Idling Energy Modeling and Reduction in Energy Harvesting Terahertz Nanonetworks for Controlling Software-Defined Metamaterials

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***Abstract*—Software-Defined Metamaterials (SDMs) are envisioned to enable the control of electromagnetic waves at an unprecedented scale. Various SDM applications will require downlink and broadcast-based transmission of control packets from a powered transmitter to energy harvesting nanonodes. The nanonode's communication system is anticipated to be a bottleneck for such nanonetworks, hence an accurate modeling of its energy consumption is needed. Time-Spread ON–OFF Keying (TS-OOK) is a prevailing scheme for nanocommunication in the Terahertz (THz) frequencies, with short pulses representing logical "1"s and silences "0"s. In the energy modeling of this scheme, a certain energy is usually attributed to the transmission or reception of the pulses, without considering the energy consumed in idling. To enable more realistic modeling, we propose an energy consumption model that additionally accounts for the idling energy. In a scenario relevant for numerous SDM applications, we demonstrate that the idling energy consumption is substantial and cannot be disregarded. To reduce the idling energy consumption, we propose a new duty cycle for the receiving nanonodes. Assuming frequent packet repetitions on the transmit side, the proposed duty cycle utilizes short wake-ups of the receiving nanonodes. Additionally, we propose two algorithms for deciding when these wake-ups should be performed. For two energy harvesting options expected to be utilized in prominent SDM applications, we show that, in case the proposed duty cycle is utilized, three orders of magnitude higher idling energy consumption can be tolerated compared to the baseline. Finally, we demonstrate encouraging performance of the proposed algorithms in increasing the communication reliability.**

***Index Terms*—Software-defined metamaterials, terahertz nanocommunication, energy harvesting, Time-Spread ON–OFF Keying, receiver wake-up, packet reception rate;**

I. Introduction

Recent developments in nanotechnology are giving rise to nanometer-size devices for enabling a variety of application domains, among the most promising ones being Software-Defined Metamaterials (SDMs) [1], [2]. The SDM applications envisage controlling a potentially large number (i.e., thousands or even millions per m^2) of metamaterial elements, allowing them to influence the properties of electromagnetic waves at an unprecedented scale. This control is envisioned to be done from mains- or battery-powered controllers in a downlink broadcast fashion, as discussed in e.g., [3]–[5]. Due to the small form factors of the receiving nanonodes, wireless communication in the Terahertz (THz) frequency band ($0.3-10$ THz) is emerging as one of the most promising paradigms for the required communication and coordination [6], [7]. By the same token, the nanonodes will in many cases not be powered by batteries, but will rely on energy-constrained capacitors. As a consequence, their only feasible powering option will be to harvest energy from the surrounding environmental sources.

Due to energy harvesting, the energy consumption of the receiving nanonodes will usually be the bottleneck of nanocommunication required for enabling the targeted SDM applications. For this reason, an accurate energy consumption model of the nanonode is needed, with the energy consumption modeling of the nanonode's communication system being one of the first required steps. Time-Spread ON–OFF Keying (TS-OOK) [8] is a *de-facto* standard modulation and channel coding scheme for nanocommunication in the THz frequencies. This is because, at these frequencies and on such a scale, carrier-based modulation schemes cannot be utilized due to technological limitations [9]. In addition, the TS-OOK scheme features high scalability, which will be required for enabling the majority of SDM applications. Finally, synchronization between the transmitting and receiving nodes is not required in TS-OOK, which indeed can hardly be achieved in the envisioned scenario due to nanonodes' energy and size constraints.

The main contributions of this paper are threefold. First, we provide an energy consumption model of a nanonode's communication system, assuming that TS-OOK is employed as the nanocommunication scheme. Our model accounts for the energy consumed in idling, besides the usually assumed energy consumed in transmission or reception of a TS-OOK pulse. We demonstrate by a numerical example that, for a realistic nanocommunication scenario, the idling energy consumption of the receiving nanonodes is not negligible. We also show that the majority of idling energy consumption arises from idling between two consequent packet receptions. Second, to reduce this energy dissipation, we propose a new duty cycle for the receiving nanonode. The proposed duty cycle utilizes packet repetitions on the transmit side. On the receive side, the nanonodes only wake up to receive a packet (or one of its repetitions), followed by going back to sleep. Third, for deciding when the nanonodes should wake up, we propose two algorithms, one utilizing the knowledge of the energy required to receive one packet, while the other additionally using the expected packet generation frequency.

Using the proposed energy consumption model, we evaluate the effects of idling energy consumption on the packet reception rate (i.e., communication reliability) in the considered nanonetwork. We do that because reliable nanocommunication will be highly relevant for various energy harvesting-powered SDM applications [10]. Moreover, we do that for two energy harvesting options (i.e., air vibrations and ultrasound power transfer) expected to be utilized in prominent SDM applications, as well as for both deterministic and stochastic traffic patterns. In addition, we consider the traffic to be broadcast-based, downlink-only, and one-to-many in a grid-like constellation, which is specific to and fully suitable for the first generation of SDMs. Our results show that, for a meaningful performance of the nanonetwork, the idling energy consumption of the nanonodes has to be *nine orders of magnitude* lower than the energy consumed in reception during the same period. We also show that, by utilizing the proposed wake-up-based duty cycle, the idling energy consumption can be up to three orders of magnitude higher for achieving the same packet reception rate as the baseline. Finally, we demonstrate superior performance of the algorithms for waking up the nanonodes compared to the baseline. Here, the algorithm that utilizes only the knowledge of the energy needed to receive a packet outperforms the other for deterministic, and vice-versa for stochastic traffic.

The remainder of this paper is structured as follows. In Section II, we provide an overview of the related works in the domains of idling energy consumption and threshold-based wake-ups in wireless networks. In Section III, we discuss the envisioned nanocommunication scenario for enabling a number of SDM applications. A model for energy consumption of an energy harvesting nanonode's communication system is proposed in Section IV. In the same section, we propose a wake-up-based duty cycle of the nanonodes and propose two algorithms for their wake-up. The evaluation methodology is outlined in Section V, while in Section VI we discuss the obtained results. Finally, we conclude the paper in Section VII.

II. Related Work

A. Idling Energy Consumption in Wireless Networks

As mentioned, a TS-OOK pulse carries one bit of information, i.e., a logical ”1”, while a logical “0” is represented by the silence. In the pioneering work on the topic [11], the authors model the interplay between energy harvesting of the nanonodes on the one hand, and the energy consumption due to packet transmission and reception on the other. The energy consumption of the receiving nanonode's communication system is modeled by assuming a certain energy consumed for transmitting or receiving a pulse [11]. In [12], the authors model the nanodevice's power consumption by considering the energy consumption of its main components, i.e., processor, actuator, communication, and memory module. Moreover, they argue that the main bottleneck in the nanodevice's energy consumption will be the communication system. Similar to [11], they model the energy consumption of the communication system by assuming certain energy consumption values for transmitting or receiving a TS-OOK pulse.

However, from more traditional wireless communication systems it is well-known that a certain amount of energy is also consumed in idling. For example, in wireless sensor networks, the value of idle listening energy in a device's communication system is in the same order of magnitude as the energy consumed in reception during the same period [13]. The current state-of-the-art systems for reducing idling energy consumption are based on the utilization of radios with very low power consumption for waking-up main radios for data reception, which is known as the Wake-up Radio (WuR)-based communication paradigm. In this paradigm, the energy consumption of the WuR in idling is roughly three orders of magnitude lower than the energy consumption of the main radio in reception [14]. That is to say, in traditional communication and even in the WuR-based paradigm the energy consumed in idling is substantial and cannot be disregarded if the aim is to accurately model the overall energy consumption. However, in TS-OOK-based nanocommunication, the energy consumption due to idling is, to the best of our knowledge, currently largely overlooked.

The only contribution we are aware of is our previous work [15], where we proposed an energy consumption model for the TS-OOK scheme and, based on it, a new duty cycle of a receiving nanonode. We evaluated the proposed duty cycle for deterministic traffic. In this paper, we expand our contributions by proposing two algorithms for intelligent wake-up of the receiving nanonodes. In addition, we generalize our findings by demonstrating the feasibility of the proposed duty cycle and promising performance of the algorithms for both deterministic and stochastic traffic patterns.

B. Energy Threshold-based Wake-up in Wireless Networks

It is an established concept that, in order to minimize their energy consumption, communicating devices should stay asleep (i.e., in a power-saving mode) most of the time and wake up only when necessary [16], [17]. The wake-up should in such a scenario be done in a way that maximizes the packet reception rate. Example-wise, the authors in [18] demonstrate that two orders of magnitude reduction in power consumption of a wireless sensor network (used for light monitoring in a road tunnel) can be achieved in WuR-based compared to idle listening-based communication. Moreover, to prolong the devices' lifetime, the authors in [19] propose a method for waking up wireless sensor network nodes based on a dynamic threshold that accounts for the data arrival rate. In [20], to maximize the lifetime of a wireless sensor network the authors base the wake-up of the nodes on their expected energy consumptions in idling and data transmission/reception. Finally, different approaches exist for waking up the main radio by utilizing an energy efficient WuR [21]–[23].

The above-outlined contributions demonstrate the feasibility and promising performance of utilizing device wake-ups for maximizing the lifetime in traditional wireless sensor networks. In wireless sensor networks, the devices are mostly battery-powered, which is not the case for the scenario with energy harvesting nanonodes that we consider. The wake-up in wireless sensor networks can be done by either utilizing the WuR or by the devices themselves accounting for data transmission and reception rates. In contrast, in the scenario we consider the limiting factor is the energy harvested by the nanonodes. Intuitively, in such a scenario the WuR is hardly feasible as it is challenging to predict the energy levels of the nanonodes due to substantial fluctuations in the energy harvesting rates [24]. Thus, with the WuRs the nanonodes could be awoken when they do not have enough energy to receive a packet. Hence, in the unsuccessful attempt to receive the packet, the nanonodes would consume the energy that they have harvested. For a similar reason, the data arrival or transmission rates become a secondary factor in the wake-up of energy harvesting nanonodes, as the nanonodes first have to account for the fact that they have harvested sufficient energy to transmit or receive a packet. Along the discussion above and contrary to the previous contributions, in this work we develop two algorithms for deciding when to wake-up a nanonode based primarily on the energy level required for receiving a packet, and secondarily on traffic arrival rates (i.e., packet generation interval).

III. Software-Defined Metamaterials

Metamaterials are manufactured structures envisioned to enable controlled manipulation of electromagnetic waves [2], [25]. Hence, metamaterials are going to be used for realizing systems with the abilities of engineered control of the reflection, absorption, or transmission of electromagnetic radiation [2], [25]. The current metamaterials are "hard-coded" for an application and operational conditions (e.g., to work for a single angle of incidence or to attenuate waves in a certain manner). To enable their reprogrammability, Liaskos et al. [26] proposed SDMs, a paradigm in which the metamaterial elements can be reconfigured at runtime through a set of software instructions. For supporting the reprogramming, the SDM paradigm envisions embedding a communication network of controllers within the metamaterial, as depicted in Figure 1. In the depicted generalized scenario, each controller interacts locally with its associated unit cell, where the unit cell represents a set of sensors and actuators being controlled by and communicating with a given controller. These sensors and actuators are used as an abstraction for functionalities of adjusting the properties (i.e., actuators) and delivering the readings (i.e., sensors) of the metamaterial elements. Moreover, in Figure 1, the routing plane is used for distributing the desired behavior of the metamaterials across the controllers, as well as for enabling the communication between the controllers and the outside world. Note that Figure 1 depicts a 2-dimensional grid-like constellation of metamaterials, also known as the metasurface. Nonetheless, 3-dimensional and non-grid constellations (e.g., randomly distributed metamaterials) are also possible [25].

The SDM paradigm is expected to roll-out in two phases distinguishable based on the complexity of the supported operations [25]. In the initial phase (also known as "the first generation of SDMs"), the aim is to showcase the capabilities of this new technology [1]. Specifically, very simple controllers and intra-SDM network infrastructure are envisioned to be deployed in the first prototypes. The controllers are in the first generation envisioned to adjust the properties of the associated unit cell in a downlink and broadcast fashion, i.e., each controller will issue commands to the associated cell, where each element of the cell will receive the same command, as depicted in Figure 2. Given that as the controllers are only envisioned to adjust the properties of metamaterials, Figure 2 depicts only the actuators. In addition, the communication plane and the gateway to the outside world have not been depicted in Figure 2 (in contrast to Figure 1), as this work is limited to controller-to-unit-cell communication.

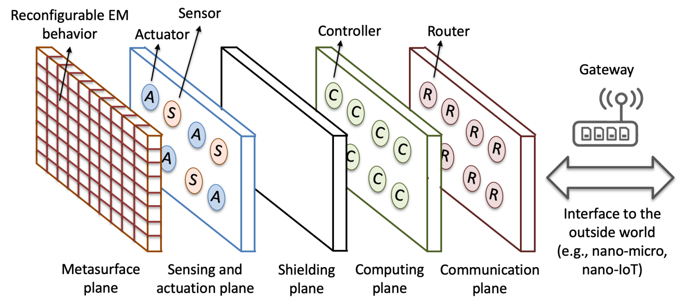


Figure 1: SDM paradigm for controlling metamaterials

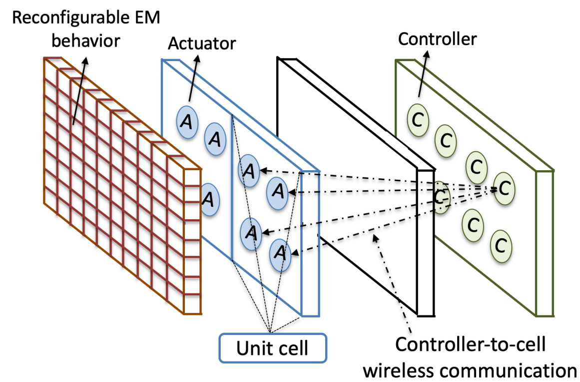


Figure 2: Considered communication scenario for enabling the first generation of SDMs

Depending on the actual application, the number of elements in the unit cells will potentially be large, ranging from hundreds to thousands [1]. The small sizes of the unit cells pose a frequency-dependent form-factor limit on the cell elements, hence the THz frequency band becomes a desired paradigm for wireless controller-to-unit-cell communication [1]. To maintain their small form factors, these cell elements will rely solely on energy harvesting, with capacitor-based storage instead of batteries. Due to energy harvesting and potentially huge number of envisioned cell elements comprising a network, in the majority of applications the energy consumption of each cell element will have to be minimized [25]. Energy harvesting for powering the cell elements (i.e., the receivers) is expected to be done by the metamaterials themselves. In this work, we consider two energy harvesting options based on two prominent metamaterial applications. The first option is to harvest energy from air vibration, which is expected in acoustic metamaterials for e.g., noise-cancellation applications. [27] The second option is ultrasound power transfer, which has been shown feasible in powering nanometer-size nodes [28] and has been considered for powering metamaterials [29], [30].

In the considered controller-to-cell communication no mobility is expected, i.e., the metamaterials and controllers are expected to be static. Moreover, the latency requirements are expected to be relaxed in this stage, i.e., in the order of seconds [1], [31]. Under such conditions, our aim is to maximize the packet reception rate in the controller-to-cell nanocommunication, while simultaneously minimizing the energy consumption of the elements of the unit cell.

IV. Modeling and Reducing Idling Energy in Energy Harvesting THz Nanonetworks

In this section, we first describe the usual duty cycle of an energy harvesting nanonode's communication system. We then propose an energy consumption model of the nanonode's communication system that incorporates the energy consumed due to idling. Note that the proposed energy model is applicable beyond the considered SDM-related scenario and for both transmitting and receiving nanonodes. To reduce the energy consumption of the receiving nanonode due to idling, we propose a new duty cycle of the nanonode's communication system based on frequent packet repetitions on the transmit and short wake-ups on receive side. Finally, we propose two algorithms for deciding when these wake-ups should occur.

A. Duty Cycle of an Energy Harvesting Nanonode

The usual duty cycle of the nanonode's communication system is given in Figure 3. As depicted in the figure, at certain points in time the energy of the nanonode will be below the level required to power its hardware. This energy level is called the "turn-off threshold" and labeled with E_{OFF}. At other times, the nanonode will harvest sufficient amounts of energy to turn on. The energy level for turning the nanonode on is defined as the "turn-on threshold" and labeled with E_{ON}. Intuitively, the nanonode will continue to harvest energy, even if turned on, until its energy level reaches the maximum energy storage capacity (E_{max}), as indicated with (8) in the figure. Upon reaching this maximum level, the energy of the nanonode will stay fixed. During the reception periods, the nanonode will lose certain amounts of energy for receiving a packet, while at the same time gaining some (in practice much lower) amounts due to harvesting. Observe that the energy of the nanonode can be at a level at which it is still turned on, but does not have sufficient energy for receiving an entire packet. In this case, the nanonode would nonetheless attempt to receive the packet. In the attempt, its energy level would drop below the turn-off threshold and the nanonode would turn off without successfully receiving the packet, as indicated by (3) in Figure 3. Note that this duty cycle does not account for the energy consumed due to idling.

B. Modeling of Idling Energy

The above-described duty cycle for an energy harvesting nanonode's communication system accounts for the fact that a certain amount of energy will be consumed in reception of a packet, with the packet consisting of n bits. In the TS-OOK scheme, a logical "1" is transmitted by using a pulse with the duration of T_{pulse}, while a logical "0" is represented by the silence. In the modeling of its energy consumption, a certain energy E_{R_X} is contributed to receiving each pulse, as shown in Figure 4. The duration between two consecutive pulses is characterized by the parameter β, as shown in the

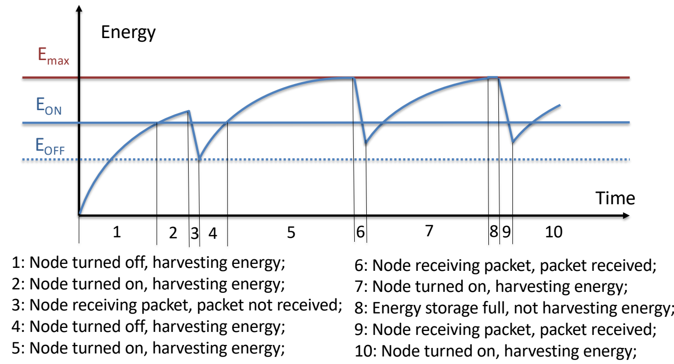


Figure 3: Duty cycle of a nanonode's communication system

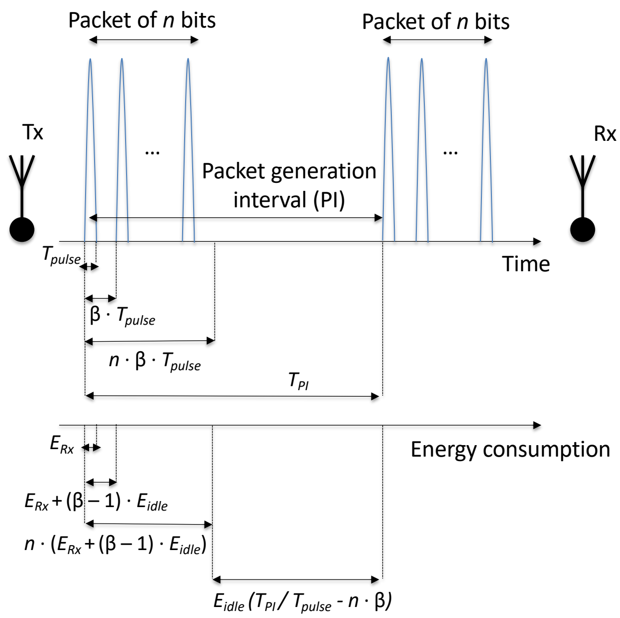


Figure 4: Model of nanonode's communication system accounting for energy consumption due to idling

figure. In between two pulses, the receiving nanonode will be idling, which will in practice consume certain amounts of energy. We specify the idling energy in the duration of a pulse T_{pulse} as E_{idle}. In this case, the energy consumed between the reception of two consecutive pulses equals $(\beta - 1)E_{idle}$, as shown in the figure. For the reception of the whole packet, the energy consumed for both reception and idling then equals $n(E_{R_x}+(\beta-1)E_{idle})$, as indicated in the figure. For simplicity reasons, in Figure 4 we have modeled the energy consumed due to the *reception* of a TS-OOK pulse. It is straightforward to model the energy of the nanonode's communication system due to the *transmission* of a pulse. This can be done by replacing the energy E_{R_x} consumed for receiving a pulse with the energy E_{T_x} consumed in the transmission of a pulse. Moreover, for simplicity reasons we have depicted a scenario in which all bits are logical "1"s. Deriving the energy consumed due to reception of a packet for the generalized case is straightforward and equals:

$$E_{Rx\&idle} = n_1(E_{R_x} + (\beta - 1)E_{idle}) + n_0 \beta E_{idle}, \qquad (1)$$

where n_1 and n_0 are the numbers of logical "1" and "0" bits in the packet, respectively.

Furthermore, the receiving nanonode will consume some energy in idling between the receptions of two consecutive packets (i.e., between the end of reception of the first and start of reception of the second packet). Assuming that the time between two consecutive receptions equals T_{PI}, the energy $E_{PI_{idle}}$ consumed due to idling between the receptions equals:

$$E_{PI_{idle}} = E_{idle}(T_{PI}/T_{pulse} - n\beta). \quad (2)$$

Let us further clarify the proposed energy model with an example. Let us assume that the energy consumed for the reception of a 100 fs long TS-OOK pulse equals 0.1 pJ, which is a standard assumption made in the literature [11], [32]. In addition, we assume β equals 100, which is again based on multiple reports from the literature [11], [12]. The packet size is 128 bits, where the numbers of "1" and "0" bits in each packet are in the ratio 1:1. Furthermore, let us assume periodic packet transmissions every 1 sec. Both assumptions are taken from the literature discussing requirements for software-defined metamaterial applications [1]. Under these assumptions and not accounting for the energy consumed in idling, the nanonode will consume $128/2$ bits·0.1 pJ = 6.4pJ for receiving a packet. Note that the nanonode will in this case not consume energy due to idling between the receptions of two consecutive packets.

Let us now assume that some energy is also consumed in idling. Specifically, let us make an optimistic assumption that the E_{idle} will be *six orders of magnitude* lower than the E_{R_x}. To put this into context, in wireless sensor networks idling energy consumption is usually and roughly speaking two times lower than the corresponding receive energy [13], while the energy consumption of a wake-up radio in idling is roughly three to maximum four orders of magnitude lower than the energy consumption of a main radio in reception [14]. Given that E_{idle} equals 10^{-7} pJ, the energy consumed due to the reception of a packet, but accounting for the energy consumed due to idling, is then 6.4012 pJ, which is not far off from 6.4 pJ derived without accounting for the idling energy consumption. However, the energy consumption of the node in idling between consecutive receptions is not negligible anymore, but equals 1 μJ!

C. Duty Cycle for Reduced Idling Energy Consumption

As motivated by the example, there is a need for reducing the idling energy consumption in energy harvesting nanonodes, predominantly in the periods between receptions (or transmissions) of consecutive packets. Under the previously described and SDM-relevant assumption that the controller is not energy-constrained, each transmitted packet can be repeated multiple times with the delay between consecutive repetitions being T_{RP}. Hence, generally speaking each packet is continuously repeated until a new packet arrives to be transmitted. Under these conditions, the receiving nanonode does not have to be continuously turned on and idling if its energy level is above E_{ON}. Adversely, we propose that the receiving nanonode turns on only at certain points and stays on for a short period of time, i.e., until it successfully receives one packet. The proposed duty cycle for the energy harvesting receiving nanonode's communication system is given in Figure 5.

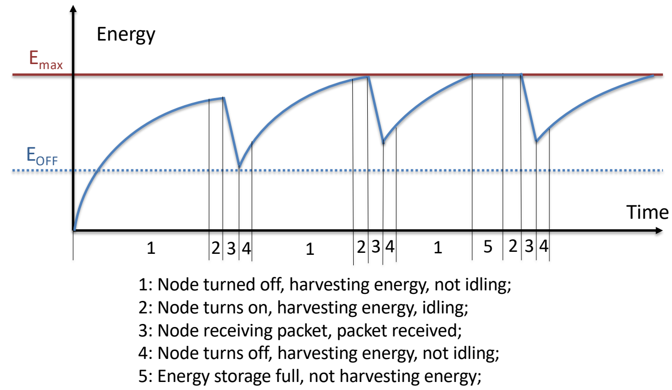


Figure 5: Proposed wake-up-based and energy-aware duty cycle for reducing idling energy consumption

The proposed duty cycle is beneficial due to the fact that the energy harvesting nanonodes are not idling between the transmissions of two consequent packets, which reduces their overall energy consumption. In other words, the idling energy is in the proposed duty cycle a less dominant factor in the overall energy consumption of the nanonode's communication system, compared to the usual one. The dominant factor is the packet transmission period T_{PI}, i.e., the energy consumption of the nanonodes increases with the decrease in the packet transmission period. In addition, the proposed duty cycle does not require synchronization between the transmitting node and the receiving nanonodes, which is particularly important for TS-OOK-based nanocommunication and SDM applications where synchronization between communicating nodes is usually infeasible [8], [9]. A clear drawback is that the proposed duty cycle increases the latency of packet delivery. However, this is not an issue for the applications envisioned to be supported by the first generation of SDMs, where the latency requirements are expected to be relaxed [25], [31]. Intuitively, this drawback can be to an extent mitigated by introducing multiple wake-up during the transmission period T_{PI}, however with the potential trade-off in terms of reduced packet reception rate.

D. Energy Threshold-based Wake-up

In this section, we propose two algorithms for waking up an energy harvesting nanonode. In both algorithms, we envision the nanonodes to wake up based primarily on their energy levels, i.e., the nanonode should wake up at a point when it has enough energy to successfully receive one packet. The intuition for such procedure comes from the fact that capacitor charging can be accurately modeled as an exponential process, as shown in Figure 6. This means that the nanonode's capacitor charges relatively fast when its energy is at low levels, while the charging rate slows down as the stored energy gets closer to the maximum storage capacity of the nanonode [11].

By waking up the nanonode as soon as it has enough energy to receive one packet, the time that the nanonode is awake is maximized, while the packet reception rate is simultaneously guaranteed. In order to calculate the energy level at which

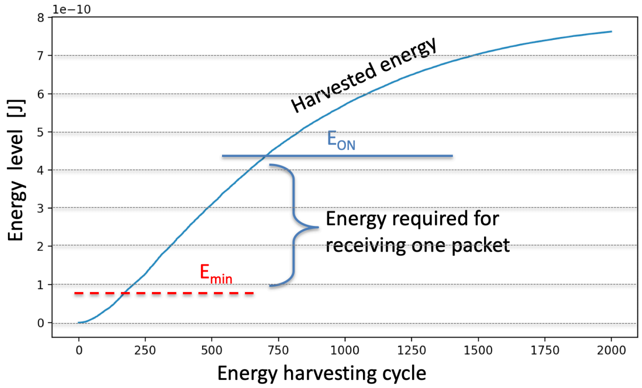


Figure 6: Intuition behind the selected energy threshold for waking up an energy harvesting nanonode

the nanonode should wake up in the proposed duty cycle, we utilize the previously discussed energy consumption model. Specifically, the energy threshold E_{ON} for waking up the nanonode is given as:

$$E_{ON} = E_{OFF} + (2n-1)(E_{R_x} + (\beta-1)E_{idle}) + T_{RP}/T_{pulse}E_{idle}. \quad (3)$$

n is the overall number of bits in a packet, which covers the worst case scenario in which all the bits are logical "1"s (i.e., reception of each bit consumes certain energy). The expression $(2n-1)$ is used to cover the worst case scenario in which the nanonode wakes up and initially receives $n-1$ bits from the previous repetition but is unable to decode the packet, hence it awaits for the next one (characterized by the expression $T_{RP}/T_{pulse}E_{idle}$) and receives all n bits before going to sleep. Note that we assume that each packet contains an end-of-packet signature (i.e., a postamble), so it is possible for the nanonodes to understand if they have received the full packet, otherwise the silences that occur when there is no transmission could be interpreted as logical "0"s.

The first algorithm (i.e., "Energy-Threshold-based Wake-Up (ETWU)") is fully based on the previous equation, i.e., if the energy level of the nanonode is above the E_{ON}, the nanonode will wake up and receive one full packet before going to sleep. In the second algorithm (i.e., "Packet-Interval-based Wake-Up (PIWU)"), the nanonode will consider the packet generation interval T_{PI} for deterministic traffic or its expected value $\mathbb{E}(T_{PI})$ for stochastic traffic patterns. If this time has passed since its last wake-up, the nanonode will check if its energy level is above E_{ON} and, if yes, it will wake up. If its energy level is below E_{ON}, it will continue harvesting and wake up once the energy level reaches the threshold E_{ON}, without further considerations for the packet generation interval.

V. Evaluation Setup and Methodology

In the evaluation, we aim at establishing the packet reception rate of a nanonetwork for supporting the first generation of SDM applications. Along the discussion from Section III, we specify a scenario with a mains- or battery-powered controller utilizing one-hop, downlink-only, and broadcast transmissions to a set of energy harvesting receivers, as depicted in Figure 7. Moreover, we account for and try to reduce the idling energy

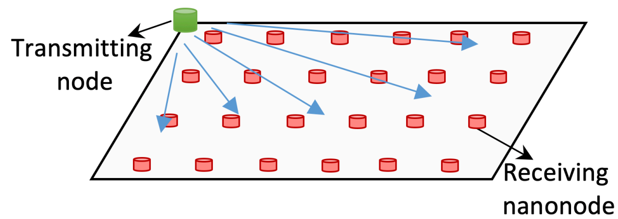


Figure 7: Envisioned until cell, i.e., a grid-like constellation of receiving nanonodes with a single transmitting node

TABLE I: Simulation parameters

Parameter	Value
Number of nanonodes	(25x25) 625
Distance between nodes [mm]	1
V_g [V]	0.42
T_X [dBm]	-20
Pulse duration [fs]	100
β	100
$E_{R_{X pulse}}$ [pJ]	0.1
Packet size [bits]	128
E_{max} [pJ]	[800, 17240]
E_{OFF} [pJ]	40
Packet generation interval [ms]	1000
Duration of simulation [ms]	10000 x packet generation interval
Repetition delay [ms]	10
Harvesting cycle duration [ms]	[20, 1.71]
Harvested chargeΔQ [pC]	6

consumption of the receiving nanonodes. We simulate the performance of the nanonetwork using the ns3-based TeraSim simulator [32], with the simulation parameters as summarized in Table I. We assume that the transmitter is not energy-constrained and always has sufficient amount of energy to transmit, if there is a packet to be transmitted. We consider a grid-like constellation with 625 nanonodes 1 mm apart from one another and with the transmitter positioned in one corner of the grid, as shown in the figure. Such a setup has been suggested for controlling static metamaterials [1], where there is no need for discovery, as the only reason why a nanonode would not be available is because it is turned off. Note that the constellation of the receiving nanonodes and the position of the transmitter are practically irrelevant, given that all the nanonodes are in its coverage. In addition, the number of receiving nanonodes is consistent with the previous discussion (Section III) and aligned with the works from the literature (e.g., [5], [25]). Finally, since the communication in the considered scenario is only envisioned to be used for issuing control commands to the energy harvesting nanonodes, we use short packets consisting of 128 (data and control) bits, with the ratio between logical "0"s and "1"s being 1:1.

A packet will not be received if it arrives at a nanonode that is at a given point in time turned off. If the nanonode is turned on, it will start receiving the packet (i.e., there is no interference and all nanonodes are in the range of the transmitting node). If the nanonode runs out of energy during the reception, it will turn off and the reception will fail. We use the above-discussed TS-OOK scheme and assume that the energy consumed for receiving a pulse equals 0.1 pJ [11], [32], [33]. The duration of the pulse equals 100 fs, with two consecutive pulses being generated at minimum β·100 fs apart (i.e., two consequent logical "1"s). These values have been suggested by various works in the literature [8], [11], [32].

The current state-of-the-art energy harvesters exploit piezoelectric effect of ZnO nanowires [34], with the energy being harvested in nanowires' compress-and-release cycles. The harvested energy can be specified with the duration of the harvesting cycle t_{cycle} and the harvested charge per cycle ΔQ. Based on the insights from [11], we model capacitor charging as an exponential process. As discussed previously, at certain points in time the nanonode could lose some energy due to the reception of a packet and this can occur between periodical energy harvesting cycles, thus the current energy $E_{n_{cycle}}$ could change between two harvesting cycles. Due to that and the fact that energy harvesting is a nonlinear process, for the modeling of energy harvesting it is required to know in which harvesting cycle n_{cycle} the nanonode is, given its current energy level $E_{n_{cycle}}$. This can be derived from [11] as follows:

$$n_{cycle} = \left\lceil \frac{-V_g C_{cap}}{\Delta Q} ln \left(1 - \sqrt{\frac{2E_{n_{cycle}}}{C_{cap} V_g^2}} \right) \right\rceil. \tag{4}$$

Upon calculating the cycle n_{cycle} in which the nanonode with $E_{n_{cycle}}$ energy is, the energy of the nanonode in the next harvesting cycle $n_{cycle}+1$ is modeled by:

$$E_{n_{cycle+1}} = \frac{C_{cap} V_g^2}{2} 2^{1-e^{-\frac{\Delta Q (n_{cycle}+1)}{V_g C_{cap}}}}, \tag{5}$$

with C_{cap} being the total capacitance of the nanonode. C_{cap} is related to the maximum energy storage capacity E_{max} and the generator voltage V_g as follows: $C_{cap} = 2E_{max}/V_g^2$.

As mentioned before, we consider two sources for harvesting energy, i.e., air vibrations utilized and ultrasound-based power transfer. The literature reports 20 ms [11] and 1.71 ms [29] long harvesting cycles for these sources, respectively. Moreover, [11], [29] report the harvesting charges ΔQ of 6 pC for ZnO nanowires' compress-and-release cycles. As often done in the literature [32], we model these charges using Gaussian distributions with 6 pC as the mean value and 0.6 pC as the standard deviation. We consider two energy storage options in correspondence to the two energy harvesting sources, a capacitor of 800 pJ [11] and a supercapacitor of 17.24 nJ [29] as their maximum energy storage capacities. We assume all harvested energy is utilized for communication, i.e., energy consumed for controlling the metamaterial elements is assumed to be negligible. we do that primarily because, to the best of our knowledge, the amount of energy needed for this control is currently unknown, hence assuming any value would at this point be a mere speculation. Note that accounting for certain energy consumed in controlling the metamaterial elements would only quantitatively change the results, i.e., the packet reception rate would be somewhat lower. This is because the nanonode's communication system is considered as the bottleneck in nanodevice's energy consumption [12].

We consider two traffic patterns, both characterized by the packet generation interval T_{PI}. For deterministic traffic, consecutive packets are generated exactly packet generation interval T_{PI} from one another. Such a setup is expected to be used in applications where the control of metamaterial elements is performed continuously with a certain period. For stochastic traffic, the packet generation times are drawn from a Poisson distribution with expected separation between two consecutive packets being T_{PI}. Such modeling is usual for traditional wireless communication (e.g., [35]) and for a discrete non-periodical control of metamaterial elements, hence we see it beneficial to consider it in our evaluation. If not stated otherwise, the packet generation interval T_{PI} is set to 1 s. This corresponds to the requirements of applications targeting control of the first generation of SDMs [1], [36].

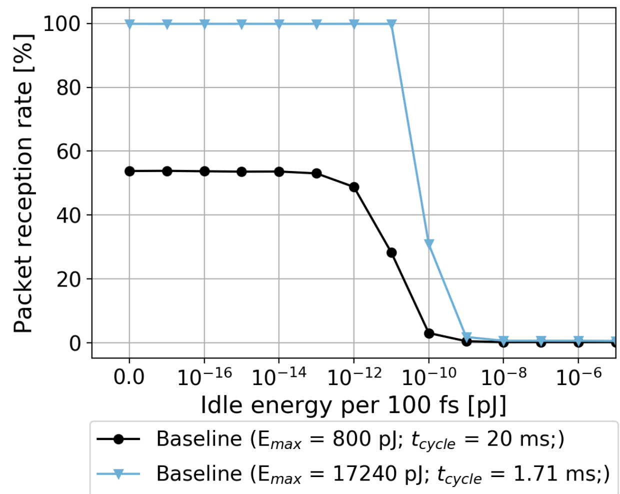


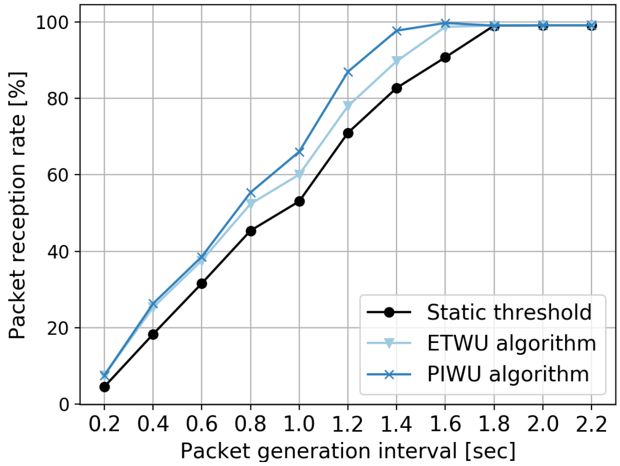
Figure 8: Packet reception rate vs. idling energy

We use packet reception rate as the performance metric, defined as the ratio between the number of packets received by each nanonode and the overall number of transmitted packets, averaged over all nanonodes. To evaluate the performance of the proposed duty cycle for reducing idling energy consumption, we introduce repetitions. Specifically, the delay T_{RP} between consecutive repetitions of a packet equals 10 ms. We specify these values due to the limitations of the TeraSim simulator, although it is intuitive that the more frequently a single packet is repeated (i.e., the shorter the delay T_{RP} is), the shorter is the period that the nanonodes have to stay turned on to receive the packet or one of its repetitions. Hence, an increase in the frequency of repetitions is beneficial in reducing the idling energy consumption of the nanonodes.

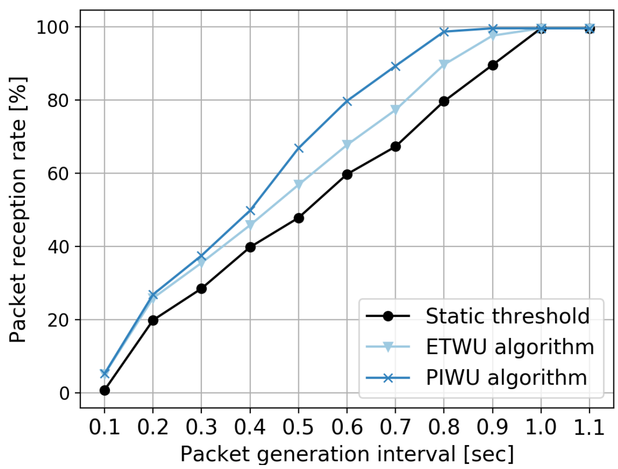
VI. Evaluation Results

A. *Effect of Idling Energy Consumption*

The aim of this section is to demonstrate that the idling energy consumption has a substantial effect on the packet reception rate in the considered nanonetwork, hence it cannot be disregarded. Figure 8 depicts the packet reception rate in case the idling energy is not considered (label "0.0" on the X-axis) in the energy consumption modeling of the receiving nanonodes' communication system. The results are depicted for deterministic traffic pattern and packet generation interval of 1 s. Note that same qualitative behavior has been observed for stochastic traffic and different packet generation intervals. As visible in the figure, the packet reception rate is in this case around 55% for the air vibration-based energy harvesting and 800 pJ capacitor-based energy storage. The reason for non-ideal packet reception rate comes from the low efficiency (i.e.,

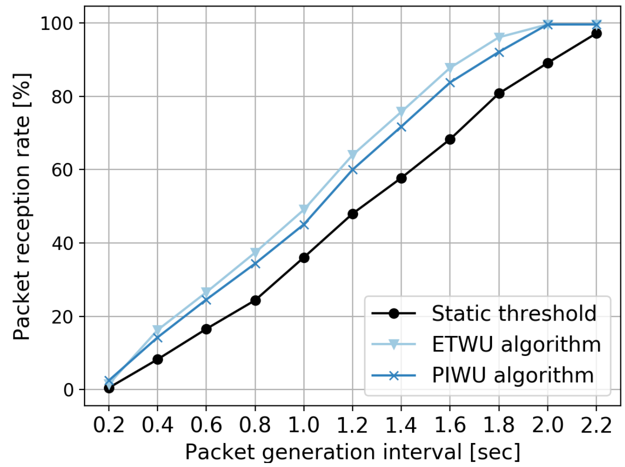


(a) E_{max} = 800 pJ, T_H = 20 ms, $E_{idle} = 10^{-10}$ pJ/100 fs

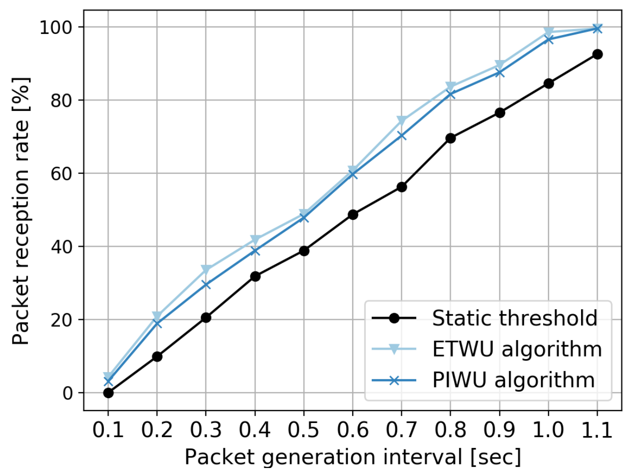


(b) E_{max} = 17.24 nJ, T_H = 1.71 ms, E_{idle} = 10^{-8} pJ/100 fs

Figure 9: Packet reception rate vs. packet generation interval for deterministic traffic patterns



(a) E_{max} = 800 pJ, T_H = 20 ms, $E_{idle} = 10^{-10}$ pJ/100 fs



(b) E_{max} = 17.24 nJ, T_H = 1.71 ms, E_{idle} = 10^{-8} pJ/100 fs

Figure 10: Packet reception rate vs. packet generation interval for stochastic traffic patterns

relatively long harvesting cycle) of air vibration-based energy harvesting. Similarly, if the idling energy is not considered, the packet reception rate is almost ideal for the ultrasound power transfer and 17.24 nJ supercapacitor-based energy storage.

If the idling energy consumption is accounted for and modeled as described in Section IV, the packet reception rate depends on the value of the idling energy E_{idle} per pulse duration. A range of these values is depicted on the X-axis in the figure. In the baseline scenario (i.e., if the usual duty cycle is utilized) the packet reception rate is practically not affected by idling energy consumption for the values lower than 10^{-13} and 10^{-11} pJ per pulse duration for the air-vibration (capacitor) and ultrasound (supercapacitor)-based harvesting (storage), respectively. For these values, the difference between packet reception rates for different energy/storage pairs comes from the fact that the ultrasound power transfer is a substantially more efficient harvesting option than the air-vibrations. Hence, the increase in energy level is faster and can withstand higher idling energy values. Nonetheless, these baseline results demonstrate that, to achieve at least a certain level of feasibility of the considered nanonetwork (i.e., packet reception rate higher than 0%), the idling energy consumption per pulse should be lower than 10^{-10} and 10^{-9} pJ (i.e., 0.1 and 1 zJ!). This is certainly going to be a challenge in the development of THz nanoreceivers, considering that the idling energy consumption is in the current communication systems at most a few orders of magnitude lower than the corresponding energy consumed in reception. We believe that this conclusion motivates the need for reducing the idling energy consumption of the receiving nanonodes.

B. *Reducing Idling Energy Consumption*

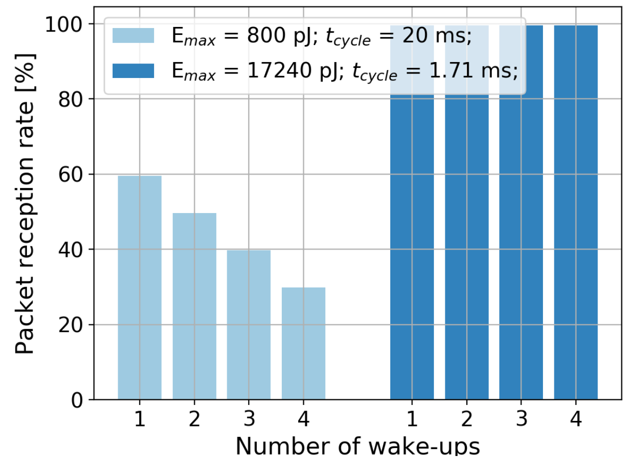
The aim of this section is to demonstrate the benefits of the proposed duty cycle for the energy harvesting nanonodes in terms of reduced idling energy consumption. Moreover, the aim is to show that the algorithms for waking up the receiving nanonodes improve the packet reception rate compared to the baseline. In the baseline, the energy level for waking up a nanonode has been set to the energy required for receiving three packets. We have observed the same qualitative results for other static threshold values compared to the ones observed in case the proposed algorithms are utilized. These are omitted for simplicity reasons.

As mentioned, if the proposed duty cycle is utilized, the packet reception rate will be affected by the packet generation interval. This is demonstrated in Figures 9 and 10 for deterministic and stochastic traffic patterns, respectively. The depiction is for each pattern given for the two considered harvesting/storage options and for the idling energy consumption per pulse of 10^{-10} and 10^{-8}, respectively. As visible, the packet reception rate increases with the increase in the packet generation interval. For example, as the packet generation interval increases from 0.2 to 1.0 s, the packet reception rate increases from less than 20% to respectively more than 60% and roughly 100% for the two harvesting/storage options. This is because the nanonodes are less frequently consuming energy for the reception if the packets are less often transmitted. This observation motivates the need for designing nanonode control mechanisms in a way that minimizes the number and frequency of transmitted control packets.

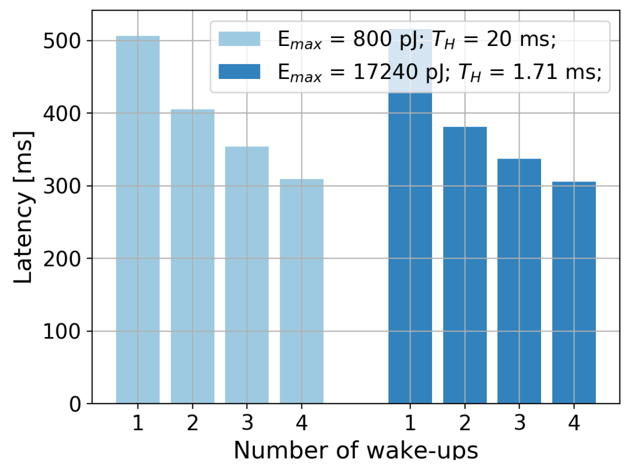
In addition, it is visible from the figures that the two proposed algorithms improve the packet reception rate compared to the baseline grounded in the utilization of a static threshold. For example, for deterministic traffic pattern, packet generation interval of 0.6 s, power transfer-based energy harvesting, and supercapacitor-based energy storage (Figure 9b), PIWU improves the packet reception rate over the baseline by roughly 20%. These results demonstrate that the selected energy threshold for turning on an energy harvesting nanonode plays an important role in terms of the packet reception rate.

For a deterministic traffic pattern, the best performing algorithm is the one that utilizes the knowledge of packet generation interval, in addition to the energy consumed for receiving a packet (i.e., PIWU). This is because the packet generation interval is deterministic, so the algorithm wakes up the nanonodes at correct times if there is enough energy to receive a packet. In contrast, by utilizing the algorithm based on a static threshold (i.e., ETWU), it can happen that the nanonode wakes up multiple times in between the transmissions of two consecutive packets. Thus, the first packet (i.e., some of its repetitions) is received twice, while the second one is not received at all, which negatively affects the packet reception rate. This negative effect is more pronounced for higher packet generation intervals, because of the longer harvesting times in between two consecutive packets, making it more probable for a nanonode to wake up twice.

In the scenario with a stochastic traffic pattern, both algorithms for the intelligent selection of the wake-up threshold outperform the selection based on a static energy threshold, as shown in Figure 10. However, performance of the two algorithms is adverse as in this case ETWU slightly outperforms PIWU, as visible in the figure. In this scenario, PIWU wakes up the nanonodes based on the *expected* packet generation interval, hence it can happen that a packet is missed by a nanonode because a particular duration between two consecutive packets was shorter than the expected packet generation interval. It can also happen that a nanonode receives a packet twice if a particular duration between two consecutive packets was longer than the expected packet generation interval. For these reasons, the benefits that PIWU introduces for deterministic traffic diminish in case of stochastic traffic.



(a) Packet reception rate



(b) Delivery latency

Figure 11: Packet reception rate vs. delivery latency trade-off with multiple wake-ups

In ETWU, a nanonode wakes up immediately if it has enough energy to receive a packet. Thus, packets are less often missed if a particular duration between two consecutive packets was shorter than the expected packet generation interval. We believe this to be the reason for superior performance of ETWU compared to PIWU in this scenario. In more general terms, for stochastic traffic pattern it seems that the optimal strategy for waking up the nanonodes is to wake them up as soon as they have enough energy to successfully receive one packet.

As discussed before, the intuitive drawback of the proposed duty cycle comes from the fact that it intrinsically increases the latency of delivering packets to the receiving nanonodes. In order words, while in the usual duty cycle the packets would either be delivered almost instantaneously or would not be delivered at all (i.e., if a nanonode is turned off), in the proposed one the increase in the latency is caused by the scheduled wake-ups of the nanonodes. To mitigate this issue to a certain extent, one can utilize multiple wake-ups in the duration of one packet generation interval. The achieved packet reception rate and latency in case multiple wake-ups are utilized are depicted in Figure 11. The depiction is given for the two considered harvesting/storage options, E_{idle} of 10^{-10} pJ, a deterministic traffic pattern with packet generation

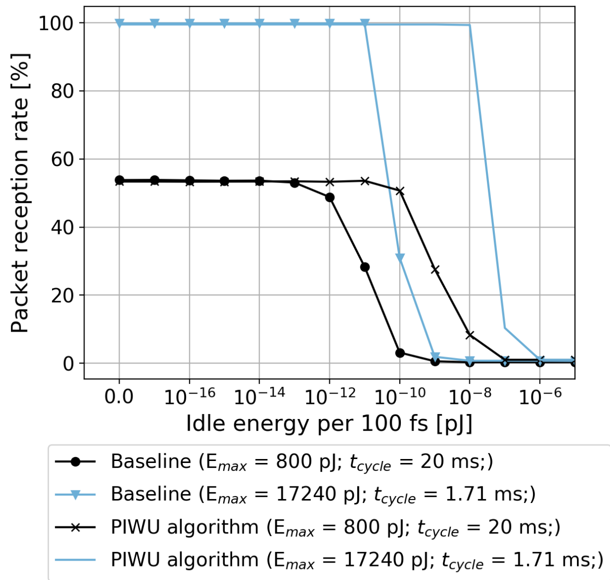


Figure 12: Improvement over the baseline

interval T_{PI} of 1 s, and for PIWU being utilized. As visible in the figure, for the air-vibrations (capacitor), an increase in the number of wake-ups decreases both the packet reception rate and latency. The selection of the number of wake-ups should, therefore, in this case be based on the application requirements and constraints. However, if the idling energy is not the limiting factor and/or energy harvesting rate is sufficiently high, as it is the case for the ultrasound-based power transfer, it is possible to reduce the latency of packet delivery, while at the same time preserving the packet reception rate, as shown in the figure. This observation motivates the need for an intelligent selection of the number of wake-ups of the receiving nanonodes that should account for the harvesting rate, energy consumed due to idling, and traffic generation interval.

Figure 12 depicts the packet reception rate in case the proposed duty cycle is utilized instead of the usually considered one. Same as before, the results are depicted for deterministic traffic pattern, packet generation interval of 1 s, and PIWU being utilized with one wake-up per packet generation interval. The same qualitative behavior is observed for a stochastic traffic pattern, other packet generation intervals, and ETWU algorithm being utilized. As visible, when the proposed duty cycle is utilized, the packet reception rate is not affected by the idling energy consumption for the idling energy values lower than 10^{-10} and 10^{-8} pJ per pulse duration for the air-vibration (capacitor) and ultrasound (supercapacitor)-based harvesting (storage) approaches, respectively. Hence, compared to the usual duty cycle, by utilizing the proposed duty cycle up to three orders of magnitude higher idling energy consumption per pulse can be tolerated without affecting the packet reception rate. Moreover, meaningful packet reception rate levels can be achieved for the idling energy per pulse lower than 10^{-8} and 10^{-6} pJ (0.01 and 1 aJ) for the two considered harvesting/storage options, respectively. In summary, the utilization of the proposed duty cycle increases the feasibility of the nanonetwork by tolerating up to three orders of magnitude higher idling energy values compared to the baseline.

VII. Conclusion

We proposed a model for energy harvesting nanonode's TS-OOK-based communication system that accounts for the energy consumed in idling, in addition to the energy consumed for packet transmission or reception. We have shown that the idling energy consumed in duration of a TS-OOK pulse should be at least nine orders of magnitude lower than the corresponding energy consumed in reception, otherwise the considered nanonetwork becomes infeasible. To increase the tolerable idling energy consumption, we proposed a new duty cycle of an energy harvesting nanonode, which is based on nanonode's periodic short wake-ups. For two SDM-relevant energy harvesting sources (i.e., air vibrations and ultrasound power transfer), we have shown that, by utilizing the proposed duty cycle instead of the usually employed one, the tolerable idling energy consumption can be increased by up to three orders of magnitude. By utilizing the proposed duty cycle and the wake-up algorithms, the controllability of SDMs can be enhanced along two important aspects. First, the states of SDM elements can be controlled with higher levels of reliability, as the nanonodes will wake up only when they have enough energy to receive a packet. Second, the control of a larger number of SDM elements can be archived compared to the baseline, as the utilization of packet repetitions allows the nanonodes to harvest energy for a longer period of time before waking up and receiving a packet.

In this work, we did not consider the interplay between the channel coding schemes and the energy threshold for waking up the receiving nanonodes. Specifically, if a certain error correction scheme is employed, the energy for waking up the nanonodes could be lower, as it would be possible to account for less than currently accounted $2n - 1$ bits, with n being the number of bits in one packet. In addition, we did not consider the role of control bits in a packet, but treated all bits as equal. We have also not considered scenarios with energy harvesting nanodevices being transmitters, as well as multi-hop communication scenarios, both being relevant for a number of SDM applications. We see the above-described points as the potential directions for our future research. Finally, we also intend to investigate approaches for intelligently and dynamically selecting the number of wake-ups of the energy harvesting nanonodes, accounting for their harvesting rates, energy consumptions, and traffic patterns. This will be done in a way that optimizes the delivery latency, while maintaining the communication reliability.

Acknowledgments

Filip Lemic's research stay at the Terahertz Wireless Communications (TWC Lab of the University of Michigan - Shanghai Jiao Tong University Joint Institute (UM-SJTU JI), Shanghai Jiao Tong University, China was supported by the Research Foundation - Flanders (FWO). The support was provided in the form of a grant for a long stay abroad (Grant Number V406320N). Dr. Chong Han acknowledges the in-part support by Ministry of Education of China Joint Research Fund under Grant Number 6141A02033350, and National Natural Science Foundation of China (NSFC) under Grant Number 61701300.

REFERENCES

[1] S. Abadal *et al.*, "Computing and communications for the software-defined metamaterial paradigm: A context analysis," *IEEE access*, vol. 5, pp. 6225–6235, 2017.

[2] X. Fu and T. J. Cui, "Recent progress on metamaterials: From effective medium model to real-time information processing system," *Progress in Quantum Electronics*, 2019.

[3] I. F. Akyildiz *et al.*, "The internet of bio-nano things," *IEEE Communications Magazine*, vol. 53, no. 3, pp. 32–40, 2015.

[4] X. Fu, F. Yang, C. Liu, X. Wu, and T. J. Cui, "Terahertz beam steering technologies: From phased arrays to field-programmable metasurfaces," *Advanced Optical Materials*, p. 1 900 628, 2019.

[5] I. F. Akyildiz and J. M. Jornet, "The internet of nano-things," *IEEE Wireless Communications*, vol. 17, no. 6, pp. 58–63, 2010.

[6] I. F. Akyildiz, Jornet, *et al.*, "Terahertz band: Next frontier for wireless communications," *Physical Communication*, vol. 12, pp. 16–32, 2014.

[7] S. Abadal, S. E. Hosseininejad, *et al.*, "Graphene-based terahertz antennas for area-constrained applications," in *Telecommunications and Signal Processing (TSP)*, IEEE, 2017, pp. 817–820.

[8] J. M. Jornet and I. F. Akyildiz, "Information capacity of pulse-based wireless nanosensor networks," in *Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, IEEE, 2011, pp. 80–88.

[9] J. M. Jornet *et al.*, "Femtosecond-long pulse-based modulation for terahertz band communication in nanonetworks," *IEEE Transactions on Communications*, vol. 62, no. 5, pp. 1742–1754, 2014.

[10] F. Lemic *et al.*, "Assessing the reliability of energy harvesting terahertz nanonetworks for controlling software-defined metamaterials," in *Nanoscale Computing and Communication*, ACM, 2019, p. 13.

[11] J. M. Jornet *et al.*, "Joint energy harvesting and communication analysis for perpetual wireless nanosensor networks in the terahertz band," *IEEE Trans. on Nanotechnology*, vol. 11, no. 3, p. 570, 2012.

[12] S. Canovas-Carrasco *et al.*, "Conceptual design of a nano-networking device," *Sensors*, vol. 16, no. 12, p. 2104, 2016.

[13] W. Ye *et al.*, "An energy-efficient mac protocol for wireless sensor networks," in *IEEE Computer and Communications*, IEEE, 2002.

[14] H. Karvonen *et al.*, "A generic wake-up radio based mac protocol for energy efficient short range communication," in *Personal, Indoor, and Mobile Radio Communication*, IEEE, 2014, pp. 2173–2177.

[15] F. Lemic, J. Marquez-Barja, and J. Famaey, "Modeling and reducing idling energy consumption in energy harvesting terahertz nanonetworks," in *IEEE Global Communications (GlobeCom), IEEE*, 2019.

[16] H. Yetgin *et al.*, "A survey of network lifetime maximization techniques in wireless sensor networks," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 828–854, 2017.

[17] I. Snigdh and N. Gupta, "Quality of service metrics in wireless sensor networks: A survey," *Journal of The Institution of Engineers (India): Series B*, vol. 97, no. 1, pp. 91–96, 2016.

[18] A. Bogliolo *et al.*, "Towards a true energetically sustainable wsn: A case study with prediction-based data collection and a wake-up receiver," in *International Symposium on Industrial Embedded Systems (SIES)*, IEEE, 2014, pp. 21–28.

[19] D.-C. Huang and J.-H. Lee, "A dynamic n threshold prolong lifetime method for wireless sensor nodes," *Mathematical and Computer Modelling*, vol. 57, no. 11-12, pp. 2731–2741, 2013.

[20] R. Zheng, J. C. Hou, and L. Sha, "Asynchronous wakeup for ad hoc networks: Theory and protocol design," UIUCDCS, Tech. Rep., 2002.

[21] T. Prabhakar, N. Soumya, P. Muralidharan, and H. Jamadagni, "A novel wake-up radio wsn mote," in *2013 Texas Instruments India Educators' Conference*, IEEE, 2013, pp. 362–368.

[22] M. Magno *et al.*, "Wake-up radio receiver based power minimization techniques for wireless sensor networks: A review," *Microelectronics Journal*, vol. 45, no. 12, pp. 1627–1633, 2014.

[23] M. Magno and L. Benini, "An ultra low power high sensitivity wake-up radio receiver with addressing capability," in *2014 IEEE 10th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, IEEE, 2014, pp. 92–99.

[24] E. Lattanzi *et al.*, "Energetic sustainability of routing algorithms for energy-harvesting wireless sensor networks," *Computer Communications*, vol. 30, no. 14-15, pp. 2976–2986, 2007.

[25] F. Lemic *et al.*, "Survey on terahertz nanocommunication and networking: A top-down perspective," *arXiv preprint 1909.05703*, 2019.

[26] C. Liaskos *et al.*, "Design and development of software defined metamaterials for nanonetworks," *IEEE Circuits and Systems Magazine*, vol. 15, no. 4, pp. 12–25, 2015.

[27] S. A. Cummer *et al.*, "Controlling sound with acoustic metamaterials," *Nature Reviews Materials*, vol. 1, no. 3, p. 16 001, 2016.

[28] M. Donohoe, S. Balasubramaniam, B. Jennings, and J. M. Jornet, "Powering in-body nanosensors with ultrasounds," *IEEE Transactions on Nanotechnology*, vol. 15, no. 2, pp. 151–154, 2015.

[29] S. Canovas-Carrasco *et al.*, "On the nature of energy-feasible wireless nanosensor networks," *Sensors*, vol. 18, no. 5, p. 1356, 2018.

[30] S. Zhang, "Acoustic metamaterial design and applications," PhD thesis, University of Illinois at Urbana-Champaign, 2010.

[31] T. Saeed, S. Abadal, C. Liaskos, A. Pitsillides, H. Taghvaee, A. Cabellos-Aparicio, M. Lestas, and E. Alarcón, "Workload characterization of programmable metasurfaces," in *Proceedings of the Sixth Annual ACM International Conference on Nanoscale Computing and Communication*, 2019, pp. 1–6.

[32] Z. Hossain *et al.*, "Terasim: An ns-3 extension to simulate terahertz-band communication networks," *Nano Communication Networks*, vol. 17, pp. 36–44, 2018.

[33] J. Xu, J. Kan, and Y. Zhang, "Centralized energy harvesting-based tdma protocol for terahertz nanosensor networks," *Sensors*, vol. 19, no. 20, p. 4508, 2019.

[34] Z. L. Wang, "Towards self-powered nanosystems: From nanogenerators to nanopiezotronics," *Advanced Functional Materials*, vol. 18, no. 22, pp. 3553–3567, 2008.

[35] A. Kos *et al.*, "Poisson packet traffic generation based on empirical data," *Systemics, cybernetics and informatics*, vol. 1/5, pp. 1–4, 2003.

[36] A. Tsioliaridou *et al.*, "A protocol for network-controlled metasurfaces," in *ACM Nanoscale Computing and Communication*, 2017.

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