Dynamic Power Allocation for Nano-Communication Networks in the Terahertz Band

Li Feng, Qinghai Yang and Kyung Sup Kwak

***Abstract*—Nano-communication networks operating in the Terahertz band are developing fast owing to the high bandwidth range. In this paper, we propose a dynamic power allocation scheme for data transmission in the nano-communication networks. Based on the time-varying energy resource of nano-node for the network, we develop a stochastic optimization model to maximize the average channel capacity. The problem of stochastic optimization is solved via the Lyapunov optimization theory, and a novel capacity-optimal power allocation (CoPA) algorithm is proposed to accommodate the nano-communication network only according to the current energy resource information of nano-nodes. Simulation results validate the theoretical analysis of our proposed scheme.**

***Key words*: Nano-communication networks, Lyapunov control, dynamic power allocation**

I. Introduction

Thanks to the advancement of nanotechnology, nano-communication networks in the THz band are excepted to bring a wide range of applications, such as bio-medical system, environmental research and military field [1]. The terahertz band, which spans from 1 THz to 10 THz, can be theoretically able to support extremely high bandwidth (in the order of Tbps). Unfortunately, because of the molecular absorption, many constraints emerging within the channel limit the implementation of THz band. One of the constraints is frequency selective path loss and noise, which may lead to the fluctuations of channel capacity [2]. Besides the frequency selective feature of the channel, nano-communication networks are characterized by nano-nodes with limited energy capacity and compute resources owing to their physical dimensions. The nano-nodes consume their energy resource after a serious of forwarding and receiving actions. To ensure the continuous availability, the nano-nodes can harvest the energy from the environment. Therefore, it is necessary to propose a novel capacity-optimal power allocation scheme by jointly considering energy harvesting and consumption processes of nano-nodes for the nano-communication networks in the THz band.

Extensive researches have devoted to execute the power allocation to improve the network capacity. However, there are several limitations in the existing solutions (e.g. the size, energy consumption and so on), which can not be directly applied in the nano-communication networks. When it comes to nano-scale scene, a optimal power allocation was developed in [3] to improve the channel capacity, while the power allocation patterns for the Terahertz Band were proposed in [4] to maximize the channel capacity. Although both of them give some channel models and power allocation methods, they ignore the nano-node's dynamic energy resource owing to the energy harvesting and consumption. Considering the variation of nano-node's available energy resource, the energy-harvesting aware routing protocol was given in [5] to ensure the data transmission. However, it does not consider the future network performance.

In this paper, we investigate the dynamic power allocation for nano-communication networks in the Terahertz band. By jointly considering the energy harvesting and consumption processes of nano-nodes, a stochastic optimization model is developed to maximize the average network capacity. Based on the Lyapunov optimization theory, a novel capacity-optimal power allocation (CoPA) algorithm is proposed to solve the optimization problem, which only requires the current energy resource information of nano-nodes.

II. System Model

A. Network Model

We consider a nano-communication network, in which there are K nano-nodes with potential energy harvesting ability. The nano-nodes are assumed distributed using a normal random distribution through the medium (e.g. a percentage of water molecules). We assume that the time horizon is slotted into the discrete time intervals indexed by t, $t = \{0, 1, 2, \cdots\}$. At a specific timeslot, each nano-node can monitor the environment around and transmit the sensed data packets to the sink over a single hop. Note that, the nano-nodes' energy resources vary with their energy harvesting and consumption processes. The timeslot duration is greater than the amount of time for completing a data transmission, but not so long that nano-nodes' energy resources change significantly. Due to their very small form factor, these nano-nodes $\mathcal{K}$ will be operating in the terahertz band. The transmission bandwidth for the THz band is divided into K narrow frequencies with equal width, and nano-node i, $i \in \mathcal{K}$, transmits its radio signal at discrete frequency f_i.

Data transmission in the THz band communication may incur significant path loss due to the molecular absorption. We assume that the temperature and pressure values of the environment are constant and normalized. Then, the path loss of THz band $A_T^i(t, f_i, d_i)$ for nano-node i is jointly influenced by the free space loss $A_S^i(f_i, d_i)$ and the molecular absorption loss $A_T^i(t, f_i, d_i)$. The specific expression is as follows,

$$\begin{aligned} A_T^i(t, f_i, d_i) &= A_S^i(f_i, d_i) \cdot A_{abs}^i(f_i, d_i) \qquad (1) \\ &= (\frac{4\pi d_i f_i}{c})^2 \cdot e^{K_{t,f_i,d_i}^i}, \end{aligned}$$

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where c is the speed of light, f_i is the frequency of nano-node i, d_i is the transmission distance between nano-node i and sink, K^i_{t,f_i,d_i} is the molecular absorption coefficient. From Eq. (1) above, we can see that the total path loss $A^i_T(t, f_i, d_i)$ is a function of THz frequency, and that the frequency selective feature is dominant for transmission involving longer distances d_i. The noise in the THz band is mainly primarily due to molecular absorption noise. The power spectral density of $N^i_{abs}(t, f_i, d_i)$ for nano-node i is given by $N^i_{abs}(t, f_i, d_i) = k_B T_0(1 - e^{-K^i_{t,f_i,d_i}})$, where k_B is the boltzmann constant and T_0 is the reference temperature 296K. Let $S^i(t, f_i)$ be the power spectral density of the transmitted radio signal at timeslot t and frequency f_i. Then, the signal-to-noise ratio (SNR) of nano-node i at timeslot t, frequency f_i and distance d_i is

$$\begin{aligned} SNR^i(t, f_i, d_i) &= \frac{S^i(t, f_i)}{A^i_T(t, f_i, d_i) N^i_{abs}(t, f_i, d_i)} \\ &= \frac{S^i(t, f_i)}{(\frac{4\pi d_i f_i}{c})^2 \cdot k_B T_0 (e^{K^i_{t,f_i,d_i}} - 1)}. \end{aligned} \quad (2)$$

B. Energy Consumption and Supply Model for Nano-nodes

Generally, nano-nodes should count for the processing and communication capabilities. Hence, the joint knowledge of energy requirements and energy harvesting mechanisms available at the nano-scale is highly important for the design of optimized architectures. Let $E^i_{Tr}(t)$, $E^i_r(t)$ be the energy required to transmit and receive a packet of x bits, respectively. Motivated by [6], the energy required to handle its transmission and reception are given by: $E_{Tr}(t) = xS^i(t, f_i)$ and $E^i_r(t) = \frac{E^i_t(t)}{10}$. Then, based on the assumption that the nano-node transmits and receives ρ packets within a timeslot, the total energy consumption $P^{Total,t}_i$ of nano-node i at timeslot t is

$$P^{Total,t}_i = E^i_r(t) + E^i_{Tr}(t) = 1.1 S^i(t, f_i) x\rho. \quad (3)$$

Conventional energy harvesting mechanisms, e.g., solar energy, wind power, or underwater turbulences, cannot be applied in this paper because of the technological limitations, but novel schemes should be adopted for providing energy to nano-machines. An accurate model describing the energy harvesting rate of piezoelectric nanogenerators has been already developed in [4]. Then, the amount of accumulated energy $E^t_{cap^i}(n^t_c)$ for nano-node i is instead expressed as,

$$E^t_{cap^i}(n^t_c) = \frac{1}{2} C^i_{cap} (V^t_{cap^i}(n^t_c))^2, \quad (4)$$

where n^t_c is the amount of compress-release cycles, $V^t_{cap^i}(n^t_c)$ is the voltage of the charging capacitor and C^i_{cap} is the capacitance of the nano-node at timeslot t. Then, the availiable energy resource of nano-node i at timeslot $t+1$ is

$$\begin{aligned} E_i(t+1) &= E_i(t) + E^t_{cap^i}(n^t_c) - P^{Total,t}_n \quad (5) \\ &= E_i(t) + \frac{1}{2} C^i_{cap} (V^t_{cap^i}(n^t_c))^2 - 1.1 x\rho S^i(t, f_i). \end{aligned}$$

At any timeslot t, the total energy consumption at nano-node i must satisfy the following energy-availability constraint,

$$E_i(t) \geq P^{Total,t}_i, \forall i \in \mathcal{K}. \quad (6)$$

We assume that each nano-node is equipped with a battery having the limited capacity $\mathcal{E}^{max}_i$. At any timeslot t, the total energy stored in battery is limited by the battery capacity, thus the following inequality must be satisfied

$$E_i(t) + \frac{1}{2} C^i_{cap} (V^t_{cap^i}(n^t_c))^2 \leq \mathcal{E}^{max}_i, \forall i \in \mathcal{K}. \quad (7)$$

III. Problem Formulation

It is shown that the THz channel capacity can be expressed as a summation of the capacity of each narrow sub-channel, and the capacity for each narrow sub-channel is given by Shannon's channel capacity. Then, the THz channel capacity at timeslot t is given by

$$\begin{aligned} C_{THz}(\mathbf{S}^t) &= \sum_{i=1}^{K} B_i \log_2(1 + SNR^i(t, f_i, d_i)), \quad (8) \\ &= \sum_{i=1}^{K} B_i \log_2(1 + \frac{S^i(t, f_i)}{(\frac{4\pi d_i f_i}{c})^2 \cdot k_B T_0 (e^{K^i_{t,f_i,d_i}} - 1)}), \end{aligned}$$

where $\mathbf{S}^t = \{S^i(t, f_i)\}_{i \in \mathcal{K}}$ and $\log_2$ is the binary logarithm. The objective in this paper is to maximize the average channel capacity under the energy constraints. Then, we have the following problem.

$$\max \quad \overline{C} = \lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} \mathbb{E}[C_{THz}(\mathbf{S}^t)] \quad (9)$$

$$\text{s.t.} \quad 0 \leq \sum_i S_i(t, f_i) \leq \mathcal{S}, \forall t \geq 0, i \in \mathcal{K}, \quad \text{(C1)}$$

$$E_i(t) \geq P^{Total,t}_i, \forall t \geq 0, i \in \mathcal{K}, \quad \text{(C2)}$$

$$E_i(t) + \frac{1}{2} C^i_{cap} (V^t_{cap^i}(n^t_c))^2 \leq \mathcal{E}^{max}_i, \forall i \in \mathcal{K}, \quad \text{(C3)}$$

where (C1) is the total energy constraint and $\mathcal{S}$ is the maximum transmit constraint. (C2) is the energy consumption constraint. (C3) is the energy budget constraint.

Eq.(9) can be viewed as a stochastic programming. The solution is to propose a dynamic power allocation algorithm, such that all of the constraints are satisfied and the utility to be maximized as high as possible. In the following section, we will develop a novel dynamic power allocation algorithm, which pushes the average channel capacity to the optimal solution of Eq.(9).

IV. Dynamic Power Allocation

A. Lyapunov optimization

To solve the problem, we propose a virtual energy queue to describe the dynamics of nano-node's energy resource, by regarding the energy consumption over time as the queue's departure process and the energy harvesting as the queue's arrival process. For simplicity, the virtual energy queue of nano-node i is denoted as E^t_i in this paper. Based on the definition of virtual energy queue E^t_i, we can obtain that E^t_i is equal to $E_i(t)$ in Eq. (5). By controlling the arrival and departure processes of the virtual energy queues appropriately via Lyapunov *drift-plus-penalty* method [7], we can maximize the average channel capacity under the energy constraints.

Let $\mathbf{\Theta}^t$ denote the matrix containing the energy queues $\{E_i^t\}_{i\in\mathcal{K}}$. We define the quadratic Lyapunov function at timeslot t as

$$L(\mathbf{\Theta}^t) = \frac{1}{2}\sum_i [-\tilde{E}_i^t]^2, \tag{10}$$

where $\tilde{E}_i^t = \mathcal{E}_i^{max} - E_i^t \geq 0$. The conditional expected Lyapunov drift at timeslot t is defined by

$$\Delta(\mathbf{\Theta}^t) :\triangleq \mathbb{E}[L(\mathbf{\Theta}^{t+1})|\mathbf{\Theta}^t] - \mathbb{E}[L(\mathbf{\Theta}^t)], \tag{11}$$

where the expectation is taken over the randomness of departure and arrival processes of the energy queues.

Following from the Lyapunov optimization framework, we add the penalty term $-V\mathbb{E}[C_{THz}(\mathbf{S}^t)|\mathbf{\Theta}^t]$ to Eq. (11) to obtain the following *drift-plus-penalty* term,

$$\Delta_V(\mathbf{\Theta}^t) = \Delta(\mathbf{\Theta}^t) - V\mathbb{E}[C_{THz}(\mathbf{S}^t)|\mathbf{\Theta}^t]. \tag{12}$$

Here $V > 0$ is a control parameter. Then, we have the following theorem regarding the *drift-plus-penalty* term.

Theorem 1. *For any feasible power allocation decision that can be implemented at timeslot t, we have*

$$\Delta_V(\mathbf{\Theta}^t) \leq \Xi - V\mathbb{E}[C_{THz}(\mathbf{S}^t)|\mathbf{\Theta}^t] + \sum_i 1.1x\rho\tilde{E}_i^t S^i(t,f_i), \tag{13}$$

where Ξ is an upper bound on the term $\Sigma_i \frac{1}{8}[C_{cap}^i(V_{cap^i}^t(n_c^t))^2]^2(\tilde{E}_i^t)^2$.

Proof: Omit due to the limited space. ∎

Our dynamic power allocation policy is designed to observe the energy queue $\mathbf{E}^t = \{E_i^t, i \in \mathcal{K}\}$, and as well to make power allocation decisions $\mathbf{S}^t$ for minimizing the right-hand-side (RHS) of Eq. (13) for the current time. That is,

$$\max V\mathbb{E}[C_{THz}(\mathbf{S}^t)|\mathbf{\Theta}^t] - \sum_i 1.1x\rho\tilde{E}_i^t S^i(t,f_i). \tag{14}$$

From above, Eq. (9) is translated into a series of optimization problems for each timeslot.

B. Adaptive Power Control for Nano-Nodes

From above, the power allocation problem for nano-node i at timeslot t can be rewritten as

$$\max \left\{ \begin{array}{c} V\sum_i [B_i \log_2(1 + \frac{S^i(t,f_i)}{(\frac{4\pi d_i f_i}{c})^2 k_B T_0 (e^{K_{t,f_i,d_i}^i} - 1)}) \\ -1.1x\tilde{E}_i^t S^i(t,f_i)] \end{array} \right\}$$
$$\text{s.t.} \quad 0 \leq \sum_i S^i(t,f_i) \leq \mathcal{S}, \forall t \geq 0, i \in \mathcal{K}. \tag{15}$$

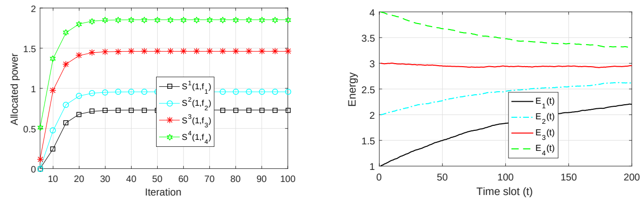
The equation above are the concave optimization problems, which can be solved efficiently by the gradient descent method [8]. Then, we can obtain the optimal power allocation for nano-node i at timeslot t as

$$\begin{cases} S^i(t,f_i) = 0, \quad \text{if } (\frac{4\pi d_i f_i}{c})^2 k_B T_0 (e^{K_{t,f_i,d_i}^i} - 1) \geq \mathcal{S}, \\ S^i(t,f_i) + (\frac{4\pi d_i f_i}{c})^2 k_B T_0 (e^{K_{t,f_i,d_i}^i} - 1) = \chi_i^t, \quad \text{otherwise}, \end{cases} \tag{16}$$

where $\chi_i^t = \frac{B_i V}{(1.1x\rho\tilde{E}_i^t + \nu^t)\ln 2}$ and ν^t is the optimal Lagrangian multiplier at timeslot t. Then, the capacity-optimal power allocation (CoPA) algorithm is given by **Algorithm 1**.

Algorithm 1 Capacity-optimal power allocation (CoPA)

Each time-slot t
for iteration index $k = 1:100$ **do**
  for each nano-node $i \in \mathcal{K}$ **do**
    if $(\frac{4\pi d_i f_i}{c})^2 \cdot k_B T_0 (e^{K_{t,f_i,d_i}^i} - 1) < \mathcal{S}$ **then**
      $S^i(t,f_i) = \chi_i^t - (\frac{4\pi d_i f_i}{c})^2 k_B T_0 (e^{K_{t,f_i,d_i}^i} - 1)$.
    else
      $S^i(t,f_i) = 0$.
    end if
  end for
  $\nu^t(k+1) = \left[\nu^t(k) - \sigma\left(\sum_i S^i(t,f_i) - \mathcal{S}\right)\right]^+$;
end for



(a) Power allocation within a timeslot (b) Energy resource verse the timeslot.
Fig. 1 Power allocation and energy resource

V. Simulation Results

In this section, we present the simulation results to illustrate the performance for our algorithm. Fig. 1.(a) exhibits the power allocation within a timeslot for nano-nodes while Fig. 1(b) plots the dynamic energy resource over time. From the figures, we observe that the proposed CoPA algorithm can obtain the optimal power allocation for a specific timeslot and contribute to the energy balance among nano-nodes.

VI. Conclusions

In this paper, we developed a stochastic optimization model to maximize the average network capacity based on the dynamic energy resources of nano-nodes in nano-communication networks. Then, a novel CoPA algorithm was proposed to solve the optimization problem via the Lyapunov optimization theory.

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