Assessing the Reliability of Energy Harvesting Terahertz Nanonetworks for Controlling Software-Defined Metamaterials

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ABSTRACT

Electromagnetic nanonetworks operating in the terahertz (THz) frequency band are emerging as a promising technology for supporting a variety of nanoscale applications. At such scales, the use of batteries is in many cases infeasible, thus the nanonodes are envisioned to operate using only capacitors that rely on energy harvesting. This will result in constrained energy storage capacity with unpredictable charging rate, which will in turn yield non-periodic intermittent on-off behavior of the nanonodes. This paradigm is currently largely unexplored, hence it is challenging to make claims about the achievable network reliability. To provide initial insights, we investigate the reliability of nanoscale THz communication in a one-hop downlink broadcast scenario in face of intermittent on-off behavior of the receiving nanonodes. We do that because we believe that the reliable communication will be highly relevant for software-controlled metamaterial applications. Our results demonstrate the need for intelligent selection of energy levels for turning on and off the battery-less nanonodes. In addition and perhaps counter-intuitively, we demonstrate that the repetitions of packets substantially degrade the reliability of the considered nanonetwork.

CCS CONCEPTS

• **Networks → Link-layer protocols**; **Network simulations**; *Network protocol design*; *Short-range networks*; *Network reliability.*

KEYWORDS

nanonetwork, reliability, energy-harvesting, metamaterials, THz

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1 INTRODUCTION

With recent advancements in nanotechnology, the development of nanodevices at the dimensions of a few hundreds of nanometers is becoming feasible. Such devices can influence events at an unprecedented granularity, paving the way for a variety of applications such as software-defined metamaterials [1] and controllable robotic materials [4]. For realizing the envisioned applications, there is a need for reliable wireless communication and coordination, which poses a large number of unresolved challenges. Traditional wireless communication technologies, predominantly operating in the frequencies lower than 100 GHz are not suitable for nanocommunication, primarily due to their large form factors. As an alternative, communication in the terahertz (THz) frequency band (0.1 - 10 THz) is emerging as one of the main technological drivers for achieving nanoscale communication and coordination [3].

Scientific research on THz-band wireless communication and networking at the nanoscale is still in its infancy. The pioneering works on the design of graphene-based nanoscale THz-band transceivers [3] and antennas [2] demonstrated the promise of THz nanocommunication. However, current works are mainly focused on communication-related issues such as propagation modeling [8], and physical layer modulation and coding [11]. Despite that, the specific nature of signal propagation in the THz frequencies also requires rethinking the higher layers of the protocol stack, which is currently to a large extent lacking [3].

Many of the envisioned nanoscale applications, specifically the ones related to software-defined metamaterials, will require reliable control of ultra-densely deployed nanonodes (i.e., thousands or even millions of devices per m^2) [1]. In addition, the nanonodes will, due to their small size, have very low energy storage capacities. Hence, in many scenarios the only feasible option for powering the nanonodes will be through energy harvesting. This will intrinsically result in a fluctuating charging rate and, thus, the nanonodes are expected behave in an unpredictable on-off fashion. For these reasons, nanoscale networking protocols should be adapted to operate under conditions implicit to energy harvesting. This, in addition to the issues raising from the specific nature of THz-band propagation, makes their operation fundamentally different from traditional networking protocols. The existing literature has to an extent focused on the relation between energy harvesting and energy consumption of nanonodes communicating in THz frequencies. The authors in [10] and [7] respectively propose and implement a model for energy harvesting nanonodes that accounts for the correlation between the energy harvesting and energy consumption processes. However, the issue of reliable communication over energy harvesting nanonetworks in the THz frequencies is, to the best of our knowledge, still entirely unexplored.

By evaluating THz-band network reliability, this paper makes the first step in closing this gap. We define network reliability as the ratio between the number of packets received by a nanonode and number of transmitted packets, averaged over all nanonodes. We consider a static scenario with broadcast downlink traffic, where a transmitting node has a constant energy supply, i.e., it is not powered by energy harvesting. Moreover, we assume an intermittent on-off behavior of the receiving nanonodes due to their constrained energy storage capacities and energy harvesting as a sole powering option [6]. We consider this scenario because we believe that the reliable downlink communication from a battery-powered transmitting node to a number of harvesting nanonodes will be highly relevant for a number of configure and control applications, such as software-controlled metamaterials and robotic materials [4, 13].

Our results show that it is challenging to achieve high network reliability, even in the scenario where the transmitting node is battery-powered. We further show that the reliability highly depends on the energy harvesting rate and number of packets sent by the transmitting node, and it is often not influenced by the energy storage capacity. In addition, we demonstrate the need for intelligent selection of nanonodes' turn-on and turn-off thresholds that should account for the expected harvesting rate, amount of traffic, and maximum energy storage capacity. For improving the reliability, we investigate the use of link layer repetitions (i.e., transmitting the same packet multiple times without waiting for acknowledgments). Contrary to traditional communication paradigms in which repetitions generally improve the reliability (e.g., [5, 15]), we show that in the repetitions substantially reduce the reliability of the considered nanonetwork. In other words, our results indicate that for energy harvesting THz nanonetworks the optimal strategy for maximizing the network reliability is to minimize the amount of received (and consequently transmitted) packets.

2 ENERGY LIFECYCLE OF A NANONODE

The usual energy lifecycle of a battery-less energy harvesting nanonode is given in Figure 1. As shown in the figure, at certain points in time the energy of the nanonode will be at a critically low level, hence the nanonode will not be able to operate. We define this energy level as the "turn-off threshold" and label it with E_{OFF}, as shown in the figure. At a certain later point in time, the nanonode will harvest sufficient amounts of energy to turn on again and will then be able to receive packets. We define this energy level as a "turn-on threshold" and label it with E_{ON}. Intuitively, the node will continue to harvest energy if it is turned on. This will continue to happen until the energy level of the nanonode reaches the maximum storage capacity (labeled with E_{max}), as shown in the figure. Upon reaching this energy level, the energy level of the nanonode will stay fixed, as indicated in the figure. Intuitively, during reception periods, the node will loose certain amounts of energy, while at the same time gaining some (in practice much lower) amount of

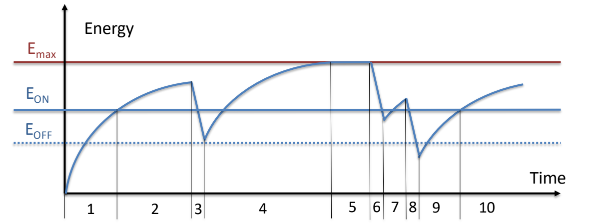


Figure 1: Intermittent nature of a nanonode

energy due to harvesting. Note that the energy of the nanonode can drop to a level in which it is still turned on, but does not have enough energy for receiving an entire packet. In such a case, the nanonode will nonetheless attempt to receive the packet and in the attempt its energy level will drop below the turn-off threshold and the node will turn off without receiving and decoding the packet. This is indicated with 8) in Figure 1.

In the current state-of-the-art energy harvesters that exploit piezoelectric effect of ZnO nanowires [14], energy is harvested in nanowires' compress-and-release cycles. The harvested energy varies across energy sources (e.g., air vibrations, hearth beats) and can be specified with the duration of the harvesting cycle t_{cycle} and the harvested charge per cycle ΔQ. As discussed in [10], energy harvesting should be modeled as an exponential process. The modeling has to account for the total capacitance C_{cap} of the nanonode, where $C_{cap} = 2E_{max}/V_g^2$, i.e., C_{cap} depends on the maximum energy storage capacity E_{max} and the generator voltage V_g.

As discussed previously, at certain points in time the nanonode could lose some energy due to reception of a packet and this can occur between periodical energy harvesting cycles, hence the current energy $E_{n_{cycle}}$ could change between two harvesting cycles. Due to that and due 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 $E_{n_{cycle}}$, which can be derived from [10] as follows:

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

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

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

3 EVALUATION METHODOLOGY

The aim of the evaluation is to establish the reliability of a nanonetwork for software-controlled metamaterials. Hence, we consider a scenario with one-hop downlink omnidirectional broadcast traffic, as shown in Figure 2. We simulate the performance of the nanonetwork using the ns3-based TeraSim simulator [7], with the simulation parameters as summarized in Table 1. Note that we have to an extent modified the simulator to support the needs of our evaluation. In our scenario, we assume that a transmitting node acts as a battery- or mains-powered gateway, thus it always has sufficient energy to transmit a packet, if there is a packet to transmit. We consider a grid-like network composed of 625 receiving nanonodes at the distance of 1 mm between neighboring nodes. The transmitting node is positioned in one corner of the grid, as shown in the figure. Such a setup has been suggested in the literature for controlling static metamaterials [1], in which there is no need for node discovery, as the only reason why a nanonode would not be able to receive a packet is because it is turned off. Note that the position of the transmitting node is not relevant in this scenario, as long as its range is high enough to reach all receiving nanonodes.

If a packet arrives at a nanonode that is at a given point in time turned off, the packet will not be received. Adversely, if the nanonode is turned on, it will start receiving the transmitted packet (i.e., all receiving nanonodes are in the range of the transmitting node and there is no interference). If during the reception the nanonode runs out of energy, it will turn off and the reception will fail. In the simulations, we use Time Spread On-Off Keying (TS-OOK) [9], a de-facto standard communication scheme for nanocommunication, based on the exchange of very short pulses spread in time. We assume the energy consumed for receiving a pulse equals 0.1 pJ, where the pulse carries one bit of information, i.e., a logical "1". The duration of the pulse is 100 fs, with two consecutive pulses being generated $\beta\times$100 fs apart from each other. These values have been suggested in the pioneering works on the topic [9, 10].

Because of their continuous and relatively frequent occurrence, we consider air vibrations as the source of harvested energy. The current literature reports 20 msec long harvesting cycles for such energy sources [10]. Moreover, the literature reports the harvesting charges ΔQ for each cycle ranging between roughly 3 and 7 pC. In order to establish the effect of the harvesting rate on the nanonetwork reliability and using the rough indications from the literature, we consider harvesting charges with mean values ranging from 1 to 9 pC per 20 msec cycle. We model these charges using Gaussian distributions with with above indicated mean values and standard deviations equaling one tenth of the mean values, which is the usual assumption made in the literature [7]. The energy-related behavior of the receiving nanonodes is then modeled based on the above-discussed energy harvesting model (i.e., Equations 1 and 2).

To establish the effect of energy storage capacity on the nanonetwork reliability, we perform our simulations for maximum energy storage capacities equaling 400, 600, 800, and 1000 pJ, which are also roughly the values reported in [10]. Similarly, to evaluate the effects of the turn-on and turn-off thresholds on the nanonetwork reliability, we specify the following $[E_{ON}, E_{OFF}]$ pairs: [100,40], [300, 40], [300, 100]. We select these values "blindly", with the aim of creating multiple simulation runs that only differ in the value of the turn-on or turn-off thresholds, so that their effects on reliability can be isolated. Note that the turn-off threshold values are chosen so that they are sufficiently high to receive a few packets of 128 bits (usual packet size reported in the literature, e.g., [1]).

In addition, we evaluate the effect of the amount of traffic on the reliability of the nanonetwork. To do that, we define the parameter called packet generation interval (PI), which statistically characterizes the packet generation frequency at the transmitting node. We model the packet generation process using a Poisson distribution

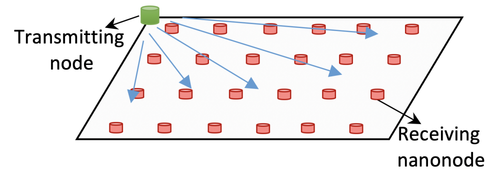


Figure 2: Envisioned grid-like constellation of receiving nanonodes with a single transmitting node

Table 1: Simulation parameters

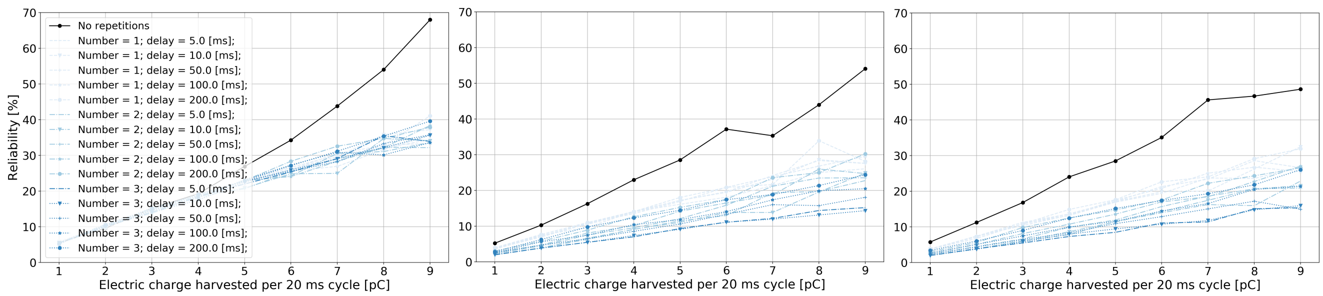
Parameter	Value
Number of nanonodes	(25x25) 625
Distance between nodes [mm]	1
V_g [V]	0.42
T_X [dBm]	-20
Pulse duration [fs], β	100, 100
$E_{R_{Xpulse}}$ [pJ]	0.1
Packet size [bits]	128
E_{max} [pJ]	[400, 600, 800, 1000]
E_{ON} [pJ]	[100, 300]
E_{OFF} [pJ]	[40, 100]
Packet generation interval [ms]	[100, 1000, 8000]
Duration of simulation [ms]	10000 x packet generation interval
Number of repetitions	[0, 1, 2, 3]
Repetition delay [ms]	[5, 10, 50, 100, 200]
Harvesting cycle duration [ms]	20
ΔQ [pC]	[1, 2, 3, 4, 5, 6, 7, 8, 9]

specified by its mean value, which is usually used for modeling the packet generation process (e.g., [5, 11]). We consider 100, 1000, and 8000 msec as the mean values for the distribution, corresponding to the requirements of applications targeting metamaterials' control [1, 12]. Additionally, our reasoning for selecting these values is to create conditions with low, medium, and high network reliability, hence potentially obtain generalizable conclusions about the effects of different parameters on the nanonetwork's reliability.

As the performance metric, we use network reliability, i.e., the ratio between the number of packets received by each nanonode and overall number of transmitted packets, averaged over all nanonodes. To potentially enhance the initially derived reliability, we introduce repetitions, which in traditional networking paradigms usually substantially improve the network reliability. In other words, we repeat the packet sent by the transmitting node after a certain delay from the initial transmission. Note that acknowledgments are not considered, as their transmissions consume large amounts of energy and are therefore ineffective for the nanonodes, as indicated in [10]. Note also that we consider a packet received by a nanonode if it is received at least once, i.e., the fact that due to repetitions it could be received multiple times by the same node does not affect the reliability of the nanonetwork. We consider various numbers of repetitions with a variety of delays between them. Due to a relatively large number of varying parameters in our simulation, we overall executed more than 5500 simulation runs, resulting in more than 1 TB of logged raw data-traces.

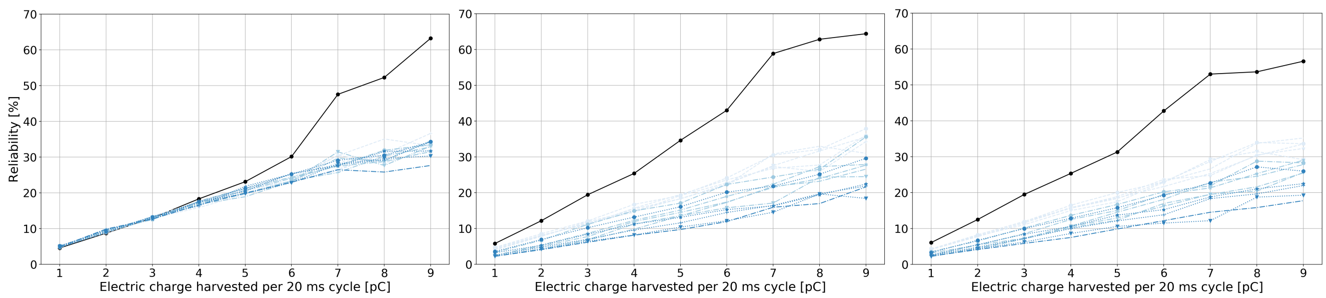
4 EVALUATION RESULTS

The following figures depict the reliability of the above-specified nanonetwork for varying packet generation intervals, energy storage capacities, and turn-on and turn-off thresholds. We derive these results for the case of no repetitions, as well as for the cases with different numbers of and delays between repetitions.



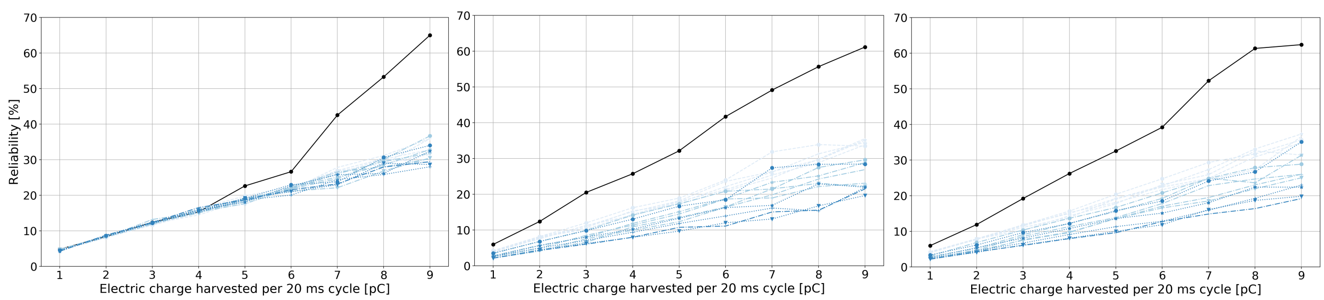
(a) E_{ON}=100 pJ, E_{OFF}=40 pJ (b) E_{ON}=300 pJ, E_{OFF}=40 pJ (c) E_{ON}=300 pJ, E_{OFF}=100 pJ

Figure 3: Reliability for PI = 1000 ms and E_{max} = 400 pJ



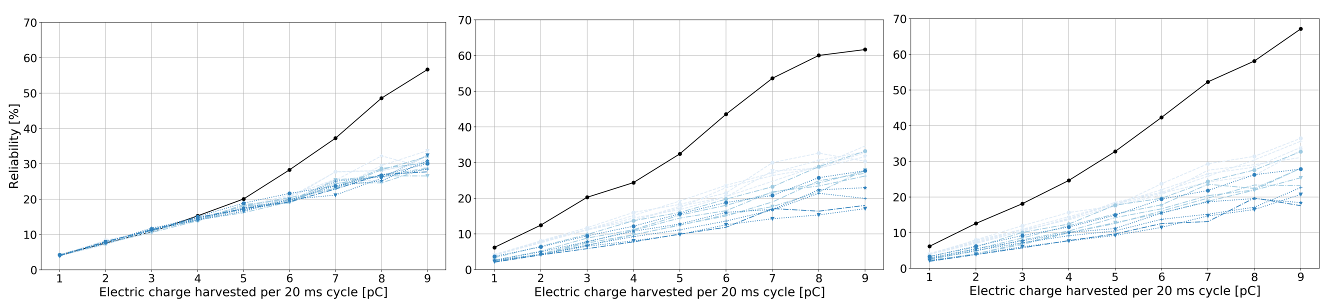
(a) E_{ON}=100 pJ, E_{OFF}=40 pJ (b) E_{ON}=300 pJ, E_{OFF}=40 pJ (c) E_{ON}=300 pJ, E_{OFF}=100 pJ

Figure 4: Reliability for PI = 1000 ms and E_{max} = 600 pJ



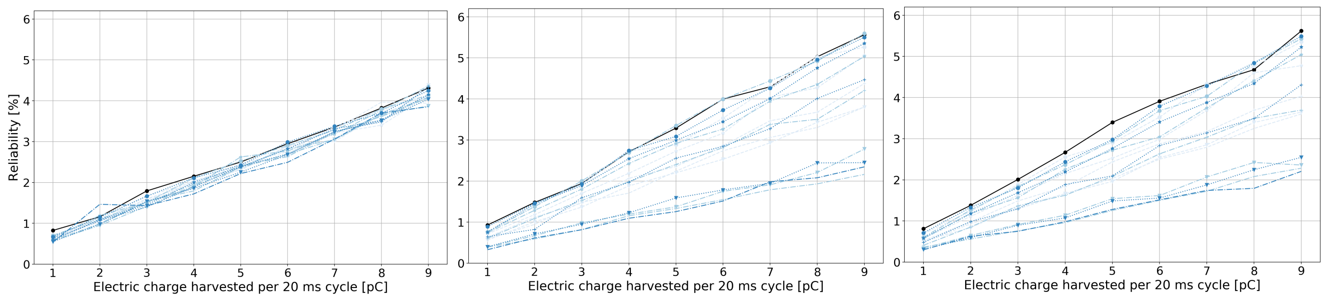
(a) E_{ON}=100 pJ, E_{OFF}=40 pJ (b) E_{ON}=300 pJ, E_{OFF}=40 pJ (c) E_{ON}=300 pJ, E_{OFF}=100 pJ

Figure 5: Reliability for PI = 1000 ms and E_{max} = 800 pJ



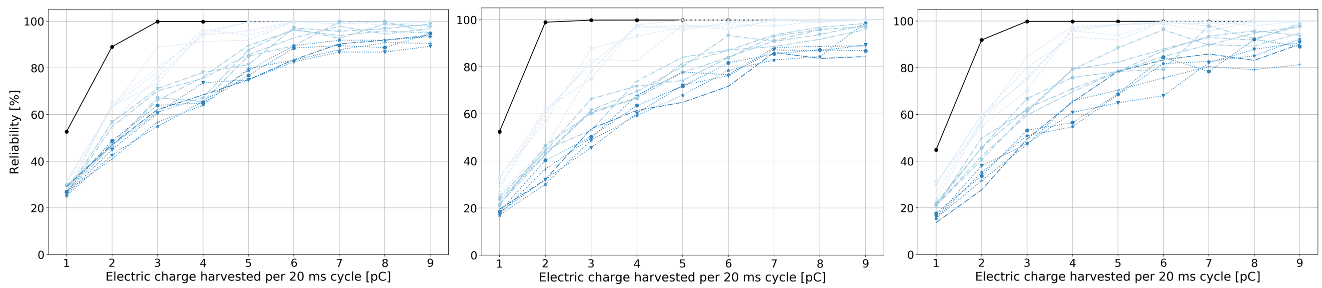
(a) E_{ON}=100 pJ, E_{OFF}=40 pJ (b) E_{ON}=300 pJ, E_{OFF}=40 pJ (c) E_{ON}=300 pJ, E_{OFF}=100 pJ

Figure 6: Reliability for PI = 1000 ms and E_{max} = 1000 pJ



(a) E_{ON}=100 pJ, E_{OFF}=40 pJ (b) E_{ON}=300 pJ, E_{OFF}=40 pJ (c) E_{ON}=300 pJ, E_{OFF}=100 pJ

Figure 7: Reliability for PI = 100 ms and E_{max} = 800 pJ



(a) E_{ON}=100 pJ, E_{OFF}=40 pJ (b) E_{ON}=300 pJ, E_{OFF}=40 pJ (c) E_{ON}=300 pJ, E_{OFF}=100 pJ

Figure 8: Reliability for PI = 8000 ms and E_{max} = 800 pJ

The first observation is that the network reliability generally increases with the increase in the energy harvesting rate. This is observed for both the cases without and with repetitions of individual packets. For example, for the packet generation interval of 1000 ms and regardless of the maximum energy storage capacity, turn-on and turn-off thresholds, as the harvesting rate increases from 1 to 9 pC per 20 msec cycle, the reliability of the network increases from less than 10% to more than 50%, as shown in Figures 3, 4, 5, and 6. We believe this observation to be intuitive and expected, however it makes a case for the correctly simulated network behavior (i.e., no implementation errors in the modified TeraSim simulator).

Second, the network reliability generally decreases with the decrease in the packet generation frequency. This can be seen by comparing the reliability across different packet generation intervals. For example, if the other parameters are kept constant and packet generation interval is increased from generating a packet each 100 ms to generating a packet each 1000 and 8000 ms, the reliability increases from a few percents to roughly 40% and almost 100%, as depicted respectively in Figures 7, 5, and 8. This is observed for the case of no repetitions, maximum storage capacity of 800 pJ, and energy harvesting rate of 6 pC per 20 msec. Same as previously, we find this observation to be intuitive, again making an argument for the correctly simulated behavior of the nanonetwork.

Third, it is interesting to observe that a higher maximum energy storage capacity is some cases slightly reduces the reliability of the nanonetwork, although intuitively higher storage capacity should result in higher reliability. For example, as the energy storage capacity is increased from 400 to 1000 pJ, while the harvested charge per 20 ms is kept at 6 pC, one can observe by comparing Figures 3(a), 4(a), 5(a), and 6(a) that the reliability is reduced from roughly 35% to less than 30%. Adversely, one can also observe by comparing Figures 3(c), 4(c), 5(c), and 6(c) that the reliability increases from less than 50% to almost 70% with the increase in the maximum energy storage capacity for harvesting rate of 9 pC per 20 ms. We believe the reason for such a non-generalizable performance pattern comes from the fact that the effect of the maximum energy storage capacity of a nanonode cannot be considered in isolation. In other words, while an increase in the maximum energy storage capacity should benefit the reliability, the effects of other parameters such as harvesting rate, turn-on and turn-off thresholds, and packet generation intervals can hinder these benefits. For example, for small packet generation intervals and small harvesting rates, the nanonode will never be fully changed, as the energy will be spent before that in the reception of packets.

Fourth, our results show that it is not possible to make a general statement about the effects on turn-on and turn-off thresholds on the nanonetwork reliability. For example, for the harvested change of 7 pC per cycle and maximum storage capacity of 400 pJ, one can observe the reliability of roughly 45 and 35% for the turn-on thresholds of 100 and 300 pJ, respectively (Figures 3(a) and 3(b)). However, for the same harvested charge and turn-on threshold, and maximum energy storage capacity of 1000 pJ, the reliability increases from less than 40% to roughly 55%, as shown in Figures 6(a) and 6(b). Similar observations can be made for the varying turn-off threshold. Hence, the effects of turn-on and turn-off thresholds on the reliability of the nanonetwork are not generalizable and vary with the variation of other parameters. This motivates the need for a more intelligent selection of the turn-on and turn-off thresholds based on the traffic patterns, expected energy harvesting rate, and nanonodes' maximum energy storage capacity.

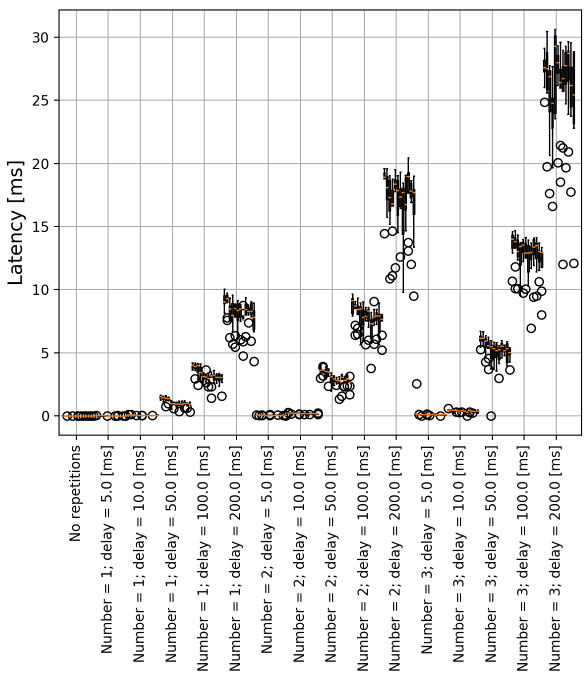


Figure 9: Packet reception latencies for $P = 1000$ ms

Finally, our results demonstrate that the utilization of repetitions does not benefit the reliability of the nanonetwork in the considered scenario. As visible in Figures 3, 4, 5, 6, 7, and 8, the usage of repetitions for a number of evaluation scenarios actually substantially reduces the reliability of the nanonetwork. This behavior is consistent across different numbers of repetitions of a packet, as well as for various delays between repetitions. The reason for such a behavior lies in the fact that repeating a packet causes a nanonode to potentially receive it multiple times (which does not benefit the reliability), hence its energy is depleted faster. As the packet generation frequency increases, this in turn results in increased probability of missing the next packet sent by the transmitter, which reduces the overall reliability. We believe that, for the considered scenario, the optimal strategy for maximizing the network reliability is to minimize the number of received (and consequently transmitted) packets. Hence, packet repetitions should not be attempted. This is further emphasized if the average latency of delivering a packet is considered. In Figure 9, we depict the average latency for evaluation scenarios differentiated based on the number of and delays between repetitions. For each scenario, the results are merged for all harvesting rates and depicted for cases differentiated based on maximum energy storage capacities, turn-on, and turn-off thresholds (i.e., 12 depictions for each scenario). As depicted, the utilization of repetitions has a much more pronounced effect on the latency than any other considered parameter. In addition, an increase in the number of repetitions, as well as in the delay between repetitions, highly increases the latency of packet delivery for a large variety of evaluation scenarios. This intuitive observation makes an argument against leveraging repetitions in an energy harvesting nanonetwork for controlling software-defined metamaterials. Note that if the packet generation interval would be deterministic instead of currently considered Poisson-distributed stochastic process, the repetitions could potentially be beneficial, if utilized intelligently. This intelligent utilization would require some decision-making strategy for deciding if the repetitions should at all be utilized, as well as how many times each transmission should be repeated and at which frequency. This decision-making strategy should certainly account for the energy harvesting rate and packet generation frequency (i.e., minimal frequency at which packets are transmitted to the receiving nanonodes). In addition, this strategy could be combined with the intelligent selection of turn-on and turn-off thresholds, so that the nanonodes turn on or off based on their reception of packets or the lack thereof.

5 CONCLUSION

In this paper, we evaluated the reliability-related behavior of a dense energy harvesting nanonetwork operating in terahertz frequency band. We have shown that the reliability depends on the energy harvesting rate and packet generation frequency, and that it often does not depend on the maximum energy storage capacity of the receiving nanonodes. We have also motivated the need for an intelligent selection of energy levels for turning the nanonodes on or off, taking into account the expected harvesting rate, traffic pattern, and energy storage capacity. Finally, we have provided an indication that packet repetitions reduce network reliability and should not be attempted for stochastic traffic patterns. Future work will be oriented toward developing intelligent strategies for turning on and off energy harvesting nanonodes, as well as for trying to intelligently utilize repetitions under deterministic traffic patterns.

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