Modeling and Reducing Idling Energy Consumption in Energy Harvesting Terahertz Nanonetworks

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***Abstract*—A variety of nanoscale applications require downlink and broadcast-based transmission of control packets from a powered transmitter to energy-harvesting nanonodes with constrained storage capacity. The nanonode's communication system is anticipated to be a bottleneck for such nanonetworks, hence an accurate modeling of its energy consumption is needed. Currently, TS-OOK is a prevailing scheme for nanocommunication in the terahertz (THz) frequencies, with short pulses representing logical "1"s and silences logical "0"s. In the energy modeling of this scheme, certain energy consumptions are attributed to the transmission and reception of the pulses. However, traditional communication systems teach us that the idling energy consumption should not be neglected. Hence, we provide an energy consumption model for TS-OOK-based nanocommunication systems that accounts for the energy consumed in idling, in addition to the transmission and reception-originated consumptions. We demonstrate that, for a meaningful performance of the considered nanonetwork, the nanonode's idling energy consumption has to be at least nine orders of magnitude lower than the corresponding energy consumption in reception. To increase the tolerable idling energy, we propose a new energy lifecycle for the receiving nanonodes. Assuming frequent packet repetitions on the transmit side, the proposed lifecycle utilizes periodic short wake-ups of the receiving nanonodes. We show that, when the proposed lifecycle is utilized, up to three orders of magnitude higher idling energy consumption can be tolerated compared to the baseline.**

I. Introduction

Recent developments in nanotechnology are bringing light to nanometer-size devices for enabling a variety of applications such as software-defined metamaterials [1] and controllable robotic materials [2]. Many of these applications envisage controlling a potentially large number (i.e., thousands or even millions per m^2) of nanonodes, allowing them to influence events at an unprecedented scale. This control will mostly be done from a mains- or battery-powered transmitter in a downlink broadcast fashion, as discussed e.g., in [3], [4]. Due to the small form factors of the receiving nanonodes, communication in the terahertz (THz) frequency band (0.1 - 10 THz) is emerging as one of the most promising paradigms for nanoscale communication and coordination [5], [6]. 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.

Hence, the energy consumption of the receiving nanonodes will often be a bottleneck of the nanoscale communication required for enabling the above-mentioned applications. Modeling the energy consumption of the nanonode's communication system is required as one of the first steps in its overall energy consumption modeling. Intuitively, this modeling will differ for different communication schemes. Nonetheless, the time-spread ON–OFF keying (TS-OOK) [7] is currently a prevailing communication scheme for nanocommunication in the THz frequency band. Thus, in the contemporary literature the energy consumption of the receiving nanonode's communication system is modeled assuming the utilization of the TS-OOK scheme. In the TS-OOK scheme, a 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 [8], 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 communication is modeled by assuming a certain energy consumed for transmitting or receiving a TS-OOK pulse. In [9], the authors model the power consumption of a nanodevice by considering the energy consumption of its main components, i.e., processor, actuator, communication system, and memory module. The authors then argue that main bottleneck in the nanodevice's energy consumption will be the communication system. Similar to [8], they model the energy consumption of the communication system by assuming certain energy consumption values for transmitting or receiving a TS-OOK pulse.

However, we know from the traditional communication systems that a certain amount of energy is usually consumed in idling. For example, in wireless sensor networks, the value of sensors' idling energy is in the same order of magnitude as the energy consumed in reception [10]. That is to say, in traditional communication the energy consumed in idling is substantial and cannot be disregarded if the aim is to accurately model the overall energy consumption of the system. However, in nanocommunication, the energy consumption of the nanonode in idling is, to the best of our knowledge, currently overlooked.

In this paper, we first provide an energy consumption model of a nanonode's communication system, assuming that the TS-OOK is employed as the nanocommunication scheme. Our model accounts for the idling energy, besides the energy consumed due to the transmission or reception of a pulse. Second, we demonstrate by a numerical example that, for a realistic nanocommunication scenario, the idling energy consumption of the receiving nanonode is not negligible. We also show that the majority of idling consumption arises from idling between two consequent packet receptions. To reduce this energy dissipation, we propose a new energy lifecycle for the receiving nanonode. The proposed lifecycle utilizes packet repetitions on the transmit side and periodic wake-ups of the receiving nanonode based on the packet generation interval.

Using the proposed energy consumption model, we evaluate the effects of idling energy of the reliability (i.e., packet reception rate) of the considered nanonetwork. We do that because the reliable nanocommunication will be highly relevant for a large variety of software-controlled metamaterial applications [1]. Our results show that, for a meaningful performance of the nanonetwork, the idling energy consumption of the receiving nanonodes has to be *nine orders of magnitude* lower than the corresponding energy consumed in reception. We also show that, by utilizing the proposed lifestyle instead of the usually considered one, the idling energy consumption can be up to three orders of magnitude higher for achieving the same reliability levels.

II. Idling Energy in Energy Harvesting Nanonetworks

In this section, we first describe the usual energy lifecycle 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. Finally, with the aim of reducing the energy consumption of the nanonode due to idling, we propose a new lifecycle of the nanonode's communication system.

A. Energy Lifecycle of an Energy Harvesting Nanonode

The usual energy lifecycle of the nanonode's communication system is given in Figure 1. As depicted in the figure, at certain points in time the energy of the nanonode will be below the level required for its operation. 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 loose 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 1. Note that this lifecycle does not account for the energy consumed due to idling.

B. Modeling of Idling Energy

The above-described lifecycle for energy harvesting nanonode's communication system accounts for the fact that a certain amount of energy will be consumed in reception of

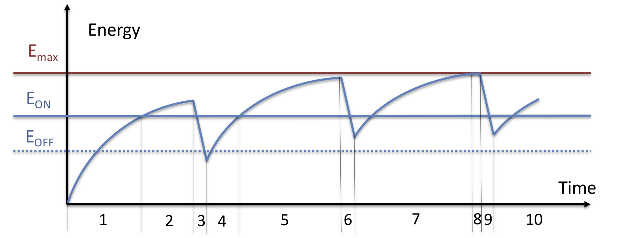


Figure 1: Energy lifecycle of a nanonode's communication system

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 2. The duration between two consecutive pulses is characterized by the parameter β, as shown in the figure. In between two pulses, the receiving nanonode would idle, which will in practice consume some 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 our depiction 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 of a packet are logical "1"s (i.e., only the short pulses are depicted, not the silences). Deriving the energy consumed due to reception of a packet for the generalized case is straightforward and equals:

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

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 [8], [11]. In addition, we assume β equals 100, which is again

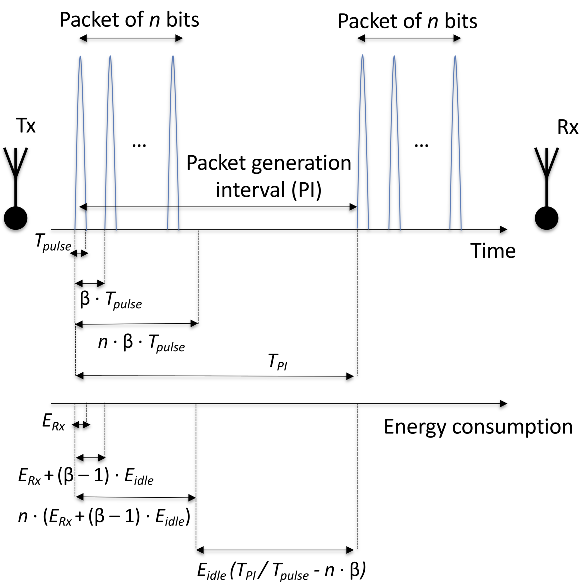


Figure 2: Model of nanonode's communication system accounting for energy consumption due to idling

based on multiple reports from the literature [8], [9]. 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 s. 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$\cdot$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 [10], while the energy consumption of a wake-up radio in idling is roughly three orders of magnitude lower than the energy consumption of a main radio in reception [12]. 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 receptions is not negligible anymore, but equals 1 μJ!

C. Energy Lifecycle 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). Note that many applications targeting software-controlled metamaterials are envisioned to issue control commands periodically, hence the transmission of packets from a battery- or mains-powered transmitting node will for many

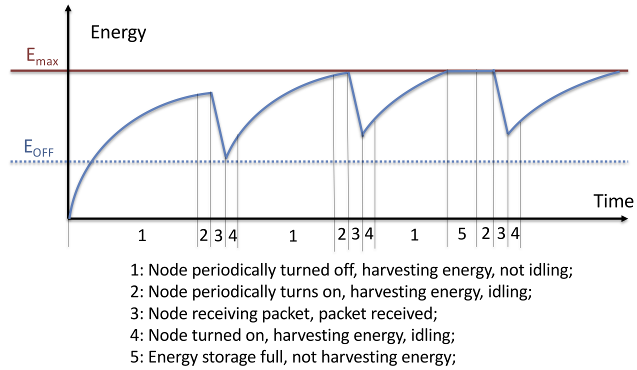


Figure 3: Proposed lifecycle for reducing idling energy consumption

applications be periodical with the period T_{PI}. Given that the transmitting node is not energy-constrained, each transmitted packet could be repeated multiple times. Hence, we propose to continuously repeat each packet until a new packet arrives to be transmitted. Under these conditions, the receiving nanonode does not have to be continuously turned on if its energy level is above E_{ON}. Adversely, we propose that the receiving nanonode turns on periodically and stays on for a short period of time, i.e., until it successful receives one packet. The proposed lifecycle for the energy-harvesting receiving nanonode's communication system is given in Figure 3.

The proposed lifecycle is beneficial due to the fact that the energy harvesting nanonodes are not continuously idling between the receptions of consecutive packets, which benefits their overall energy consumption. In other words, the idling energy is in to the proposed lifecycle a less dominant factor in the energy consumption of the nanonode's communication system, compared to the usual lifecycle. The dominant factor is the packet transmission period T_{PI} of transmitting the packets, i.e., the energy consumption of the nanonodes increases with the decrease in the packet transmission period. In addition, the proposed lifecycle does not require tight synchronization between the transmitting node and the receiving nanonodes, which is particularly important for nanocommunication where synchronization between communicating nodes is usually infeasible [7], [13]. A clear drawback of the lifecycle is that it increases the latency of packet delivery. 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 network reliability.

III. Evaluation Methodology

In the evaluation, we aim at establishing the reliability of a nanonetwork for software-controlled metamaterial applications. Hence, we specify a scenario with one-hop downlink omnidirectional broadcast traffic, as depicted in Figure 4. In the evaluation, we account for and try to reduce the idling energy consumption of the receiving nanonodes. We simulate the performance of the nanonetwork using the ns3-based TeraSim simulator [11], with the simulation parameters as summarized in Table I. We assume that the transmitting node 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 nanonetwork of 625 receiving nanonodes 1 mm apart from one another, with the transmitting node 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 receiving nanonode would not be available is because it is turned off. Note that the position of the transmitter is irrelevant, given that all the nanonodes are in its coverage.

The 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 communication scheme and assume that the energy consumed for receiving a pulse equals 0.1 pJ. 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 [7], [8].

The current state-of-the-art energy harvesters exploit piezoelectric effect of ZnO nanowires [14], 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 [8], we model energy harvesting 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 [8] as follows:

$$n_{cycle} = \left\lceil \frac{-V_g C_{cap}}{\Delta Q} ln \left(1 - \sqrt{\frac{2E_{n_{cycle}}}{C_{cap}V_g^2}} \right) \right\rceil. \quad (3)$$

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 with:

$$E_{n_{cycle+1}} = \frac{C_{cap}V_g^2}{2} 2^{1-e^{-\frac{\Delta Q(n_{cycle}+1)}{V_g C_{cap}}}}, \quad (4)$$

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: $C_{cap} = 2E_{max}/V_g^2$.

We consider two types of sources for harvesting energy, i.e., air vibrations and ultrasound-based power transfer. The literature reports 20 msec [8] and 1.71 msec [15] long harvesting cycles for these sources, respectively. Moreover, [8], [15] report the harvesting charges ΔQ of 6 pC for ZnO nanowires' compress-and-release cycles. As often done in the literature [11], we model these charges using Gaussian distributions with with 6 pC as the mean value and 0.6 pC as the standard deviation. We consider two energy storage types, a capacitor of 800 pJ [8] and a supercapacitor of 17.240 nJ [15] of their maximum energy storage capacities. We consider periodic transmissions of packets to the receiving nanonodes, with the packet generation interval of 1000 msec. This corresponds to the requirements of applications targeting control of the first generation of metamaterials [1], [16].

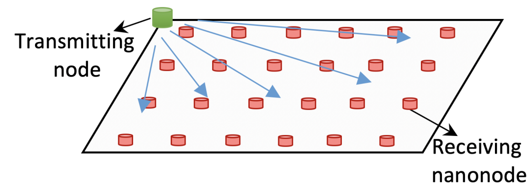


Figure 4: Envisioned grid-like constellation of receiving nanonodes with a single transmitting node

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], β	100, 100
$E_{R_{X pulse}}$ [pJ]	0.1
Packet size [bits]	128
E_{max} [pJ]	[800, 17240]
E_{ON}, E_{OFF} [pJ]	300, 40
Packet generation interval [ms]	1000
Duration of simulation [ms]	10000 x packet generation interval
Number of repetitions	99
Repetition delay [ms]	10
Harvesting cycle duration [ms]	[20, 1.71]
Harvested charge ΔQ [pC]	6

We use network reliability 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 energy lifecycle for reducing the energy due to idle listening, we introduce repetitions. Specifically, each packet is repeated 99 times, with the delay between consecutive repetitions being 10 ms. We specify these values due to the limitations of the TeraSim simulator, although it is intuitive that the more times a single packet is repeated, the shorter is the period that the nanonodes have to stay turned on in order to receive a packet or one of its repetitions. Hence, an increase in the number of repetitions is beneficial for reducing the idling energy consumption of the receiving nanonodes.

IV. Evaluation Results

Figure 5 depicts the nanonetwork reliability in case the idling energy is not at all considered (label "Ignored" on the X-axis in the figure) in the modeling of the energy consumption of the receiving nanonodes' communication system. As visible in the figure, the reliability of the nanonetwork 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 reliability comes from the low efficiency (i.e., relatively long harvesting cycle) of air vibration-based energy harvesting. Similarly, if the idling energy is not considered, the reliability of the nanonetwork 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 II, the reliability of the nanonetwork depends on the value selected for the idling energy consumption E_{idle} per pulse duration. A range of these values is depicted on the X-axis in the figure. As visible in the figure, in the baseline scenario (i.e., if the usual energy lifecycle is utilized) the reliability of the nanonetwork is practically not affected by idling energy consumption for idle energy consumption 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 of idling energy, the difference between network reliabilities for different energy/storage pairs comes from the fact that the ultrasound-based power transfer is a substantially more efficient energy harvesting option than the air-vibrations. Hence, the increase in nanonode's energy level due to harvesting is faster and can withstand higher idling energy consumption values. Nonetheless, these baseline results demonstrate that, in order to achieve at least a certain level of feasibility of the considered nanonetwork (i.e., network reliability 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 presumably going to be a challenge in the development of the receiving nanonodes, considering that the idling energy consumption is in the current communication systems at most a few orders of magnitude lower than the corresponding energy consumption in reception. We believe that this conclusion motivates the need for reducing the idling energy consumption of the receiving nanonodes.

Figure 5 also depicts the reliability achieved when the proposed lifecycle is utilized instead of the usually considered one. As visible in the figure, when the proposed lifecycle is utilized, the nanonetwork reliability is not affected by the idling energy consumption for the idling energy consumption 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 lifecycle, by utilizing the proposed lifecycle up to three orders of magnitude higher idling energy consumption per pulse can be tolerated without affecting the reliability of the nanonetwork. Moreover, meaningful levels of reliability can be achieved for the idling energy consumption per pulse lower than 10^{-8} and 10^{-6} pJ (0.01 and 1 aJ) for the two considered energy harvesting/storage options, respectively. In summary, the utilization of the proposed lifecycle substantially increases the nanonetwork feasibility by tolerating up to three orders of magnitude higher idling energy values.

As mentioned, if the proposed lifecycle is utilized, the reliability of the nanonetwork will be affected by the packet generation interval. This is demonstrated in Figure 6 for the two considered harvesting/storage options and for the idling energy consumption per pulse of 10^{-10} and 10^{-8}, respectively. As visible in the figure, as the packet generation interval increases, the nanonetwork reliability increases. For example,

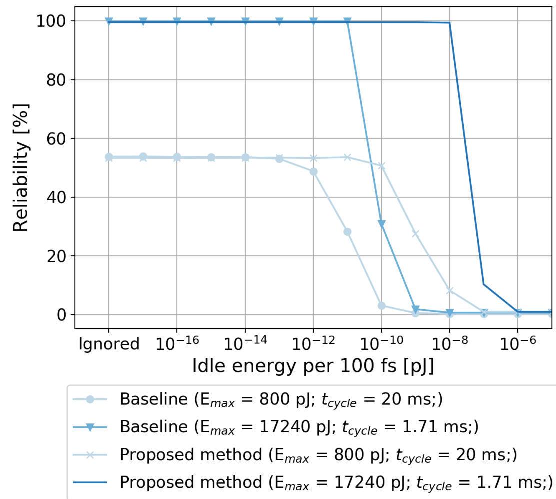


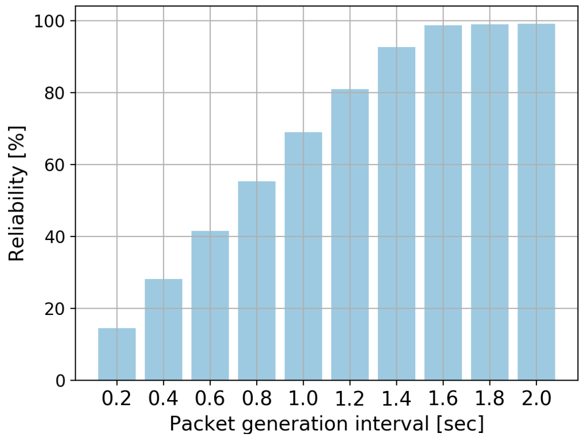
Figure 5: Network reliability vs. idling energy

as the packet generation interval increases from 0.2 to 1.0 s, the reliability increases from less than 20% to respectively more than 60% and roughly 100% for the two harvesting/storage options. This is because the receiving nanonodes are less frequently consuming energy for the reception if the packets are less frequently transmitted. This observation motivates the need for designing nanonodes' control mechanisms in a way that minimizes the packet transmission frequency.

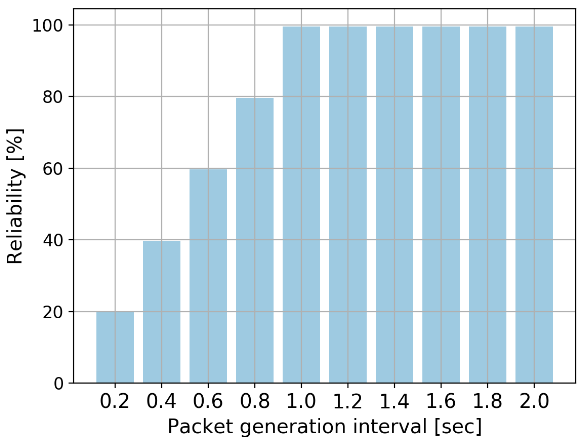
As mentioned before, the intuitive drawback of the proposed lifecycle comes from the fact that it intrinsically increases the latency of delivering packets to the receiving nanonodes. In other words, while in the usual lifecycle the packets would either be delivered almost instantaneously or would not be delivered at all (i.e., if a nanonode is turned off), in the proposed one the latency increase 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 reliability and latency in case multiple wake-ups are utilized are depicted in Figure 7 for the two considered harvesting/storage options and for E_{idle} of 10^{-10} pJ. As visible, for the air-vibrations (capacitor), an increase in the number of wake-ups decreases both the reliability 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 the 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 reliability, 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 packet generation interval.

V. Conclusion

In this paper, we proposed a model for energy harvesting nanonode's communication system that accounts for the energy consumed in idling, in addition to the energy consumed

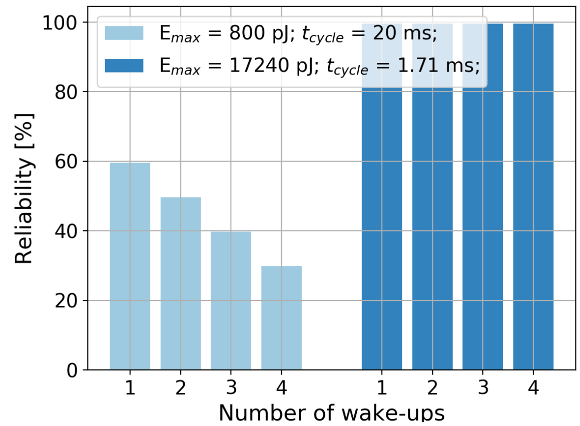


(a) E_{max} = 800 pJ, t_{cycle} = 20 ms, $E_{idle} = 10^{-10}$ pJ per 100 fs

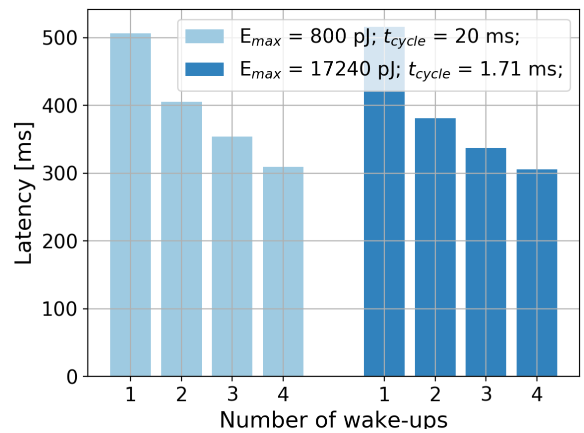


(b) E_{max} = 17240 pJ, t_{cycle} = 1.71 ms, $E_{idle} = 10^{-8}$ pJ per 100 fs

Figure 6: Reliability vs. packet generation frequency



(a) Reliability



(b) Latency

Figure 7: Reliability-latency trade-off with multiple wake-ups

for packet transmission or reception. By utilizing the proposed model, 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 lifecycle of an energy harvesting receiving nanonode, which is based on nanonode's periodic short wake-ups. Assuming periodic packet transmissions, we have shown that, by utilizing the proposed lifecycle instead of the usually employed one, the tolerable idling energy consumption is increased by up to three orders of magnitude. Future work will aim at evaluating the proposed lifecycle for stochastic traffic, as well as developing strategies for intelligent selection of the number of wake-ups based on traffic patterns and energy-related behavior of the receiving nanonodes.

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