, lately referred to as the *wonder material of the 21st century* [11,22], points to the Terahertz Band (0.1–10.0 THz) as the radiation frequency band of novel nano-antennas [11,22,17]. Interestingly enough, novel graphene-based RF components for nano-transceivers are also envisioned to operate in this frequency band [14,16,15].

The Terahertz Band (0.1–10.0 THz) is one of the least explored communication frequency ranges in the EM spectrum [6]. In [8,12], we developed a new channel model for Terahertz Band communications and showed how the absorption from several molecules in the medium attenuates and distorts the traveling waves and introduces colored Gaussian noise. Despite these phenomena, this band can theoretically support very large bit-rates, up to several Terabit/second. However, it is not likely that very limited nano-devices will require these very high transmission bit-rates. Alternatively, and probably more importantly, having a very large bandwidth *enables new simple communication and medium sharing mechanisms* suited for the expectedly very limited capabilities of nano-devices.

In this direction, we have recently introduced a new communication scheme for nano-devices based on the exchange of very short pulses spread in time called TS-OOK (Time Spread On–Off Keying) [9]. 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. 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 [17]. 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 spectroscopy and biological imaging [20].

Due to the expectedly very high nano-device density in nanonetworks, novel Medium Access Control (MAC) protocols are needed to regulate the access to the channel and to coordinate concurrent transmissions among nano-devices. Classical MAC protocols cannot directly be used in nanonetworks because they do not capture either the limitations of nano-devices or the peculiarities of the Terahertz Band:

- First, the majority of existing MAC protocols for wireless networks have been designed for band-limited channels. This is not the case of nanonetworks because, as shown in [8,12], the Terahertz channel provides nano-devices with an almost 10 THz wide window. This is the main difference between graphene-enabled wireless communication for nanonetworks in the Terahertz Band and the classical wireless paradigms.
- Second, classical MAC protocols which are based on carrier-sensing techniques cannot be used in pulse-based communication systems. Only some solutions proposed for Impulse Radio Ultra Wide Band (IR-UWB) networks [7] could be considered, but their complexity limits their usefulness in the nanonetwork scenario. For example, it does not seem feasible to generate and distribute orthogonal time hopping sequences among nano-devices as in IR-UWB.
- Third, the main limitation for nano-devices results from the very limited energy that can be stored in nano-batteries, which requires the use of novel energy-harvesting systems [18,21]. As a result, the energy of nano-devices has both positive and negative temporal fluctuations which change the availability of the nano-device to communicate over time.

In this paper, we present a PHysical Layer Aware MAC protocol for Electromagnetic nanonetworks in the Terahertz Band (PHLAME). This protocol is built on top of the Rate Division Time-Spread On–Off Keying (RD TS-OOK), which is a revised version of our recently proposed pulse-based communication scheme for nano-devices, and it exploits the benefits of novel low-weight channel coding schemes. PHLAME is based on the joint selection by the transmitter and the receiver of the optimal communication parameters and channel coding scheme which minimize the interference in the nanonetwork and maximize the probability of successfully decoding the received information. Moreover, the fluctuations in the energy of the nano-devices are taken into account. 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 graphene-based nano-devices.

The main contributions in this paper are summarized as follows:

- We describe the Rate Division Time Spread On–Off Keying (RD TS-OOK), which is a revised version of the communication scheme based on the exchange of femtosecond-long pulses that we introduced in [9], in order to support variable symbol rates.
- We propose a PHysical Layer Aware MAC protocol for EM nanonetworks (PHLAME), which adapts the RD TS-OOK coding parameters according to the transmitter and the receiver perceived channel quality and available resources.
- We analytically study the performance of the proposed protocol in terms 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 remainder of this paper is organized as follows. In Section 2, we describe the new pulse-based communication scheme which is considered in our analysis. In Section 3, we present our new MAC protocol for EM nanonetworks and highlight the novelties of this solution. In Section 4, we analytically investigate the performance of the presented protocol in terms of energy consumption, delay and throughput. In Section 5, we provide numerical results for the performance of PHLAME. Finally, we conclude the paper in Section 6.

2. Rate division time spread on–off keying

The Rate Division Time Spread On–Off Keying (RD TS-OOK) is a new modulation and channel access 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 [9,10].

The functioning of this communication scheme is as follows. Assuming that a nano-device needs to transmit a binary stream (e.g., the output of a nanosensor),

- *A logical "1" is transmitted by using a one-hundred-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 shown in [8,12], this type of noise is only present when molecules are excited; if no nano-device 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.
- *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 [7], the symbols, i.e., the pulses or the silences, are not transmitted in a burst, but spread in time. This time should also allow for the molecular absorption noise to diminish. By determining the time between symbols T_s, after the detection of the first transmitted pulses a nano-device does not need to continuously sense the channel. During this time, the receiver may follow additional transmissions or just remain inactive.
- *The time between symbols T_s and the symbol rate $\beta = T_s/T_p$ are different for different nano-devices and for different types of packets.* This is done to minimize the probability of multiple sequential symbol collisions in a packet. If all the nano-devices are transmitting at the same symbol rate, a collision in one symbol entails a collision in every symbol until the end of the first packet. These type of collisions 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 [7]. Due to the complexity of generating, distributing and updating these sequences among nano-devices, we advocate for the variation of the transmission symbol rate β [19].

RD TS-OOK provides almost orthogonal channels to nano-devices in close vicinity. First, symbol collisions are very unlikely due to the very short length of the transmitted symbols T_p and due to the fact that the time between symbols T_s is much longer than the symbol duration T_p. Second, even if a symbol collision occurs, 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. Moreover, by allowing different nano-devices to transmit at different symbol rates, a collision in a given symbol does not lead to multiple consecutive collisions in the same packet.

Fig. 1 illustrates an example of RD TS-OOK for the case in which two nano-devices start transmitting to a third

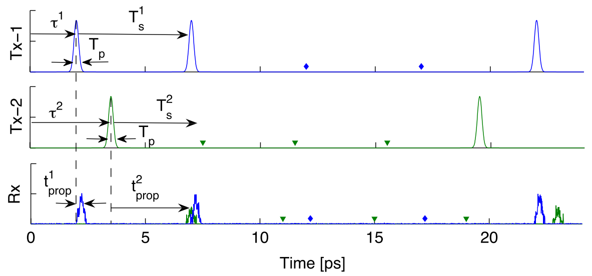

Fig. 1. RD TS-OOK illustration: (top) first nano-device transmitting the sequence "11,001"; (middle) second nano-device transmitting the sequence "10,001"; (bottom) overlapped sequences at the receiver side.

common receiver, with different initial transmission times τ^1 and τ^2. The upper plot corresponds to the sequence "11,001", which is transmitted by the first nano-device. 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 nano-device, "10,001", with a different symbol rate T_s^2. In this example, the second nano-device is farther from the receiver than the first nano-device. As a result, the signal at the receiver suffers from higher attenuation, longer delay, and more noise. The signal at the receiver side 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 nano-device overlaps with the second symbol of the first nano-device. As a result of using different symbol rates, consecutive symbols in both nano-devices do not overlap.

3. PHysical Layer Aware MAC Protocol for Electromagnetic nanonetworks

The PHysical Layer Aware MAC Protocol for Electromagnetic nanonetworks (PHLAME) is a novel MAC protocol tailored to the peculiarities of the Terahertz Band and which takes into account the limitations of future electronic nano-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, which we describe next.

3.1. 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 (i) the transmission symbol rate and (ii) the channel coding scheme which make the data transmission more reliable. The handshaking process is divided in two substages,

- 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^i that will be used to transmit the data packet. The strength of RD TS-OOK against collisions increases when different nano-devices transmit at different rates. In PHLAME, every transmitting node randomly selects a symbol rate from a set of coprime rates, which have been shown to minimize the probability of having catastrophic collisions [19]. The EDC field is a conventional checksum field to detect transmission errors.

The TR packet is transmitted using a Common Coding Scheme (CCS), which specifies a predefined symbol rate β^0 and channel coding scheme. When using the same symbol rate β^0, catastrophic collisions might occur among TR packets. However, the TR packets are very short and the EDC field should suffice to detect simple errors in the majority of the cases. Finally, the transmitter waits for a timeout before trying to retransmit the TR packet, if necessary.

- 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 the 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 [18,21]. This time is much longer than the packet transmission delay and this poses a major constraint.

If the handshake is accepted, the receiver replies to the transmitter with a `Transmission Confirmation(TC)` packet, which is encoded by 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). This depends on the perceived channel quality, which can be estimated from the received pulse shape and intensity, or the measured noise.

To achieve the target PER, we consider that nano-devices make use of low-weight channel codes concatenated with simple repetition codes [10]. For this, first, the DCS field specifies the channel code weight, i.e., the average number of logical "1"s in the encoded data. By reducing the code weight, i.e., by encoding the information using more logical "0"s than logical "1"s, both molecular absorption noise and interference can be mitigated without affecting the achievable information rate, as we showed in [10]. 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 decode the information in the majority of the cases.

3.2. Data transmission process

At this point, a `Data Packet(DP)` is transmitted at the symbol rate β^i specified by the transmitter in the DSR field, and encoded with the weight and repetition order 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 the receiver assumes that the handshaking process failed.

4. Performance analysis

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

4.1. System model

We make the following considerations in our analysis:

- The path-loss and noise in the Terahertz Band are computed by using the models introduced in [8,12]. A standard medium with 10% of water vapor is considered.
- The interference is modeled as in [10], 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 [5].
- 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 [18].
- 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) [13].
- 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 PHLAME 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 consider that a n-repetition code is a coding scheme that replicates n times each symbol, either pulses or silences.

4.2. Energy consumption

The energy consumption is contributed by the consumption at the transmitter and at the receiver. Currently, the energy consumption of graphene-based nanoelectronics 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.

4.2.1. Transmitter energy consumption

This is mainly governed by the number 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:

(1) The handshaking process fails because:
   (a) The TR packet collides with other packets
   (b) The receiver cannot allocate one more transmission due to memory constraints.
   (c) The receiver is in the energy recovery stage.
(2) The handshaking process fails because the TC packet collides at the transmitter.
(3) The handshaking process 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 PHLAME (TR, TC and DP) has a different number of bits and it 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, as we discussed in [10].

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^{Rx} refers to the probability of acceptance at the receiver, and p_s^{TR} and p_s^{TC} refer to the probability of successful reception of the TR and the TC packets, respectively. p_a^{Rx} is computed by taking into account the maximum number K of simultaneous incoming packets that the receiver can handle and its energy status. p_s^{TR} and p_s^{TC} are 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.

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:

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

4.2.2. 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:

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

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.

4.3. Packet latency

To study the packet latency we should take into account that the different types of packets in PHLAME 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} stand for the packet duration of TR, TC and DP packets, respectively; B^{TR}, B^{TC} and B^{DP} are the number of bits in the TR, TC and DP packets, respectively; $\beta_{\min}$ and $\beta_{\max}$ stand for 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.

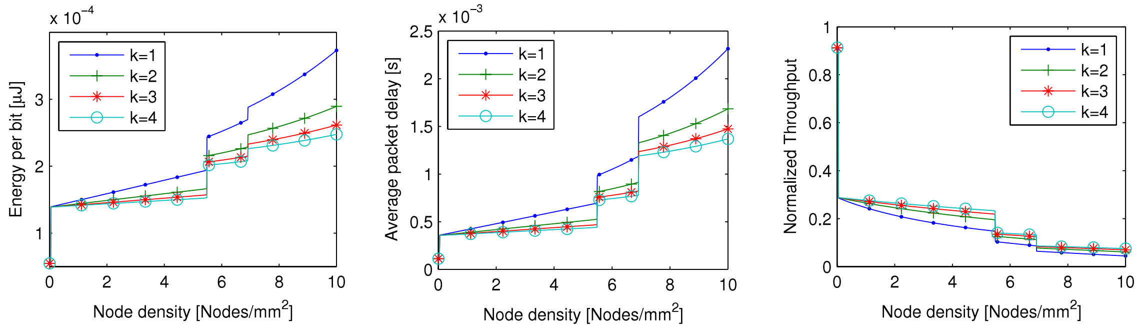

Fig. 2. Energy per bit consumption, average packet delay and normalized throughput as functions of the node density for different maximum number of simultaneous packets that can be handled by the receiver.

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

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

4.4. 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 nano-device scenario. For this, we divide the nano-device bit-rate that PHLAME can provide by the maximum achievable bit-rate imposed by RD TS-OOK. This is given by:

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

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 $\beta_{\max}$, $\beta_{\min}$ are the maximum and minimum symbol data rate, respectively.

5. Numerical results

In this section we provide numerical results on the performance of PHLAME in terms of energy consumption, packet latency and normalized throughput.

5.1. Energy consumption

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, and this has a twofold impact on the 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 a non repetition code to a 3-repetition code, a 5-repetition code, and so on. At the same time, 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 PHLAME, the DPs are directly transmitted without any type of handshaking. There are almost three orders of magnitude difference between PHLAME 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 PHLAME 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.

5.2. Packet latency

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

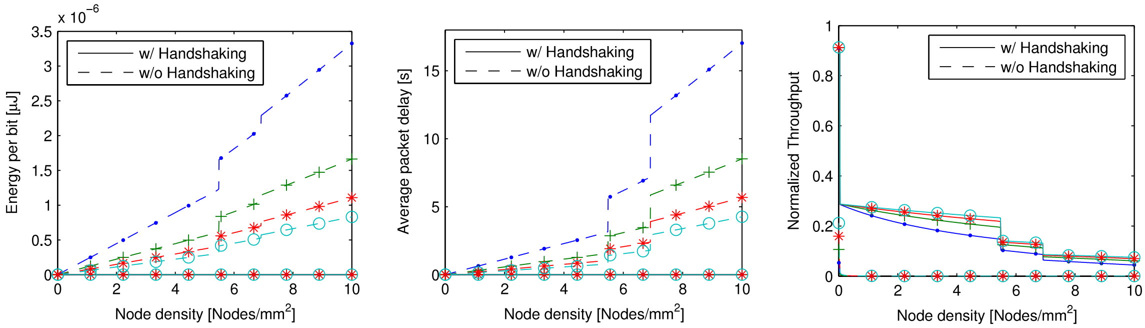

Fig. 3. Comparison between PHLAME and similar protocol without handshaking stage in terms of the energy per bit consumption, average packet delay and normalized throughput as functions of the node density for different maximum number of simultaneous packets that can be handled by the receiver.

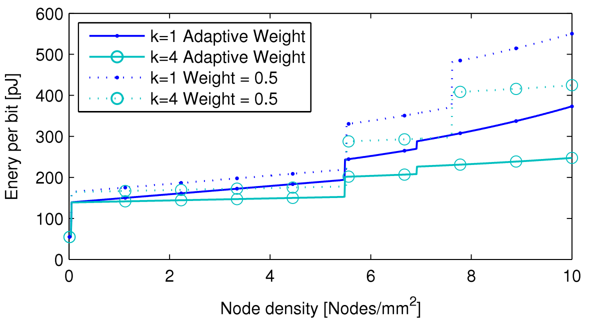

Fig. 4. Energy per bit consumption as a function of the node density for different code weights.

comes from the change in the repetition code order that is necessary to achieve the target PER. 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 PHLAME is compared to that of RD TS-OOK without handshaking process.

5.3. Throughput

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 PHLAME 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, it determines the best communication parameters and coding scheme.

6. Conclusions

Wireless communication among nano-devices 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 nano-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 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 the encoding scheme and the 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, PHLAME 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.

Acknowledgment

This work was supported by Fundación Caja Madrid.

References

[1] I.F. Akyildiz, F. Brunetti, C. Blazquez, Nanonetworks: a new communication paradigm, Computer Networks Journal 52 (12) (2008) 2260–2279.
[2] I.F. Akyildiz, J.M. Jornet, Electromagnetic wireless nanosensor networks, Nano Communication Networks Journal 1 (1) (2010) 3–19.
[3] I.F. Akyildiz, J.M. Jornet, The internet of nano-things, IEEE Wireless Communications Magazine 17 (6) (2010) 58–63.
[4] I.F. Akyildiz, J.M. Jornet, M. Pierobon, Nanonetworks: a new frontier in communications, Communications of the ACM 54 (11) (2011) 84–89.
[5] A. Goldsmith, Wireless Communications, Cambridge University Press, New York, NY, USA, 2005.
[6] IEEE 802.15 Wireless Personal Area Networks-Terahertz Interest Group (IGthz). [Online] Available: http://www.ieee802.org/15/pub/IGthz.html.
[7] 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 Physical, IEEE Standard for Information Technology, Telecommunications and Information Exchange between Systems Std.

[8] J.M. Jornet, I.F. Akyildiz, Channel capacity of electromagnetic nanonetworks in the terahertz band, in: Proceedings of IEEE International Conference on Communications, ICC, May 2010.
[9] J.M. Jornet, I.F. Akyildiz, Information capacity of pulse-based wireless nanosensor networks, in: Proceedings of the 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, SECON, Jun 2011.
[10] J.M. Jornet, I.F. Akyildiz, Low-weight channel coding for interference mitigation in electromagnetic nanonetworks in the terahertz band, in: Proceedings of IEEE International Conference on Communications, ICC, Jun 2011.
[11] J.M. Jornet, I.F. Akyildiz, Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band, in: Proc. of 4th European Conference on Antennas and Propagation, EUCAP, Apr 2010.
[12] J.M. Jornet, I.F. Akyildiz, Channel modeling and capacity analysis of electromagnetic wireless nanonetworks in the terahertz band, IEEE Transactions on Wireless Communications 10 (10) (2011) 3211–3221.
[13] L. Kleinrock, Queueing systems, Volume 1: Theory, Wiley-Interscience, 1975.
[14] Y.M. Lin, C. Dimitrakopoulos, K.A. Jenkins, D.B. Farmer, H.Y. Chiu, A. Grill, P. Avouris, 100-GHz transistors from wafer-scale epitaxial graphene, Science 327 (5966) (2010) 662.
[15] J. Moon, D. Curtis, D. Zehnder, S. Kim, D. Gaskill, G. Jernigan, R. Myers-Ward, C. Eddy, P. Campbell, K.-M. Lee, P. Asbeck, Low-phase-noise graphene fets in ambipolar rf applications, IEEE Electron Device Letters 32 (2011) 270–272.
[16] T. Palacios, A. Hsu, H. Wang, Applications of graphene devices in rf communications, IEEE Communications Magazine 48 (2010) 122–128.
[17] M. Rosenau da Costa, O.V. Kibis, M.E. Portnoi, Carbon nanotubes as a basis for terahertz emitters and detectors, Microelectronics Journal 40 (4–5) (2009) 776–778.
[18] Z.L. Wang, Towards self-powered nanosystems: from nanogenerators to nanopiezotronics, Advanced Functional Materials 18 (22) (2008) 3553–3567.
[19] M. Weisenhorn, W. Hirt, Uncoordinated rate-division multiple-access scheme for pulsed uwb signals, IEEE Transactions on Vehicular Technology 54 (5) (2005) 1646–1662.
[20] D. Woolard, P. Zhao, C. Rutherglen, Z. Yu, P. Burke, S. Brueck, A. Stintz, Nanoscale imaging technology for thz-frequency transmission microscopy, International Journal of High Speed Electronics and Systems 18 (1) (2008) 205–222.
[21] S. Xu, Y. Qin, C. Xu, Y. Wei, R. Yang, Z.L. Wang, Self-powered nanowire devices, Nature Nanotechnology 5 (2010) 366–373.
[22] G. Zhou, M. Yang, X. Xiao, Y. Li, Electronic transport in a quantum wire under external terahertz electromagnetic irradiation, Physical Review B 68 (15) (2003) 155309.

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