# Packet Size Optimization for Wireless Nanosensor Networks in the Terahertz Band

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***Abstract*—Wireless Nanosensor Networks (WNSNs), i.e., networks of miniaturized devices with unprecedented sensing capabilities, are at the basis of transformative applications in the biomedical, environmental and industrial fields. Recent developments in plasmonic nano-antennas point to the Terahertz (THz) band (0.1-10 THz) as the frequency range of communication among nanosensors. While this potentially enables extremely high data rates in WNSNs, the very high path-loss at such frequencies and the limited power of energy-harvesting nano-devices limit the achievable throughput. In this paper, the link throughput maximization problem in WNSNs is addressed by taking into account the device and communication interdependencies in WNSNs. The optimal data packet size which maximizes the link efficiency is derived by capturing the device, channel, physical and link layer peculiarities of WNSNs. The energy harvesting limits and the successful packet transmission time are defined as the optimization problem constraints, and the optimal solution is derived by using a bisection method. Numerical results are provided to analyze the impact of the packet size for different error control strategies. The results show that the optimal packet size quickly decreases with the transmission distance, approaching several hundreds bits for distances beyond a few millimeters.**

## I. INTRODUCTION

Nanotechnology is enabling the development of nano-devices, which are able to perform unprecedented tasks at the nanoscale. One example of these nano-devices is given by the miniature sensing devices called nanosensors, which can detect and measure new types of events with unbeatable accuracy by leveraging the properties of novel nanomaterials. By means of communication, these nanosensors will form Wireless Nanosensor Networks (WNSNs) [1] which will be able to achieve more complex tasks and introduce an extensive range of novel applications in the bio-medical, industrial, and military fields as well as for consumer goods.

Several wireless technologies have been proposed to enable the communication between nanosensors such as molecular communication and ultrasonic communication. Among others, recent developments in plasmonic nano-antennas [2] enable the communication in the Terahertz (THz) band (0.1–10 THz) and even at higher frequencies.

The THz band provides nanosensors with a very large bandwidth, which potentially enables extremely high data rates in the order of multi Gigabits-per-second (Gbps) [3]. However, the very high propagation loss at such frequencies combined with the very limited transmission power of nanosensors result in extremely short communication distances. Moreover, the limited capacity of nano-batteries, which requires the use of time-consuming energy-harvesting procedures [4], [5], and the limited computational capabilities of nanosensors, affect the throughput of WNSNs. All these interdependencies motivate the joint analysis of the nano-device capabilities, the THz band peculiarities and their impact on the achievable throughput.

There have been many cross-layer studies on packet size optimization in wireless communication networks for a myriad of environments, including terrestrial, underwater, underground, and intra-body sensor networks [6], [7], [8], [9]. However, all these works cannot be directly applied for energy-harvesting networks, in which the energy fluctuates with time instead of monotonically decreasing. In this direction, several energy consumption optimization problems for wireless networks with energy harvesting nodes have been proposed over the recent years [10], [11], [12]. All these works are mainly focused on optimizing the utilization of the harvested energy following a general approach to find the trade-off between the consumed energy and the achieved quality of service. While the aforementioned studies are applicable to general wireless communication networks, in [13], a study is performed for the specific case of communication in nanonetworks. However, the impact of such energy management policies on the achievable throughput at the link layer is not analyzed.

In this paper, we address the throughput maximization problem in WNSNs, by taking into account the device and communication interdependencies in WNSNs. In particular, a link throughput optimization problem is defined, and the optimal data packet size which maximizes the link efficiency is derived by capturing the power, energy and computational constraints of nanosensors; the very high path-loss and very large bandwidth of the THz-band channel; the possibility to communicate by transmitting one-hundred-femtosecond-long pulses, which can virtually create parallel orthogonal channels between nanosensors [14]; and three different error control strategies tailored to WNSNs, namely, Automatic Repeat reQuest (ARQ), Forward Error Correction (FEC) and novel Error Prevention Codes (EPCs), which have been designed with the WNSNs peculiarities in mind [15]. Both the energy harvesting limits and the successful packet transmission time are defined as the optimization problem constraints, and the

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optimal solution is derived by using a bisection method. Our results show that the link efficiency quickly decreases when considering the energy constraints compared to the scenario that there is no energy shortage. The decrease depends on various parameters including the error-control technique, the communication distance, and the harvesting capability of the nanosensors. Similarly, the packet size quickly decreases with the transmission distance, approaching several hundreds bits for distances beyond a few millimeters.

The remainder of the paper is organized as follows. In Sec. II, we define the system model for WNSNs and discuss the throughput optimization problem while defining different constraints for various error-control methods. Sec. III contains the approach to solve the optimization problem, and covers the related algorithm to find the optimal solution for our problem. In Sec. IV, we numerically study the optimal packet size for different error-control techniques and compare the performance of them under different conditions. Finally, we conclude the paper in Sec. V.

## II. SYSTEM MODEL AND OPTIMIZATION PROBLEM FORMULATION

Two nanosensors with a single communication link between them is assumed. Nanosensors communicate with each other using TS-OOK [14], i.e., a recently proposed communication scheme based on the transmission of one-hundred-femtosecond-long pulses by following an asymmetric On-Off Keying modulation spread in time. Such mechanism can effectively provide nanomachines with orthogonal communication channels, thus minimizing the potential multi-user interference. The transmitter node is a nanomachine with the capability of harvesting energy by means of piezoelectric nano-generators [4], which converts kinetic energy into electricity by exploiting nanowires. At the receiver node it is assumed that always enough energy is available to receive the packets successfully, and the receiver has enough amount of memory to buffer the received data. Based on these assumptions, first a throughput optimization problem with the objective of maximizing the link throughput between a pair of transceivers in a WNSN is defined, by capturing the aforementioned constraints in a general form. Then the constraints are explained in details for different error-control techniques respectively.

We start with the definition of throughput in a WNSN link as the rate of successful message transmission measured in bits per second (bps), which is given by $S = \frac{Useful\ Data\ Length}{Successful\ Transmission\ Time}$. Without loss of generality, instead we can optimize the link utilization efficiency $\eta$ for a given transmission rate $r$ which can be further defined as:

$$\eta = \frac{1}{r} \cdot \frac{L_{data}}{N_{ret} \cdot T_{tx}}, \tag{1}$$

where $L_{data}$ is the $useful\ data\ length$ in bits, $N_{ret}$ represents the expected number of retransmissions needed for the packet to be received and processed successfully at the receiver node according to the chosen error-control method. $T_{tx}$ is the total time required to accomplish a complete packet transmission including the time required to harvest enough energy for transmission, and will be defined later in Sec. II-A as one of the constraints of the optimization problem. Hence, for a chosen error-control technique, to find optimal data length $L^*_{data}$ which maximizes the link efficiency, the optimization problem can be formulated as follows.

### A. Channel Efficiency Maximization Problem for WNSNs

We define next the optimization problem with the objective function of maximizing the channel efficiency in WNSNs, and the constraints which will be defined later in Sec. II-B through II-D in details according to the error-control method.

### Optimization Problem [P1]

$$\begin{aligned} Given:&\quad r, \psi^{\mathcal{E}}, \phi^{\mathcal{E}}, N_0, p_x^{\mathcal{E}}, f, d, \theta^{\mathcal{E}}, \tau^{\mathcal{E}}, E_{tx}^{\mathcal{E}}, \lambda_{harv} \\ Find:&\quad L^*_{data} \\ Maximize:&\quad \eta = \frac{1}{r} \cdot \frac{L_{data}}{N_{ret} \cdot T_{tx}} \\ Subject\ to:& \end{aligned}$$

$$L_{data} > 0 \tag{2}$$

$$N_{ret} = \frac{1}{1 - p_e} \tag{3}$$

$$p_e = \psi^{\mathcal{E}}(BER, L_{data}, L^{\mathcal{E}}) \tag{4}$$

$$BER = \phi^{\mathcal{E}}\left(\frac{E_{tx}^{bit}}{\overline{PL} \cdot N_0}, p_x^{\mathcal{E}}\right) \tag{5}$$

$$T_{tx} = max\{T_{tx}^{\mathcal{E}}, T_{tx-harv}^{\mathcal{E}}\} \tag{6}$$

$$T_{tx}^{\mathcal{E}} = \theta^{\mathcal{E}}(L_{data}, L^{\mathcal{E}}, T_{proc}^{\mathcal{E}}, T_{t/o}^{\mathcal{E}}, T_{prop}) \tag{7}$$

$$T_{tx-harv}^{\mathcal{E}} = \tau^{\mathcal{E}}(L_{data}, L^{\mathcal{E}}, E_{tx}^{\mathcal{E}}, p_x^{\mathcal{E}}, \lambda_{harv}) \tag{8}$$

$$E_{tx}^{\mathcal{E}} \leq \lambda_{harv} \cdot T_{tx-harv}^{\mathcal{E}} \tag{9}$$

where:

- $p_e = \psi^{\mathcal{E}}(BER, L_{data}, L^{\mathcal{E}})$ is the *Packet Error Rate* (PER), which is a function of the *Bit Error Rate (BER)*, data length $L_{data}$, and the length of the redundant bits $L^{\mathcal{E}}$, which depends on the error-control scheme $\mathcal{E}$.
- $BER = \phi^{\mathcal{E}}\left(\frac{E_{tx}^{bit}}{\overline{PL} \cdot N_0}, p_x^{\mathcal{E}}\right)$ is a function of energy required to transmit a bit $E_{tx}^{bit}$, the path loss $\overline{PL}$, and the noise spectral density $N_0$. It also depends on the pulse probability $p_x^{\mathcal{E}}$ that itself varies according to the chosen error-control method $\mathcal{E}$.
- $\overline{PL}(f, d)$ is the path loss between the transmitter and receiver nodes and depends on the transmission frequency $f$ and the distance between the nodes $d$.
- $T_{tx}^{\mathcal{E}} = \theta^{\mathcal{E}}(L_{data}, L^{\mathcal{E}}, T_{proc}^{\mathcal{E}}, T_{t/o}^{\mathcal{E}}, T_{prop})$ is the *packet round-trip time* or the total time needed for the packet to be transmitted and the acknowledgment to be received. $T_{proc}^{\mathcal{E}}$ and $T_{t/o}^{\mathcal{E}}$ are the processing time for a complete packet transmission and the time-out before retransmission respectively, for a chosen $\mathcal{E}$. $T_{prop}$ is the propagation time and is relative to the distance between

the transmitter and receiver nanomachines and it can be rewritten as $d/c$, where $c$ is the speed of light.

- $T_{tx-harv}^{\mathcal{E}} = \tau^{\mathcal{E}}(L_{data}, L^{\mathcal{E}}, E_{tx}^{\mathcal{E}}, p_x^{\mathcal{E}}, \lambda_{harv})$ is the time to harvest enough energy for a complete transmission including processing and transmitting the data.
- $E_{tx}^{\mathcal{E}}$ is the energy consumed to transmit a packet of length $L_{data}$. Note that this energy contains both the required energy to process data according to the selected $\mathcal{E}$, and the required energy for transmitting the data which depends on $L_{data}$, $L^{\mathcal{E}}$, and $p_x^{\mathcal{E}}$.
- $\lambda_{harv}$ is the rate at which the nanosensor transmitter mote is able to harvest energy in J/s.

Here we assume that the nano-transmitter always transmits with the maximum available energy, hence the inequality in (9) reduces to equality, and therefore the function $\tau^{\mathcal{E}}$, can be defined as follows:

$$\tau^{\mathcal{E}} = \frac{E_{tx}^{\mathcal{E}}}{\lambda_{harv}}. \tag{10}$$

Hence the two constraints (8) and (9) can be merged into one constraint as in (10). Moreover, for the $BER$, the function $\phi^{\mathcal{E}}$ does not depend on the optimization variable $L_{data}$, and depends on the physical layer parameters. In this paper we use the derived values for $BER$ in [16], as given values of the proposed optimization problem.

As it can be seen, the optimization problem defined in **[P1]** is a general problem with functions $\psi^{\mathcal{E}}$, $\theta^{\mathcal{E}}$, and $E_{tx}^{\mathcal{E}}$ which has to be tailored for three different error-control techniques, namely ARQ, FEC, and EPC, which are addressed as follows.

### *B. Automatic Repeat reQuest (ARQ) Constraints*

The *packet error rate* in ARQ is defined as follows:

$$\psi^{\mathcal{E}} = 1 - (1 - BER^{ARQ})^{l}, \tag{11}$$

where $l = L_{data} + L_{CRC}$, and $L_{CRC}$ is the length of *Cyclic Redundancy Check* (CRC) used for error detection. Moreover, the *packet round-trip time* is given by the following equation:

$$\begin{aligned} T_{tx}^{ARQ} &= T_{tx,data}^{ARQ} + T_{CRC} \\ &\quad + p_{s,data}^{ARQ} p_{s,ack}^{ARQ} (2T_{prop} + T_{CRC} + T_{tx,ack}^{ARQ}) \\ &\quad + (1 - p_{s,data}^{ARQ} p_{s,ack}^{ARQ}) T_{t/o}^{ARQ}, \end{aligned} \tag{12}$$

where $T_{tx,data}^{ARQ}$ and $T_{tx,ack}^{ARQ}$ are the data and acknowledgment transmission times and are given by $l/r$ and $L_{ack}/r$ respectively, where $L_{ack}$ is the acknowledgment packet length. $T_{CRC}$ refers to the delay caused by computational process of the CRC, and is given by $(L_{data} \cdot T_{clk})$, where $T_{clk}$ is the inverse of the nanomachine's clock frequency. $p_{s,data}^{ARQ}$ and $p_{s,ack}^{ARQ}$ are *data* and *acknowledgment* packet success rate respectively and can be obtained from (11) with $l = L_{data}$ and $l = L_{ack}$ respectively. Finally $T_{t/o}^{ARQ}$ is defined as follows:

$$T_{t/o}^{ARQ} = 1.1(2T_{prop} + T_{CRC} + T_{tx,ack}^{ARQ}), \tag{13}$$

which is the propagation delay to transmit the data and receive the acknowledgment, plus the time the receiver takes to process the CRC and transmit the acknowledgement packet, plus a ten percent margin time. The energy required for transmission process in ARQ can be defined as follows [16]:

$$E_{tx}^{ARQ} = E_{tx,data}^{ARQ} + E_{CRC} + p_{s,data}^{ARQ} p_{s,ack}^{ARQ} E_{rx,ack}^{ARQ}, \tag{14}$$

where $E_{tx,data}^{ARQ}$ and $E_{rx,ack}^{ARQ}$ refer to the energy required to transmit the data packet and receive the acknowledgement packet, and are given by $(l \cdot p_x^{\mathcal{E}} \cdot E_{tx}^{bit})$ and $(p_{s,data}^{ARQ} \cdot p_{s,ack}^{ARQ} \cdot L_{ack} \cdot E_{rx}^{bit})$ respectively. $E_{CRC}$ stands for the consumed energy caused by computational process of the CRC, and is given by $(L_{CRC} \cdot L_{data}(E_{shift} + E_{hold}))$, where $E_{shift}$ and $E_{hold}$ are the energies consumed to shift and hold a registry value in a shift register. Note that the value of $E_{CRC}$ is defined based on the assumption that a CRC is implemented by exploiting shift registers and XOR logic gates as described in [16].

### *C. Forward Error Correction (FEC) Constraints*

For the FEC, the *packet error rate* depends on the *Block Error Rate* (BLER), and is defined as follows:

$$\psi^{\mathcal{E}} = 1 - (1 - BLER^{FEC})^{n}, \tag{15}$$

where $n$ is the number of blocks per data packet payload, and $BLER^{FEC}$ is given as follows:

$$BLER^{FEC} = \sum_{j=t+1}^{k} \binom{k}{j} (BER)^{j} (1 - BER)^{k-j}, \tag{16}$$

where $k$ refers to the block size and $t$ is the error correction capability of the code. Moreover, the *packet round-trip time* for FEC can be defined as follows:

$$\begin{aligned} T_{tx}^{FEC} &= T_{tx,data}^{FEC} + T_{code}^{FEC} + p_{s,data}^{FEC}(T_{prop} + T_{decode}^{FEC}) \\ &\quad + (1 - p_{s,data}^{FEC}) T_{t/o}^{FEC}, \end{aligned} \tag{17}$$

where $T_{tx,data}^{FEC}$ is the data transmission time and is given by $l/r$, where $l$ is the total length of the transmitted *data* and is equal to $(L_{data} + L^{FEC})$, and $L^{FEC}$ is the length of the redundant bits added for error correction. $T_{code}^{FEC}$ and $T_{decode}^{FEC}$ refer to the latency caused by coding and decoding processes of the *data* respectively, given by $T_{code}^{FEC} = 2nT_{clk}$, and $T_{decode}^{FEC} = (k+1)nT_{clk}$ [16]. $p_{s,data}^{FEC}$ is the *data* packet success rate and can be obtained from (15). Finally, $T_{t/o}^{FEC}$ is given by:

$$T_{t/o}^{FEC} = 1.1(2T_{prop} + T_{decode}^{FEC}). \tag{18}$$

The function $E_{tx}^{\mathcal{E}}$ for FEC mode is defined as follows:

$$E_{tx}^{FEC} = E_{tx,data}^{FEC} + E_{code}^{FEC}, \tag{19}$$

where $E_{tx,data}^{FEC}$ refers to the energy required to transmit the data packet, given by $(l \cdot p_x^{\mathcal{E}} \cdot E_{tx}^{bit})$, and $E_{code}^{FEC}$ stands for the consumed energy caused by computational process of coding the *data* in transmitter, given by $n \cdot k(E_{load} + E_{hold})$, where $E_{load}$ and $E_{hold}$ are the energies consumed to load and hold a registry value in a shift register. The value of $E_{code}^{FEC}$ is defined based on the assumption that a Hamming code is exploited for the FEC which can be implemented by using shift registers as well as XOR and AND logic gates as described in [16].

### *D. Error Prevention Codes (EPC) Constraints*

Instead of correcting channel errors or just detecting them and asking for retransmissions *a posteriori*, the idea of preventing channel errors from occurring in advanced or *a priori*, has been recently proposed [15]. The idea comes from the fact that both the molecular absorption in the Terahertz Band and the multi-user interference in TS-OOK [14], are correlated to the transmitted signal. Therefore, by exploiting low weight codes, i.e., codewords with lower average number of logical "1"s, both the molecular absorption noise and the multi-user interference can be reduced, which effectively results in lower BERs. For the EPC, the *packet error rate* is given by [16]:

$$\psi^{\mathcal{E}} = 1 - (1 - BER^{EPC})^{nk}, \tag{20}$$

where $n$ is the number of blocks per data packet payload, and $k$ refers to the block size. Moreover, the *packet round-trip time* in EPC is defined as follows:

$$\begin{aligned} T_{tx}^{EPC} = T_{tx,data}^{EPC} + T_{code}^{EPC} + p_{s,data}^{EPC}(T_{prop} + T_{decode}^{EPC}) \\ + (1 - p_{s,data}^{EPC})T_{t/o}^{EPC}, \end{aligned} \tag{21}$$

where $T_{tx,data}^{EPC}$ is the data transmission time and is given by $l/r$, where $l$ is the total length of the transmitted *data* and is equal to $(L_{data} + L^{EPC})$, and $L^{EPC}$ is the length of the redundant bits added by error prevention codes. $T_{code}^{EPC}$ and $T_{decode}^{EPC}$ refer to latency caused by coding and decoding processes of the *data* respectively, given by $T_{code}^{EPC} = T_{decode}^{EPC} = 2nT_{clk}$ [16]. $p_{s,data}^{EPC}$ is the *data* packet success rate and can be obtained from (20). Finally, $T_{t/o}^{EPC}$ is given as follows:

$$T_{t/o}^{EPC} = 1.1(2T_{prop} + T_{decode}^{EPC}). \tag{22}$$

Eventually, the following equation describes the energy required to accomplish the transmission process $E_{tx}^{\mathcal{E}}$ in EPC:

$$E_{tx}^{EPC} = E_{tx,data}^{EPC} + E_{code}^{EPC}, \tag{23}$$

where $E_{tx,data}^{EPC}$ refers to the energy required to transmit the data packet, and is given by $(l \cdot p_x^{\mathcal{E}} \cdot E_{tx}^{bit})$, and $E_{code}^{EPC}$ stands for the consumed energy caused by computational process of coding the *data* in transmitter, and is given by $n \cdot (l_d + k)(E_{load} + E_{hold})$, where $l_d$ is the length of useful data bits in a transmitted block. Note that the value of $E_{code}^{EPC}$ is defined based on exploiting logic gates and parallel-load shift registers to implement the EPC as described in [16].

## III. PROBLEM SOLUTION APPROACH AND ALGORITHM

To solve the optimization problem **[P1]**, we start with the equality constraints (3), (4), and (5). As it is mentioned earlier in Sec. II-A, the *BER* does not depend on the optimization variable and the constraint (5) can be defined as a given parameter to our optimization problem. Moreover the equalities (3) and (4) can be merged with the objective function of **[P1]**. For the equality constraint (6) which contains the nonsmooth maximum function, we can also plug it in the objective function by defining $\eta = min\{\eta_1(L_{data}), \eta_2(L_{data})\}$, and using auxiliary functions $\eta_1(L_{data})$ and $\eta_2(L_{data})$ as follows:

$$\eta_1 = \frac{1}{r} \cdot \frac{L_{data}(1 - \psi^{\mathcal{E}})}{\theta^{\mathcal{E}}}, \quad \eta_2 = \frac{1}{r} \cdot \frac{L_{data}(1 - \psi^{\mathcal{E}})}{\tau^{\mathcal{E}}}. \tag{24}$$

Note that $\eta_1(L_{data})$ and $\eta_2(L_{data})$ only depend on $L_{data}$ as the optimization variable, and all other parameters are assumed to be given. Also the functions $\psi^{\mathcal{E}}$, $\theta^{\mathcal{E}}$, and $\tau^{\mathcal{E}}$ are all functions of $L_{data}$ which are defined in Sections II-B through II-D for different error-control techniques. Therefore, the following equivalent optimization problem can be defined:

**Optimization Problem [P2]**

$$\begin{aligned} Given: &\quad r, \psi^{\mathcal{E}}, \theta^{\mathcal{E}}, \tau^{\mathcal{E}} \\ Find: &\quad L_{data}^{*} \\ Minimize: &\quad -\eta = max\{-\eta_1(L_{data}), -\eta_2(L_{data})\} \\ Subject\ to: &\quad L_{data} > 0 \end{aligned}$$

Note that here we are using the standard minimization problem by changing the sign of the functions $\eta$, $\eta_1(L_{data})$ and $\eta_2(L_{data})$, and using $max$ function instead of $min$. It can be shown that **[P2]** is a Quasi-Convex optimization problem. More specifically, $-\eta_1(L_{data})$ and $-\eta_2(L_{data})$ are Quasi-Convex functions and since "nonnegative weighted maximum" function preserves Quasi-Convexity, therefore the objective function $-\eta(L_{data})$ is Quasi-Convex as well. Moreover, the inequality constraint (2) is a convex set, hence **[P2]** is a Quasi-Convex optimization problem. For solving this optimization problem we define the epigraph form of the problem and use a bisection method as follows:

**Epigraph form of Optimization Problem [P2]**

$$\begin{aligned} Given: &\quad r, \psi^{\mathcal{E}}, \theta^{\mathcal{E}}, \tau^{\mathcal{E}} \\ Find: &\quad L_{data}^{*} \\ Minimize: &\quad t \\ Subject\ to: &\quad -\eta(L_{data}) - t \leq 0 \\ &\quad -L_{data} < 0 \end{aligned}$$

Now, our quasi-convex optimization problem can be solved as a sequence of convex feasibility problems as follows:

$$\begin{aligned} Given: &\quad r, \psi^{\mathcal{E}}, \theta^{\mathcal{E}}, \tau^{\mathcal{E}} \\ Find: &\quad L_{data}^{*} \\ Subject\ to: &\quad -\eta(L_{data}) - t \leq 0 \\ &\quad -L_{data} < 0 \end{aligned} \tag{25}$$

The above feasibility problem is convex, since all its inequality constraints are convex. Now let us define $p^*$ as the optimal value of our optimization problem in **[P2]**. If the problem (25) is feasible, then $p^* \leq t$, and if it is not feasible, then $p^* \geq t$. Therefore by using a bisection method we can solve our quasi-convex optimization problem, by solving a convex feasibility problem in each iteration of the algorithm. For the bisection algorithm we have to determine a lower bound $l$ and an upper bound $u$ for the possible values of $p^*$. Since we are dealing with efficiency $(-\eta)$ as our objective function so we know that always $\eta \in [0, 1]$. Hence we can set the bounds to $l = -1$ and $u = 0$. However, it can be easily observed that $min(-\eta) \geq max\{min(\eta_1), min(\eta_2)\} \geq -1$, and since $\eta_1$ and $\eta_2$ are both quasi-convex, differentiable, and continuous, we can directly calculate the min value of them and use it for the lower bound as $l = max\{min(-\eta_1), min(-\eta_2)\}$ which results in less iterations.

## IV. NUMERICAL RESULTS AND PERFORMANCE EVALUATION

In this section we numerically study the performance of different error-control techniques, in terms of maximum link throughout achievable under the energy harvesting and transmission delay constraints.

In our analysis we use the following parameters. We consider that nanosensors communicate by using TS-OOK, hence every bit of logic “1” is transmitted as a pulse (which is modeled as the derivative of a one-hundred-femtosecond long Gaussian pulse) with energy of $E_{tx}^{bit} = 1$ aJ, and the logic “0” is transmitted as silence [14]. The propagation of the pulses is modeled by utilizing the THz-band channel model in [3]. Both TS-OOK and this model have been validated by means of extensive simulations with COMSOL Multi-physics. Due to the limited computational capability of nanomachines, only very simple error-control methods are utilized. For the ARQ, we use a 16-bit CRC for error correction with a 2 bytes long acknowledgement packet; a Hamming(15,11) code is assumed for the FEC; and, for EPC, a 16-bit low-weight code with codeword size of 19 bits is used (EPC type II [16]). The resulting probability to transmit a pulse $p_x^{\mathcal{E}}$ is 0.5 for ARQ and FEC, and 0.31 for EPC.

We further consider that the nanosensors communicate with a bit rate of $r = 100$ Gbps, and the the clock period to compute the latency caused by the CRC or coding and decoding processes is $T_{clk} = 1$ ps. We also consider the energy required to shift, hold, and load in a shift register as $E_{shift} = E_{hold} = E_{load} = 0.1$ aJ. The communication distance range is assumed to be $d = 1 - 100$ mm, and the energy harvesting rate ranges $\lambda_{harv} = 1 - 400$ nJ/s.

The link efficiency $\eta$ of the ARQ is shown in Fig. 1 as a function of packet size for a fixed distance and energy harvesting rate. $\eta_1^{ARQ}$ in this figure represents the link efficiency affected only by the transmission time, i.e., the nanotransmitter has enough energy to transmit and does not need time to harvest energy. In contrary $\eta_2^{ARQ}$, shows the link efficiency which is only affected by energy harvesting time consumption, i.e., the transmission time is always less than the time needed to harvest energy. Finally, $\eta^{ARQ}$ shows the trade-off between these two scenarios and shows the link efficiency considering both constraints. As shown in Fig. 1, as we increase the packet size, at some point, the energy harvesting time consumption becomes dominant and restricts the efficiency of the link.

In Fig. 2, the link efficiency $\eta$ of different error-control techniques is shown as a function of packet size for a fixed distance and energy harvesting rate. As it can be seen in this figure, EPC performs better than the other two techniques for very small packet sizes, and as we increase the packet size FEC outperforms EPC, while ARQ has the lowest efficiency.

Fig. 3 and Fig. 4 depict the optimal link efficiency and the optimal packet size respectively, for different error-control techniques as a function of distance for a fixed energy harvesting rate. It can be seen that for very short distances EPC outperforms the other two error-control methods, while transmitting smaller packets. However, FEC has a better performance for longer distances and uses bigger packets for transmission. The ARQ optimal packet size is in between the other two methods, and has the lowest link efficiency.

Finally, in Fig. 5, we show the optimal link efficiency for different error-control methods as a function of energy harvesting rate, for a fixed distance. This figure shows that FEC and EPC have better performance for low energy harvesting

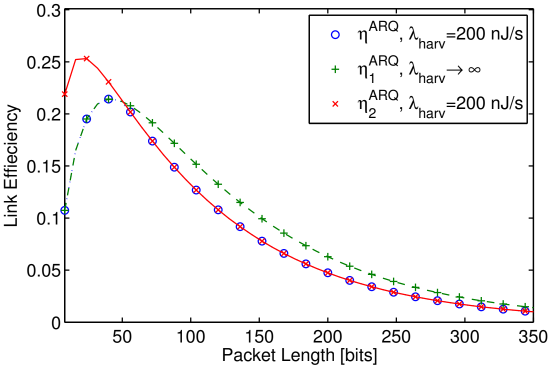

Fig. 1. Link efficiency for ARQ, when $d = 1$ cm.

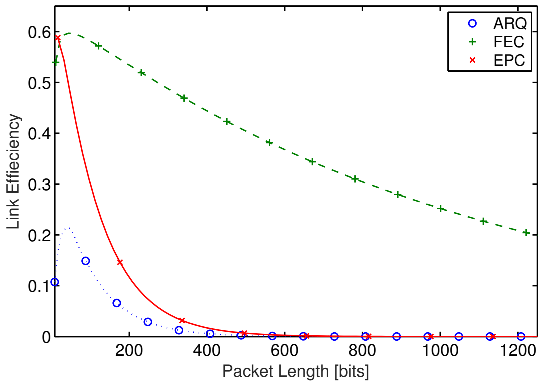

Fig. 2. Link efficiency for $d = 1$ cm and $\lambda_{harv} = 200$ nJ/s.

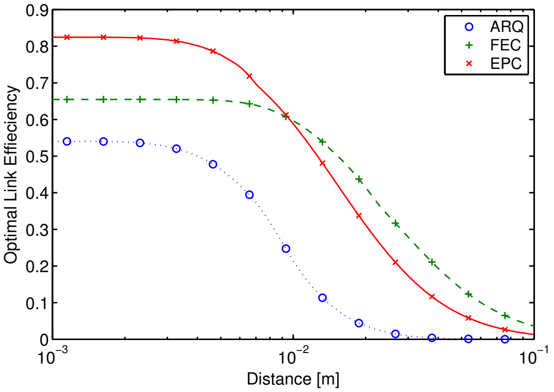

Fig. 3. Optimal link efficiency for $\lambda_{harv} = 200$ nJ/s, and $L_{data}^{max} = 16$ Kbits.

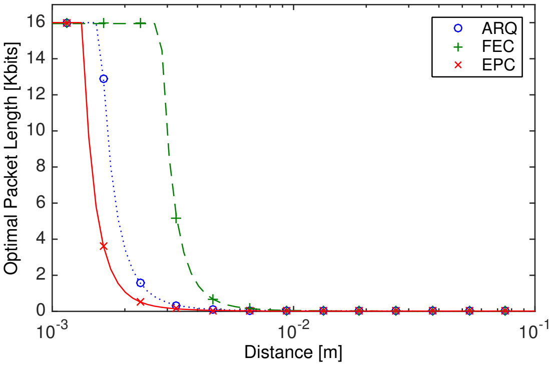

Fig. 4. Optimal packet size for $\lambda_{harv} = 200$ nJ/s, and $L_{data}^{max} = 16$ Kbits.

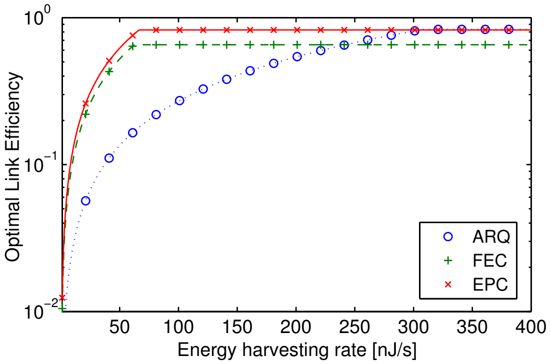

Fig. 5. Optimal link efficiency for $d = 1$ mm, and $L_{data}^{max} = 16$ Kbits.

rates, while ARQ outperforms the other two techniques when the nanomachine is capable to harvest energy at higher rates.

As the results show, the optimal packet size abruptly decreases with distance. Transmission of very small packets can cause message delivery delay and eventually leads to low link efficiency. A remedy to overcome the drawbacks caused by transmitting very small packets, is to utilize the concept of packet train, in which a train of packets are transmitted consecutively without releasing the channel [6]. For each packet train a single acknowledgment will be sent, which may contain either a cumulative acknowledgement for all packets in the train, or a request for retransmission of specific packets.

## V. CONCLUSIONS

In this paper, we have addressed the trade-off between the energy harvesting and data transmission process time to improve the link throughput efficiency in WNSNs. In particular, we have developed an optimization problem with the objective function of link throughput efficiency and the constraints that cover the latency caused by both the energy harvesting and data transmission process, while considering the peculiarities of nanosensors. The optimal packet size which maximizes the link throughput in WNSNs has been analyzed for three different error-control techniques, which included ARQ using a 16-bit CRC, FEC based on Hamming(15,11) codes for error correction, and EPC with a 16-bit low-weight code. The analysis has captured the peculiarities of THz band, as well as nano-devices and their capabilities of harvesting energy and data transmission. The results show that EPC outperforms the other two techniques in terms of link throughput efficiency in short range communications as well as low energy harvesting rates. Also, we have shown that in case of higher energy harvesting rates ARQ provides a higher link throughput than FEC and EPC in similar conditions. For each error control strategy, the optimal packet size has been obtained. It has been shown that this quickly decreases with distance, and the transmission of very short frames, just hundreds of bits long, becomes necessary to maximize the link utilization for distances beyond a few millimeters. These results provide the design requirements in terms of special computation and energy harvesting capabilities needed for nanomachines that will be exploited for different applications.

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