Optimal Resource Allocations for Statistical QoS Provisioning to Support mURLLC Over FBC-EH-Based 6G THz Wireless Nano-Networks

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***Abstract*— One of most important techniques for enabling the sixth-generation (6G) mobile wireless network lies in how to efficiently guarantee various stringent quality-of-service (QoS) performance-metrics to support the emerging massive Ultra-Reliable Low-Latency Communications (mURLLC) in 6G. Correspondingly, finite blocklength coding (FBC) has been developed as an effective technique to significantly improve various QoS indices for mURLLC through implementing short-packet communications. On the other hand, Terahertz (THz) band wireless nano-communications have been widely envisioned as a promising 6G technique to efficiently support ultra-high data-rate (up to 1 Tbps). One of the major constraints over THz-band nano-networks is the severely limited energy that can be accessed by nano devices. Towards this end, various novel energy harvesting (EH) mechanisms have been proposed to remedy the energy scarcity problem. However, how to accurately characterize the relationships among THz wireless channels, energy consumption, and EH models for FBC based nano communications remains a challenging problem to support statistical delay and error-rate bounded QoS provisioning over FBC based 6G THz wireless nano-networks. To overcome these challenges, in this paper we propose optimal resource allocation policies to achieve the maximum ϵ-effective capacity in the THz band over FBC-EH-based nano-networks. Particularly, we establish nano-scale system models and characterize wireless channel models in the THz band using FBC. In order to support statistical delay and error-rate bounded QoS provisioning, we formulate and solve the ϵ-effective capacity maximization problem under several different EH constraints for our proposed schemes. Simulation results are included, which validate and evaluate our proposed schemes in the finite blocklength regime.**

***Index Terms*— Statistical delay and error-rate bounded QoS, THz band, mutual information, FBC, EH, joint resource allocation, ϵ-effective capacity, 6G wireless nano-networks.**

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I. Introduction

WHILE 5G is being deployed around the world, the efforts and initiatives from academia, industry, and standard bodies have started to look beyond 5G, conceptualize 6G mobile wireless networks, and propose various promising 6G techniques to support very stringent quality-of-service (QoS) requirements [1]–[8] for wireless networks, including ultra-high data-rate ($\approx$1 Tbps), bounded end-to-end delay ($<$ 1 ms), super-reliability ($>$ 99.99999%), extra-high energy efficiency, etc. [9]–[11]. Correspondingly, 6G defines a new and important service class of *massive Ultra-Reliable Low-Latency Communications* (mURLLC) to quantitatively design and evaluate its QoS performances [12]. In this context, Terahertz (0.1–10 THz) band communications and wireless networks have been widely envisioned as the promising 6G wireless techniques to efficiently support the QoS requirements of mURLLC. This is because THz wireless networks with nano-architectures can alleviate spectrum scarcity and feasibly achieve ultra-high data-rates of up to 1 Tbps, while taking into account constraints of scalability, dimension, topology, processing-power, storage, energy capacities, etc.

Inspired by the new service class mURLLC, finite blocklength coding (FBC) has been proposed [13]–[16] to support both latency and reliability requirements for time-sensitive wireless services by using short-packet data communications. The authors of [13] have shown that the codeword blocklength can be as short as 100 channel symbols for reliable communications, which significantly reduce the latency while efficiently upper-bounding the error rate. The authors of [17] have studied different properties of channel codes that approach the fundamental limits of a given memoryless wireless channel in the finite blocklength regime. The maximum achievable coding rate using FBC over additive white Gaussian noise (AWGN) channels has been derived in [18].

On the other hand, the limited available bandwidth for communication systems in the microwave frequency range motivates the exploration of higher frequency bands in supporting statistical delay-bounded QoS provisioning. Towards this end, researchers have proposed millimeter wave (mmWave) communication systems. Despite the much higher operating frequency, the available bandwidth is less than 10 GHz, which requires communication systems to achieve a *spectral efficiency* on the order of 100 bits/second/Hz for supporting 1 Terabit-per-second (Tbps) for 6G wireless networks [19], [20]. However, this is several times above the state-of-the-art for wireless communication systems. To satisfy the increasing demand for higher-speed of current wireless systems, THz band communication techniques [21], [22] have been proposed to provide an unprecedentedly large bandwidth, ranging from several tens of GHz up to a few THz, while satisfying the increasing demand of 100 Gbps and even 1 Tbps data rates [23]. However, the large pathloss and molecular noise introduced by THz wireless systems may produce transmission errors during the data transmissions, resulting in distorted multimedia signals received. Therefore, it is desirable to apply FBC technique for short-packet data transmissions to support time-sensitive wireless services while statistically guaranteeing both delay and error-rate bounded QoS provisioning in the THz band. Previous works have presented a holistic vision of 6G systems for 6G-driven applications, performance metrics, and new service classes such as THz, mURLLC, QoS metrics, etc. [9]. However, previous works mainly focus on analyzing specific QoS requirements, while the statistical QoS provisioning based THz-band communications in supporting mURLLC have neither been well understood nor thoroughly studied.

Motivated by the potential of THz technologies, researchers have focused on leveraging the advantages of nanomaterials, such as graphene [24]–[27], to integrate THz communication systems into a set of applications. There have been a limited number of studies of channel characterization for THz-band nano-communication systems, which incorporate molecular absorption, spreading loss, and shadowing into a theoretical THz channel model [28], [29]. The authors of [30] have reviewed the current state-of-the-art technologies and applicability of nano communication in biomedical application. The authors of [31] have shown that the large bandwidth in the THz band is susceptible to shadowing and noise. The joint effects of path loss and shadowing for THz wireless channels have been studied in [32]. The channel modeling of the THz wave propagating and the corresponding channel capacity modeling with different power allocation schemes for electromagnetic communications have been studied in [33]. The channel capacity in the THz band is numerically evaluated by using a new THz-band propagation model with different channel molecular compositions and under different power allocation schemes in [34].

Furthermore, one of the major constraints of wireless nano-networks is the severely limited energy that can be accessed by nano devices. As a result, researchers have investigated energy harvesting (EH) techniques over THz band wireless nano-networks. However, the conventional EH techniques, such as solar and wind power, cannot be utilized in wireless nano-networks due to technology limitations. Novel nano-scale EH techniques have been investigated to harvest energy from various resources, such as vibration and blood sugar, to address the energy scarcity problem for nano devices. The authors of [35] have conducted detailed studies of EH techniques, energy sources, storage technologies, and examples of applications and network deployments for EH based nano sensors. Optimal energy management policies for EH based sensor nodes have been proposed in [36]. Although there are some studies of EH and energy consumption models

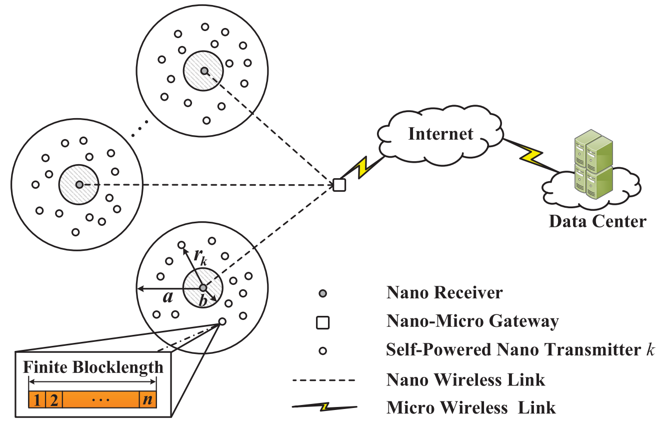

Fig. 1. The system architecture model for our proposed FBC-EH-based wireless nano-networks in the THz band, where a is the radius of the THz-band covered region, b is the radius of the blind area, and n is the codeword blocklength used in FBC.

for nano-scale communications, how to accurately model and characterize the relationships among THz-band wireless channel, energy consumption, and EH models employing FBC based nano-communication still remains a major challenge in the THz band while supporting both delay and error-rate bounded QoS provisioning.

To effectively overcome the above-mentioned challenges, in this paper we develop FBC-EH based optimal resource allocation policies for *self-powered* nano devices in the THz band over wireless nano-networks under statistical delay and error-rate bounded QoS constraints. Particularly, we establish THz-band wireless communications model, EH model, and FBC based channel-coding model. Then, we analyze the interference, channel capacity, and channel dispersion functions in the THz band using FBC. Considering statistical delay and error-rate bounded QoS provisioning, we formulate and solve the ϵ-effective capacity maximization problem for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks. Simulations are conducted, which evaluate and validate our proposed schemes in the THz band over FBC-EH-based wireless nano-networks.

The rest of this paper is organized as follows: Section II establishes THz-band nano communication system models. Section III characterizes the interference, channel capacity, and channel dispersion in the THz band using FBC. Section IV formulates and solves the ϵ-effective capacity maximization problem under statistical delay and error-rate bounded QoS provisioning in the finite blocklength regime in the THz band. Section V evaluates the system performance for our proposed schemes in the THz band in the finite blocklength regime. The paper concludes with Section VI.

II. The System Models

Fig. 1 shows the system architecture model for our proposed FBC-EH-based wireless nano-networks in the THz band, where for each THz-band covered region in a circled area, a is the radius of the THz-band covered region and b is the radius of a very small blind area ($b \ll a$), and there is one nano receiver and $(K+1)$ self-powered nano transmitters, without the use of nano-batteries, randomly distributed within the THz-band covered region, which follows a spatial Poisson process with an arrival-rate intensity equal to λ nodes/cm^2 [37]. Consider the THz-band covered region, denoted by $A(a) \subseteq \mathbb{R}^2$, with radius a. Without loss of generality, we consider that the nano receiver is located at the center of the THz-band covered region $A(a)$. We can derive the probability of finding $(K+1)$ nano transmitters in the THz-band covered region $A(a)$ as follows:

$$\Pr\{(K+1) \text{ nano transmitters in } A(a)\} = \frac{[\lambda \|A(a)\|_\phi]^{(K+1)}}{(K+1)!} \exp\left[-\lambda \|A(a)\|_\phi\right] \quad (1)$$

where $\|A(a)\|_\phi$ denotes the area of the THz-band covered region $A(a)$. Denote by r_k $(k = 1, \ldots, (K+1))$ the transmission distance from the self-powered nano transmitter k, as shown in Fig. 1, to its assigned nano receiver within the THz-band covered region, which is a random variable. Then, we can formulate the probability density function (PDF) of the distribution of transmission distance r_k, denoted by $f_D(r_k)$, from the nano transmitter k to its nano receiver of interest within the THz-band covered region as follows [38]:

$$f_D(r_k) = \begin{cases} \frac{2r_k}{a^2-b^2}, & \text{for } b < r_k < a; \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

A. THz-Band Channel Model

1) Path Loss Model: In our proposed THz-band channel model, both the spreading loss and shadow fading characteristics of the transmission medium are considered as the main sources of signal attenuation. In the THz band, the path-loss is mainly characterized by the spreading loss and the molecular absorption loss [33]. The total path loss, denoted by $H_k(f, r_k)$, in the THz band for nano device k can be derived as follows [33]:

$$H_k(f, r_k) = H_{k,\text{spread}}(f, r_k) H_{k,\text{abs}}(r_k) \quad (3)$$

where $H_{k,\text{spread}}(f, r_k)$ and $H_{k,\text{abs}}(r_k)$ represent the spreading loss and molecular absorption attenuation, respectively, at transmission distance r_k and operating frequency f, which are defined as follows:

$$\begin{cases} H_{k,\text{spread}}(f, r_k) = \frac{c}{4\pi f r_k}; \\ H_{k,\text{abs}}(r_k) = \exp\left(-\frac{\alpha_{\text{abs}} r_k}{2}\right), \end{cases} \quad (4)$$

where c is the speed of light in free space and α_{abs} is the medium absorption coefficient, which depends on the molecular composition in the channel along the transmission path. Then, we can derive the received power, denoted by $\mathcal{P}_{\text{pathloss,r}}(r_k)$, at the nano receiver with the transmission distance r_k due to pathloss as follows:

$$\mathcal{P}_{\text{pathloss,r}}(r_k) = S(f) \left(\frac{c}{4\pi f r_k}\right)^2 e^{-\alpha_{\text{abs}} r_k} \quad (5)$$

where $S(f)$ is the power spectral density of the transmitted pulse. In addition, we can derive the received power, denoted by $\mathcal{P}_{\text{shadow,r}}(r_k)$, from nano transmitter k to its nano receiver with the transmission distance r_k due to shadowing as follows [39]:

$$\mathcal{P}_{\text{shadow,r}}(r_k) = (r_k)^{-\eta} G 10^{\frac{\xi_k}{10}} \quad (6)$$

where G denotes the channel gain constant, η is the path loss exponent, ξ_k is a random variable which represents the shadow fading characteristics of the transmission medium. Note that the parameters of the path-loss and shadowing models can be extracted based on empirical measurements or Monte Carlo simulations. According to the Central Limit Theorem, the shadow fading variable ξ_k can be considered as a normal distributed random variable with zero mean and standard deviation σ, i.e., $\xi_k \sim \mathcal{N}(0, \sigma^2)$. Then, we can derive the total received power, denoted by $\mathcal{P}_{\text{total}}(r_k)$, at the nano receiver across the transmission distance r_k from the nano transmitter k as follows:

$$\mathcal{P}_{\text{total}}(r_k) = (r_k)^{-\eta} G 10^{\frac{\xi_k}{10}} S(f) \left(\frac{c}{4\pi f r_k}\right)^2 e^{-\alpha_{\text{abs}} r_k}. \quad (7)$$

2) Noise Model: The noise in the THz band is mainly contributed by the molecular absorption noise, which is caused by vibrating molecules [33], [40]. The total power of the molecular absorption noise, denoted by $N_k(r_k)$, in the THz band is composed of the background noise, denoted by N_b, and the self-induced noise, denoted by $N_{k,s}(r_k)$, which is given as follows [41]:

$$N_k(r_k) = N_b + N_{k,s}(r_k) \quad (8)$$

where

$$\begin{cases} N_b = B(T_0, f) \left(\frac{c}{\sqrt{4\pi} f_0}\right)^2; \\ N_{k,s}(r_k) = S(f)\left(1 - e^{-\alpha_{\text{abs}} r_k}\right) \left(\frac{c}{4\pi f r_k}\right)^2, \end{cases} \quad (9)$$

where T_0 is the reference temperature of the medium, f_0 is the design centre frequency, and $B(T_0, f)$ is the Planck's function, which is given by [42]

$$B(T_0, f) = \frac{2h\pi f^3}{c^2} \left(e^{\frac{hf}{k_B T_0}} - 1\right)^{-1} \quad (10)$$

where k_B is the Boltzmann's constant and h is the Planck constant. We can observe from Eq. (9) that the background noise N_b depends on the temperature and composition of the medium. On the other hand, the self-induced noise $N_{k,s}(r_k)$ depends on the transmitted signal.

We define $\boldsymbol{x}_k^n \triangleq \left[x_k^{(1)}, \ldots, x_k^{(n)}\right]$ as the transmit signal vector from nano transmitter k, where n is the codeword blocklength. The transmit signal vector $\boldsymbol{x}_k^n$ is chosen randomly according to $\mathcal{N}(0, \overline{\mathcal{P}})$ with the following average power constraint:

$$\|\boldsymbol{x}_k^n\|^2 \leq \sqrt{n\overline{\mathcal{P}}} \quad (11)$$

where $\|\cdot\|^2$ denotes the Euclidean norm and $\overline{\mathcal{P}}$ is the average transmit power for the nano device. Define $\boldsymbol{y}_k^n \triangleq \left[y_k^{(1)}, \ldots, y_k^{(n)}\right]$ as the receive signal vector. Accordingly,

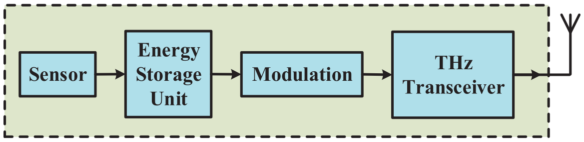

Fig. 2. The piezoelectric nanogenerator model in the THz band.

we can derive the received signal, denoted by $\boldsymbol{y}_k^n$, for transmitting n data blocks from nano transmitter k to its nano receiver in the THz band in the finite blocklength regime as follows:

$$\boldsymbol{y}_k^n = \sqrt{\mathcal{P}_{\text{total}}(r_k)}\boldsymbol{x}_k^n + \sum_{i=1, i\neq k}^{K+1} \sqrt{\mathcal{P}_{\text{total}}(r_i)}\boldsymbol{x}_i^n + \boldsymbol{n}_k \quad (12)$$

where $\mathcal{P}_{\text{total}}(r_k)$ and $\mathcal{P}_{\text{total}}(r_i)$ are the received signal powers at the nano receiver across the transmission distances r_k and r_i from nano transmitters k and i, respectively, as specified by Eq. (7), $\boldsymbol{x}_k^n$ and $\boldsymbol{x}_i^n$ represent the transmitted signal from nano transmitter k and i, respectively, r_i is the transmission distance from the nano transmitter i to its assigned nano receiver, and $\boldsymbol{n}_k$ denotes the absorption noise with power given by Eq. (8).

B. EH Model for Piezoelectric Nanogenerators

Recently, researchers have developed the piezoelectric nanogenerators [43], [44] for converting mechanical energy into electrical energy, as shown in Fig. 2. Due to the low energy consumption of nano devices over a short distance in the THz band, the energy harvested from the environment should be sufficient to power the nano devices. Without loss of generality, we assume that all harvested energy can be stored in the nanocapacitor. We can derive the stored energy, denoted by E_{cap}, in the nanocapacitor after a number of cycles, denoted by n_{cyc}, as follows [45]:

$$E_{\text{cap}}(n_{\text{cyc}}) = \frac{1}{2}C_{\text{cap}}\left[V_{\text{cap}}(n_{\text{cyc}})\right]^2 \quad (13)$$

where C_{cap} and $V_{\text{cap}}(n_{\text{cyc}})$ are the total capacitance and voltage function of the nano-capacitor, respectively. Then, the voltage function $V_{\text{cap}}(n_{\text{cyc}})$ of the charging nanocapacitor can be derived as follows:

$$\begin{aligned} V_{\text{cap}}(n_{\text{cyc}}) &= V_g\left[1-\exp\left(-\frac{n_{\text{cyc}}t_{\text{cyc}}}{R_g C_{\text{cap}}}\right)\right] \\ &= V_g\left[1-\exp\left(-\frac{n_{\text{cyc}}\Delta Q}{V_g C_{\text{cap}}}\right)\right] \end{aligned} \quad (14)$$

where V_g represents the generator voltage, R_g is the resistor, t_{cyc} is the time between consecutive cycles, and ΔQ is the amount of electric charge obtained from one cycle. We can derive the maximum energy, denoted by $E_{\text{cap}}^{\max}(n_{\text{cyc}})$, stored in the nanocapacitor as follows:

$$E_{\text{cap}}^{\max}(n_{\text{cyc}}) = \frac{1}{2}C_{\text{cap}}\left(V_g\right)^2. \quad (15)$$

Furthermore, the energy harvesting rate, denoted by λ_{eh}, in Joule/second can be computed as a function of the current energy $E_{\text{cap}}(n_{\text{cyc}})$ in the nano-capacitor and the increment in the energy of the nano-capacitor, denoted by ΔE, which is given as follows [46]:

$$\lambda_{\text{eh}} = \frac{V_g\Delta Q}{t_{\text{cyc}}}\left[\exp\left(-\frac{\Delta Q n_{\text{cyc}}}{V_g C_{\text{cap}}}\right) - \exp\left(-\frac{2\Delta Q n_{\text{cyc}}}{V_g C_{\text{cap}}}\right)\right]. \quad (16)$$

C. Channel Coding Rate in the Finite Blocklength Regime

Definition 1. The (n, M, ϵ_k)-Code. We define a message set $\mathcal{M} = \{1, \ldots, M\}$ and a message m is uniformly distributed on $\mathcal{M}$, where M is the total number of codewords and ϵ_k is the decoding error probability. Correspondingly, we define an (n, M, ϵ_k)-code as follows:

- An encoder Υ: $\{1, \ldots, M\} \mapsto \mathcal{A}^n$ that maps the message $m \in \{1, \ldots, M\}$ into a codeword, denoted by $\boldsymbol{x}_{\boldsymbol{k}}^{\boldsymbol{n}}$, with length n, where $\mathcal{A}^n$ is the codebook which represents the set of all the possible codewords mapped by the encoding function Υ.
- A decoder $\mathcal{D}$: $\mathcal{B}^n \mapsto \{1, \ldots, M\}$ that decodes the received message into $\widehat{m}$, where $\mathcal{B}^n$ is the set of received codewords of length n and $\widehat{m}$ denotes the estimated signal received at the receiver. The decoder $\mathcal{D}$ need to satisfy the following maximum error probability constraint:

$$\Pr\{\widehat{m} \neq m\} \leq \epsilon_k. \quad (17)$$

We define $Q_{Y_k^n}$ as an arbitrary distribution on the output alphabet. Define the modified information density, denoted by $\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n)$, for nano transmitter (device) k as follows [47]:

$$\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n) \triangleq \frac{1}{n}\log_2\left[\frac{P_{Y_k^n|X_k^n}(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n)}{Q_{Y_k^n}(y_k^n)}\right] \quad (18)$$

where $P_{Y_k^n|X_k^n}$ denotes the conditional probability distribution function.

Definition 2. The Channel Coding Rate. In [13], the maximum achievable coding rate, denoted by $R(n, r_k, \mathcal{P}_k)$, (in bits per channel use) with error probability ϵ_k $(0 \leq \epsilon_k < 1)$, transmitted power, denoted by $\mathcal{P}_k$, and coding blocklength n for nano transmitter k in the finite blocklength regime can be determined as follows [13]:

$$R(n, r_k, \mathcal{P}_k) = C(r_k, \mathcal{P}_k) - \sqrt{\frac{V(r_k, \mathcal{P}_k)}{n}}Q^{-1}(\epsilon_k) + \frac{\mathcal{O}(\log n)}{n} \quad (19)$$

where $Q^{-1}(\cdot)$ is the inverse of Q-function, $\mathcal{O}(\cdot)$ is the big O notation so that $\mathcal{O}(\log n)/n$ is negligible when n gets large, and $C(r_k, \mathcal{P}_k)$ and $V(r_k, \mathcal{P}_k)$ are the channel capacity and channel dispersion, respectively. Eq. (19) implies that, given a codeword with finite length n, the achievable coding rate can be derived by the right-hand side of Eq. (19) with decoding error probability no larger than ϵ_k.

III. The THz-Band Wireless Channel Modeling in the Finite Blocklength Regime

In this section, we characterize the functions of aggregate interference, channel capacity, channel dispersion, and the ϵ-effective capacity, respectively, in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks.

A. The Aggregate Interference Modeling for the THz-Band Channels

Using Eqs. (7) and (8), we can derive the signal to interference and noise ratio (SINR) function, denoted by $\gamma_k^{(l)}(\boldsymbol{r})$ ($l = 1, \ldots, n$), between nano transmitter k and its nano receiver for transmitting the lth data block in the THz band as follows:

$$\gamma_k^{(l)}(\boldsymbol{r}) = \frac{\mathcal{P}_k \mathcal{P}_{\text{total}}(r_k)}{N_{I_k^{(l)}}(\boldsymbol{r}) + N_k(r_k)} \tag{20}$$

where $\boldsymbol{r}$ represents the vector of distances r_k ($k = 1, 2, \ldots, (K+1)$) between nano transmitter k and its nano receiver, $N_{I_k^{(l)}}(\boldsymbol{r})$ is the aggregate interference power, and $N_k(r_k)$ is the noise power. To guarantee the successful reception of the transmitted symbol at the nano receiver, the received SINR should be larger than a threshold, denoted by γ_{th}, i.e., $\gamma_k^{(l)}(\boldsymbol{r}) \geq \gamma_{\text{th}}$. We have

$$\frac{\mathcal{P}_k\,(r_k)^{-\eta}\, G 10^{\frac{\xi_k}{10}} S(f) \left(\frac{c}{4\pi f r_k}\right)^2 e^{-\alpha_{\text{abs}} r_k}}{N_k(r_k) + N_{I_k^{(l)}}(\boldsymbol{r})} \geq \gamma_{\text{th}}. \tag{21}$$

We can derive the aggregate interference, denoted by $I_k^{(l)}(\boldsymbol{r})$, at the nano receiver for transmitting the lth data block in the THz band as follows:

$$I_k^{(l)}(\boldsymbol{r}) = \sum_{i=1, i\neq k}^{K+1} \sqrt{\mathcal{P}_i\,(r_i)^{-\eta}\, G 10^{\frac{\xi_i}{10}} S(f)} \left(\frac{c}{4\pi f r_i}\right) \times e^{-\frac{\alpha_{\text{abs}} r_i}{2}} + N_i(r_i). \tag{22}$$

Due to the high density of wireless nano-networks, i.e., as $K \to \infty$, we can invoke the Central Limit Theorem and assume that the aggregate interference can be modeled as a Gaussian random process, i.e., $I_k^{(l)}(\boldsymbol{r}) \sim \mathcal{N}\left(\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})], \text{Var}_{I_k^{(l)}}(\boldsymbol{r})\right)$, where $\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})]$ and $\text{Var}_{I_k^{(l)}}(\boldsymbol{r})$ are the mean and variance of the aggregate interference, respectively, and $\mathbb{E}_{\boldsymbol{r}}[\cdot]$ is the expectation operation with respect to $\boldsymbol{r}$. We derive the closed-form expressions for characterizing the mean $\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})]$ and the variance $\text{Var}_{I_k^{(l)}}(\boldsymbol{r})$, respectively, of the aggregate interference in the following theorem.

Theorem 1: **If** the aggregate interference $I_k^{(l)}(\boldsymbol{r})$ is given by Eq. (22) for our proposed THz-band channel model, **then** the *mean* and *variance* of the aggregate interference between nano transmitter k and its nano receiver in the THz band over wireless nano-networks are characterized by the following two claims, respectively.

Claim 1. The *mean* $\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})]$ of the aggregate interference is accurately estimated by its lower-bound as follows:

$$\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})] \geq \frac{2\lambda\pi a^2 \Lambda \sqrt{\overline{\mathcal{P}}} \left(\frac{2}{\alpha_{\text{abs}}}\right)^{1-\frac{\eta}{2}}}{a^2 - b^2} \left[\gamma\left(1 - \frac{\eta}{2}, \frac{\alpha_{\text{abs}} a}{2}\right) - \gamma\left(1 - \frac{\eta}{2}, \frac{\alpha_{\text{abs}} b}{2}\right)\right] \tag{23}$$

where $\gamma(\cdot,\cdot)$ is the lower incomplete Gamma function and

$$\Lambda \triangleq \frac{c\sqrt{GS(f)}}{4\pi f}. \tag{24}$$

Claim 2. The *variance* $\text{Var}_{I_k^{(l)}}(\boldsymbol{r})$ of the aggregate interference is approximated as follows:

$$\begin{aligned}\text{Var}_{I_k^{(l)}}(\boldsymbol{r}) \approx{}& \frac{6\lambda\pi a^2 \Lambda^2 \overline{\mathcal{P}} (\alpha_{\text{abs}})^{-\eta}}{a^2 - b^2} [\gamma(-\eta, a\alpha_{\text{abs}}) - \gamma(-\eta, b\alpha_{\text{abs}})] \\ &+ \sum_{i=1, i\neq k}^{K+1} N_{i,b} + \frac{2\lambda\pi a^2 \Lambda^2}{a^2 - b^2} \left[\log\left(\frac{a}{b}\right) - \text{Ei}\left(-\alpha_{\text{abs}} a\right) \right. \\ &\left. + \text{Ei}\left(-\alpha_{\text{abs}} b\right)\right] - \left(\frac{2\lambda\pi a^2 C}{a^2 - b^2}\right)^2 \overline{\mathcal{P}} \left(\frac{2}{\alpha_{\text{abs}}}\right)^{2-\eta} \\ &\times \left[\gamma\left(1 - \frac{\eta}{2}, \frac{\alpha_{\text{abs}} a}{2}\right) - \gamma\left(1 - \frac{\eta}{2}, \frac{\alpha_{\text{abs}} b}{2}\right)\right]^2. \end{aligned} \tag{25}$$

Proof: To derive the closed-form expressions for the mean and variance of the aggregate interference, we prove **Claim 1** and **Claim 2**, respectively, for this theorem as follows.

Claim 1. We can derive the mean of aggregate interference $\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})]$ between nano node k and its nano receiver in the THz band over wireless nano-networks as follows:

$$\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})] = \mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1, i\neq k}^{K+1} \sqrt{\mathcal{P}_i \mathcal{P}_{\text{total}}(r_i)}\right]. \tag{26}$$

Then, in order to calculate the mean of aggregate interference $\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})]$, first we need to calculate the expression function given in the right-hand-side of Eq. (26) as follows:

$$\begin{aligned}&\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1, i\neq k}^{K+1} \sqrt{\mathcal{P}_i \mathcal{P}_{\text{total}}(r_i)}\right] \\ &= \mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1, i\neq k}^{K+1} \sqrt{\mathcal{P}_i\,(r_i)^{-\eta}\, G 10^{\frac{\xi_i}{10}} S(f)} \left(\frac{c}{4\pi f r_i}\right) e^{-\frac{\alpha_{\text{abs}} r_i}{2}}\right] \\ &= \Lambda \mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1, i\neq k}^{K+1} \sqrt{\mathcal{P}_i 10^{\frac{\xi_i}{10}}} F(r_i)\right] \end{aligned} \tag{27}$$

where Λ is given by Eq. (24) and

$$F(r_i) \triangleq r_i^{-\frac{\eta}{2}-1} e^{-\frac{\alpha_{\text{abs}} r_i}{2}}. \tag{28}$$

Then, we need to calculate the function $\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1, i\neq k}^{K+1} \sqrt{\mathcal{P}_i 10^{\frac{\xi_i}{10}}} F(r_i)\right]$. Assuming that random number $\mathcal{K}$ interfering nano nodes (transmitters) is equal to κ, we can obtain the conditional expectation function as follows [38]:

$$\begin{aligned}&\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1, i\neq k}^{K+1} \sqrt{\mathcal{P}_i 10^{\frac{\xi_i}{10}}} F(r_i) \middle| \mathcal{K} = \kappa\right] \\ &= \sum_{i=1, i\neq k}^{K+1} \mathbb{E}_{\boldsymbol{r}}\left[\sqrt{\mathcal{P}_i 10^{\frac{\xi_i}{10}}} F(r_i) \middle| \mathcal{K} = \kappa\right] = \kappa \mathbb{E}_{r_i}\left[\sqrt{\mathcal{P}_i 10^{\frac{\xi_i}{10}}} F(r_i)\right] \\ &\geq \kappa \mathbb{E}_{r_i}\left[\sqrt{\mathcal{P}_i 10^{\frac{\xi_i}{10}}}\right] \mathbb{E}_{r_i}[F(r_i)] = \kappa\sqrt{\overline{\mathcal{P}}} \mathbb{E}_{r_i}\left[F(r_i)\right] \end{aligned} \tag{29}$$

where $\mathbb{E}_{r_i}[\cdot]$ is the expectation operation with respect to r_i and

$$\mathbb{E}_{r_i}[F(r_i)] = \int_b^a r_i^{-\frac{\eta}{2}-1} e^{-\frac{\alpha_{\text{abs}} r_i}{2}} f_D(r_i) dr_i$$

$$
\begin{aligned}
&= \frac{2}{a^2-b^2}\int_b^a r_i^{-\frac{\eta}{2}} e^{-\frac{\alpha_{\text{abs}} r_i}{2}} dr_i \\
&= \frac{2\left(\frac{2}{\alpha_{\text{abs}}}\right)^{1-\frac{\eta}{2}}}{a^2-b^2}\int_{\frac{\alpha_{\text{abs}} b}{2}}^{\frac{\alpha_{\text{abs}} a}{2}} r_i^{-\frac{\eta}{2}} e^{-r_i} dr_i \\
&= \frac{2\left(\frac{2}{\alpha_{\text{abs}}}\right)^{1-\frac{\eta}{2}}}{a^2-b^2}\Bigg[\gamma\left(1-\frac{\eta}{2},\frac{\alpha_{\text{abs}} a}{2}\right) \\
&\quad -\gamma\left(1-\frac{\eta}{2},\frac{\alpha_{\text{abs}} b}{2}\right)\Bigg]. \qquad (30)
\end{aligned}
$$

In addition, using the spatial Poisson process, we can obtain the mean and variance of the number of interfering nano nodes $\mathcal{K}$ as follows:

$$
\begin{cases}\mathbb{E}[\mathcal{K}] = \lambda\pi a^2; \\ \text{Var}(\mathcal{K}) = \lambda\pi a^2,\end{cases} \qquad (31)
$$

where $\mathbb{E}[\cdot]$ and Var$(\cdot)$ are the standard expectation and variance operations, respectively. Correspondingly, using Eqs. (30) and (31), we can obtain the following equation:

$$
\begin{aligned}
&\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\sqrt{\mathcal{P}_i 10^{\frac{\xi_i}{10}}F(r_i)}\right] \\
&\geq \mathbb{E}\left[\mathcal{K}\right]\sqrt{\overline{\mathcal{P}}}\mathbb{E}_{r_i}\left[F(r_i)\right] \\
&= \frac{2\lambda\pi a^2\sqrt{\overline{\mathcal{P}}}\left(\frac{2}{\alpha_{\text{abs}}}\right)^{1-\frac{\eta}{2}}}{a^2-b^2} \\
&\quad\times\left[\gamma\left(1-\frac{\eta}{2},\frac{\alpha_{\text{abs}} a}{2}\right)-\gamma\left(1-\frac{\eta}{2},\frac{\alpha_{\text{abs}} b}{2}\right)\right]. \qquad (32)
\end{aligned}
$$

As a result, by plugging Eq. (32) back into Eq. (27), we can characterize the mean of aggregate interference $\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})]$ as follows:

$$
\begin{aligned}
\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})] \geq \frac{2\lambda\pi a^2\Lambda\sqrt{\overline{\mathcal{P}}}\left(\frac{2}{\alpha_{\text{abs}}}\right)^{1-\frac{\eta}{2}}}{a^2-b^2}&\Bigg[\gamma\left(1-\frac{\eta}{2},\frac{\alpha_{\text{abs}} a}{2}\right) \\
&-\gamma\left(1-\frac{\eta}{2},\frac{\alpha_{\text{abs}} b}{2}\right)\Bigg] \qquad (33)
\end{aligned}
$$

which is Eq. (23). Thus, we complete the proof for **Claim 1** in Theorem 1.

Claim 2. We can derive the variance of the aggregate interference $\text{Var}_{I_k^{(l)}}(\boldsymbol{r})$ for our proposed THz-band nano-communication schemes as follows:

$$
\text{Var}_{I_k^{(l)}}(\boldsymbol{r}) = \mathbb{E}_{\boldsymbol{r}}\left[\left(I_k^{(l)}(\boldsymbol{r})\right)^2\right]-\left(\mathbb{E}_{\boldsymbol{r}}[I_k^{(l)}(\boldsymbol{r})]\right)^2 \qquad (34)
$$

where

$$
\begin{aligned}
\mathbb{E}_{\boldsymbol{r}}\left[\left(I_k^{(l)}(\boldsymbol{r})\right)^2\right] &= \mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\mathcal{P}_i\mathcal{P}_{\text{total}}(r_i)+N_i(r_i)\right] \\
&+2\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\sum_{j=1}^{i-1}\sqrt{\mathcal{P}_i\mathcal{P}_j\mathcal{P}_{\text{total}}(r_i)\mathcal{P}_{\text{total}}(r_j)}\right]. \qquad (35)
\end{aligned}
$$

To obtain the variance of aggregate interference by $\text{Var}_{I_k^{(l)}}(\boldsymbol{r})$, first we need to obtain the following equation:

$$
\begin{aligned}
\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\mathcal{P}_i\mathcal{P}_{\text{total}}(r_i)\right] &= \mathbb{E}_{\boldsymbol{r}}\Bigg[\sum_{i=1,i\neq k}^{K+1}\mathcal{P}_i\left(r_i\right)^{-\eta}G10^{\frac{\xi_i}{10}}S(f) \\
&\quad\times\left(\frac{c}{4\pi f r_i}\right)^2 e^{-\alpha_{\text{abs}} r_i}\Bigg] \\
&= \Lambda^2\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\mathcal{P}_i 10^{\frac{\xi_i}{10}}\widetilde{F}(r_i)\right] \qquad (36)
\end{aligned}
$$

where

$$
\widetilde{F}(r_i) \triangleq (r_i)^{-\eta-2}e^{-\alpha_{\text{abs}} r_i}. \qquad (37)
$$

Since the transmission power $\mathcal{P}_i$ is upper-bounded by $\overline{\mathcal{P}}$, we can then obtain the conditional expectation function as follows:

$$
\begin{aligned}
&\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\mathcal{P}_i 10^{\frac{\xi_i}{10}}\widetilde{F}(r_i)\middle|\mathcal{K}=\kappa\right] = \kappa\mathbb{E}_{r_i}\left[\mathcal{P}_i 10^{\frac{\xi_i}{10}}\widetilde{F}(r_i)\right] \\
&\geq \kappa\mathbb{E}_{r_i}\left[\mathcal{P}_i 10^{\frac{\xi_i}{10}}\right]\mathbb{E}_{r_i}\left[\widetilde{F}(r_i)\right] = \kappa\overline{\mathcal{P}}\mathbb{E}_{r_i}\left[\widetilde{F}(r_i)\right] \qquad (38)
\end{aligned}
$$

where

$$
\begin{aligned}
\mathbb{E}_{r_i}\left[\widetilde{F}(r_i)\right] &= \int_b^a (r_i)^{-\eta-2}e^{-\alpha_{\text{abs}} r_i}f_D(r_i)dr_i \\
&= \frac{2}{a^2-b^2}\int_b^a (r_i)^{-\eta-1}e^{-\alpha_{\text{abs}} r_i}dr_i \\
&= \frac{2(\alpha_{\text{abs}})^{-\eta}}{a^2-b^2}\int_{b\alpha_{\text{abs}}}^{a\alpha_{\text{abs}}}(r_i)^{-\eta-1}e^{-r_i}dr_i \\
&= \frac{2(\alpha_{\text{abs}})^{-\eta}}{a^2-b^2}\left[\gamma\left(-\eta,a\alpha_{\text{abs}}\right)-\gamma\left(-\eta,b\alpha_{\text{abs}}\right)\right]. \qquad (39)
\end{aligned}
$$

Using Eqs. (31), (36), and (39), we can obtain the following in equation:

$$
\begin{aligned}
\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\mathcal{P}_i\mathcal{P}_{\text{total}}(r_i)\right] &\geq \frac{2\lambda\pi a^2\Lambda^2\overline{\mathcal{P}}(\alpha_{\text{abs}})^{-\eta}}{a^2-b^2} \\
&\quad\times\left[\gamma\left(-\eta,a\alpha_{\text{abs}}\right)-\gamma\left(-\eta,b\alpha_{\text{abs}}\right)\right]. \qquad (40)
\end{aligned}
$$

We also need to show that the following equations hold true:

$$
\begin{aligned}
\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}N_i(r_i)\right] &= \mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\left(N_{i,b}+N_{i,s}(r_i)\right)\right] \\
&= \sum_{i=1,i\neq k}^{K+1}N_{i,b}+\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}N_{i,s}(r_i)\right] \\
&= \sum_{i=1,i\neq k}^{K+1}N_{i,b}+\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}S(f)\left(1-e^{-\alpha_{\text{abs}} r_i}\right)\right.
\end{aligned}
$$

$$\times\left(\frac{c}{4\pi f r_i}\right)^2\Bigg]$$
$$=\sum_{i=1,i\neq k}^{K+1} N_{i,b}+\Lambda^2\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\widehat{F}(r_i)\right] \quad (41)$$

where

$$\widehat{F}(r_i)\triangleq (r_i)^{-2}\left(1-e^{-\alpha_{\text{abs}}r_i}\right). \quad (42)$$

Similarly, we can obtain the conditional expectation function as follows:

$$\mathbb{E}_{\boldsymbol{r}|\mathcal{K}}\left[\sum_{i=1,i\neq k}^{K+1}\widehat{F}(r_i)\middle|\mathcal{K}=\kappa\right]=\kappa\mathbb{E}_{r_i}\left[\widehat{F}(r_i)\right] \quad (43)$$

where $\mathbb{E}_{\boldsymbol{r}|\mathcal{K}}[\cdot]$ represents conditional expectation operations and

$$\begin{aligned}\mathbb{E}_{r_i}\left[\widehat{F}(r_i)\right] &= \int_b^a (r_i)^{-2}\left(1-e^{-\alpha_{\text{abs}}r_i}\right)f_D(r_i)dr_i\\ &=\frac{2}{a^2-b^2}\int_b^a\frac{1-e^{-\alpha_{\text{abs}}r_i}}{r_i}dr_i=\frac{2}{a^2-b^2}\\ &\quad\times\left[\log\left(\frac{a}{b}\right)-\text{Ei}\left(-\alpha_{\text{abs}}a\right)+\text{Ei}\left(-\alpha_{\text{abs}}b\right)\right]\end{aligned} \quad (44)$$

where $\log(\cdot)$ represents $\log_e(\cdot)$ and $\text{Ei}(x)$ is the exponential integral function, which is defined as follows:

$$\text{Ei}(x)\triangleq-\int_{-x}^{\infty}\frac{e^{-t}}{t}dt. \quad (45)$$

Similar to Eq. (40), we can obtain the following equation:

$$\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\widehat{F}(r_i)\right]=\frac{2\lambda\pi a^2}{a^2-b^2}\Bigg[\log\left(\frac{a}{b}\right)-\text{Ei}\left(-\alpha_{\text{abs}}a\right)+\text{Ei}\left(-\alpha_{\text{abs}}b\right)\Bigg]. \quad (46)$$

Furthermore, due to the high density of wireless nano-networks, we assume that the distances r_i $(i=1,\ldots,K+1$ and $i\neq k)$ between its nano receiver and all interfering nano nodes are approximately the same. As a result, we get

$$\begin{aligned}&\mathbb{E}_{\boldsymbol{r}}\left[\sum_{i=1,i\neq k}^{K+1}\sum_{j=1}^{i-1}\sqrt{\mathcal{P}_i\mathcal{P}_j\mathcal{P}_{\text{total}}(r_i)\mathcal{P}_{\text{total}}(r_j)}\right]\\ &\geq\Lambda^2\mathbb{E}\left[\mathcal{K}\right]\mathbb{E}_{r_i}\left[\mathcal{P}_i 10^{\frac{\xi_i}{10}}\widetilde{F}(r_i)\right]\\ &\geq\frac{2\lambda\pi a^2\Lambda^2\overline{\mathcal{P}}(\alpha_{\text{abs}})^{-\eta}}{a^2-b^2}\left[\gamma\left(-\eta,a\alpha_{\text{abs}}\right)-\gamma\left(-\eta,b\alpha_{\text{abs}}\right)\right].\end{aligned} \quad (47)$$

Therefore, plugging Eqs. (40) and (47) back into Eq. (35), we can obtain the following equation:

$$\begin{aligned}\mathbb{E}_{\boldsymbol{r}}\left[\left(I_k^{(l)}(\boldsymbol{r})\right)^2\right]&\approx\frac{6\lambda\pi a^2\Lambda^2\overline{\mathcal{P}}(\alpha_{\text{abs}})^{-\eta}}{a^2-b^2}\big[\gamma\left(-\eta,a\alpha_{\text{abs}}\right)\\ &\quad-\gamma\left(-\eta,b\alpha_{\text{abs}}\right)\big]+\sum_{i=1,i\neq k}^{K+1}N_{i,b}+\frac{2\lambda\pi a^2\Lambda^2}{a^2-b^2}\\ &\quad\times\left[\log\left(\frac{a}{b}\right)-\text{Ei}\left(-\alpha_{\text{abs}}a\right)+\text{Ei}\left(-\alpha_{\text{abs}}b\right)\right].\end{aligned} \quad (48)$$

Consequently, substituting Eq. (48) back into Eq. (34), we can derive the approximate variance of aggregate interference $\text{Var}_{I_k^{(l)}}(\boldsymbol{r})$ as follows:

$$\begin{aligned}\text{Var}_{I_k^{(l)}}(\boldsymbol{r})&\approx\frac{6\lambda\pi a^2\Lambda^2\overline{\mathcal{P}}(\alpha_{\text{abs}})^{-\eta}}{a^2-b^2}\left[\gamma(-\eta,a\alpha_{\text{abs}})-\gamma(-\eta,b\alpha_{\text{abs}})\right]\\ &\quad+\sum_{i=1,i\neq k}^{K+1}N_{i,b}+\frac{2\lambda\pi a^2\Lambda^2}{a^2-b^2}\Bigg[\log\left(\frac{a}{b}\right)-\text{Ei}\left(-\alpha_{\text{abs}}a\right)\\ &\quad+\text{Ei}\left(-\alpha_{\text{abs}}b\right)\Bigg]-\left(\frac{2\lambda\pi a^2 C}{a^2-b^2}\right)^2\overline{\mathcal{P}}\left(\frac{2}{\alpha_{\text{abs}}}\right)^{2-\eta}\\ &\quad\times\left[\gamma\left(1-\frac{\eta}{2},\frac{\alpha_{\text{abs}}a}{2}\right)-\gamma\left(1-\frac{\eta}{2},\frac{\alpha_{\text{abs}}b}{2}\right)\right]^2\end{aligned} \quad (49)$$

which is Eq. (25). Thus, we complete the proof for **Claim 2** in Theorem 1. ∎

Remarks on Theorem 1: The expressions derived in Theorem 1 for the *mean* and *variance* of the aggregate interference play the important roles in modeling the *channel capacity* and *channel dispersion*, which are to be investigated in Section III-C and Section III-D, respectively, over our proposed THz-band wireless nano-networks.

B. The ϵ-Effective Capacity in the Finite Blocklength Regime

Statistical delay-bounded QoS guarantees [3] have been extensively studied for analyzing queuing behavior for time-varying arrival and service processes. Traditionally, the effective capacity measures queuing process which is independent of the decoding error at the receiver. Based on the Large Deviation Principle (LDP) [48], under sufficient conditions, the queueing process $Q_k(t)$ converges in distribution to a random variable $Q_k(\infty)$ such that

$$-\lim_{Q_{\text{th},k}\to\infty}\frac{\log\left(\Pr\left\{Q_k(\infty)>Q_{\text{th},k}\right\}\right)}{Q_{\text{th},k}}=\theta_k \quad (50)$$

where $Q_{\text{th},k}$ represents the overflow threshold at the nano device k and $\theta_k>0$ is defined as the *QoS exponent* for the nano device k. To be more specific, Eq. (50) states that the probability of the queuing process exceeding a certain threshold $Q_{\text{th},k}$ decays exponentially fast as the threshold $Q_{\text{th},k}$ increases. As shown in [49], a smaller θ_k corresponds to a slower decay rate, which implies that the system can only provide a looser QoS guarantee, while a larger θ_k leads to a faster decay rate, which means that a more stringent QoS can be supported. In particular, when $\theta_k\to 0$, the system can tolerate an arbitrarily long delay; when $\theta_k\to\infty$, the system cannot tolerate any delay.

For our proposed FBC-EH based 6G THz wireless communication schemes, we need to consider both delay and error-rate bounded QoS requirements. Thus, we introduce the new concept of ϵ-effective capacity as follows.

Definition 3. The ϵ-Effective Capacity. For an (n,M,ϵ_k)-code, given a desired decoding error probability ϵ_k and QoS exponent θ_k, the *ϵ-effective capacity*, denoted by $EC_\epsilon(\theta_k)$, between the nano transmitter k and its nano receiver within the THz-band covered region is defined as the maximum constant arrival rate for a given service process and decoding error probability in supporting our proposed statistical delay and error-rate bounded QoS provisioning in the finite blocklength regime is given as follows:

$$EC_\epsilon(\theta_k) \triangleq -\frac{1}{\theta_k}\log\left\{\mathbb{E}_{r_k}\left[\epsilon_k+(1-\epsilon_k)\,e^{-\theta_k n R(n,r_k,\mathcal{P}_k)}\right]\right\} \tag{51}$$

where $\mathbb{E}_{r_k}[\cdot]$ denotes expectation with respect to the random variable of transmission distance r_k between the nano transmitter k and its nano receiver within the THz-band covered region and $R(n,r_k,\mathcal{P}_k)$ is the maximum achievable coding rate specified by Eq. (19). To derive the ϵ-effective capacity $EC_\epsilon(\theta_k)$, we need to derive the closed-form expressions for characterizing both *channel capacity* $C(r_k,\mathcal{P}_k)$ and *channel dispersion* $V(r_k,\mathcal{P}_k)$, which are elaborated on in the following two sections, respectively.

C. The Channel Capacity Modeling Over the THz Band in the Finite Blocklength Regime

Leveraging the Shannon Limit Theorem, we can derive the *channel capacity* $C(r_k,\mathcal{P}_k)$ in terms of the mutual information $I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)$ for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks as follows:

$$C(r_k,\mathcal{P}_k)=\sup_{P_{X_k^n}(\boldsymbol{x}_k^n)}\left\{I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)\right\} \tag{52}$$

where $P_{X_k^n}(\boldsymbol{x}_k^n)$ is the input symbol probability and $I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)$ is the *mutual information*, which is given as follows:

$$I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)=\mathbb{E}\left[\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n)\right]=\frac{1}{n}\mathbb{E}\left[\log_2\left(\frac{P_{Y_k^n|X_k^n}(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n)}{Q_{Y_k^n}(\boldsymbol{y}_k^n)}\right)\right] \tag{53}$$

where $\mathbb{E}[\cdot]$ is the expectation operation over the transmit and receive signals. The theorem that follows bellow derives the closed-form expression for the upper-bound to accurately approximate the channel capacity $C(r_k,\mathcal{P}_k)$ given by Eq. (52) over the THz band in the finite blocklength regime.

Theorem 2: The upper-bound on the *mutual information* $I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)$ given by Eq. (53) for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks is given as follows:

$$I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)\le\frac{1}{2}\log_2\left[\frac{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right] -(\log_2 e)\left[\frac{\mathcal{P}_k\left[\mathcal{P}_{\text{total}}(r_k)+1\right]}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]. \tag{54}$$

Proof: To derive the upper-bound given by Eq. (54) on the mutual information $I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)$ given by Eq. (53) to accurately approximate the channel capacity $C(r_k,\mathcal{P}_k)$ given by Eq. (52), we need to proceed with the following four steps.

Step 1. We need to derive the conditional distribution function $P_{Y_k^n|X_k^n}(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n)$ as follows:

$$P_{Y_k^n|X_k^n}(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n)=\frac{1}{\left[2\pi\left(N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right)\right]^{\frac{n}{2}}}\times\exp\left\{-\frac{\left\|\boldsymbol{y}_k^n-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n-\boldsymbol{x}_k^n\right\|^2}{2\left[N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}\right\} \tag{55}$$

where $\|\cdot\|$ is the Euclidean norm and $\mathbf{I}_n$ is the identity matrix with size n.

Step 2. To derive the modified information density $\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n)$, we need to apply the mean and variance of interference derived in Eqs. (23) and (25) and select the reference output distribution for the THz wireless channel as $Q_{Y_k^n}(\boldsymbol{y}_k^n)=\mathcal{N}\left(\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n,\left(\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right)\mathbf{I}_n\right)$.

Step 3. Using Eqs. (53) and (55), we derive the *modified information density* $\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n)$ as follows:

$$\begin{aligned}
\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n)&=\frac{1}{n}\log_2\Bigg\{\frac{\left[2\pi\left(\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right)\right]^{\frac{n}{2}}}{\left[2\pi\left(N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right)\right]^{\frac{n}{2}}}\\
&\quad\times\exp\left\{-\frac{\left\|\boldsymbol{y}_k^n-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n-\boldsymbol{x}_k^n\right\|^2}{2\left[N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}\right\}\\
&\quad\times\exp\left\{\frac{\left\|\boldsymbol{y}_k^n-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n\right\|^2}{2\left[\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}\right\}\Bigg\}\\
&=\frac{1}{n}\log_2\left\{\frac{\left[2\pi\left(\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right)\right]^{\frac{n}{2}}}{\left[2\pi\left(N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right)\right]^{\frac{n}{2}}}\right\}\\
&\quad+\frac{(\log_2 e)}{2n}\left[\frac{\left\|\boldsymbol{y}_k^n-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n\right\|^2}{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right.\\
&\quad\left.-\frac{\left\|\boldsymbol{y}_k^n-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n-\boldsymbol{x}_k^n\right\|^2}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\\
&=\frac{1}{2}\log_2\left[\frac{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\\
&\quad+\frac{(\log_2 e)}{2n}\left[\frac{\left\|\boldsymbol{y}_k^n-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n\right\|^2}{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right.\\
&\quad\left.-\frac{\left\|\boldsymbol{y}_k^n-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n-\boldsymbol{x}_k^n\right\|^2}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right].
\end{aligned} \tag{56}$$

Using Eq. (12), we obtain the following equation:

$$\begin{aligned}\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n) = &\frac{1}{2}\log_2\left[\frac{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\\ &+\frac{(\log_2 e)}{2n}\left[\left\|\sqrt{\mathcal{P}_{\text{total}}(r_k)}\boldsymbol{x}_k^n\right.\right.\\ &+\sum_{i=1,i\neq k}^{K+1}\sqrt{\mathcal{P}_{\text{total}}(r_i)}\boldsymbol{x}_i^n+\boldsymbol{n}_k-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\\ &\times\mathbf{I}_n\Big\|^2\left\{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right\}^{-1}\\ &-\left\|\sqrt{\mathcal{P}_{\text{total}}(r_k)}\boldsymbol{x}_k^n+\sum_{i=1,i\neq k}^{K+1}\sqrt{\mathcal{P}_{\text{total}}(r_i)}\boldsymbol{x}_i^n\right.\\ &+\boldsymbol{n}_k-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n-\boldsymbol{x}_k^n\Big\|^2\\ &\times\left.\left\{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right\}^{-1}\right].\end{aligned}\tag{57}$$

Step 4. Using Eqs. (53) and (57), we can derive an *upper-bound* on the mutual information $I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)$ as follows:

$$\begin{aligned}I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n) = &\ \mathbb{E}\left[\frac{1}{2}\log_2\left[\frac{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\right.\\ &+\frac{(\log_2 e)}{2n}\left\{\left\|\sqrt{\mathcal{P}_{\text{total}}(r_k)}\boldsymbol{x}_k^n+\sum_{i=1,i\neq k}^{K+1}\sqrt{\mathcal{P}_{\text{total}}(r_i)}\boldsymbol{x}_i^n+\boldsymbol{n}_k\right.\right.\\ &-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n\Big\|^2\left\{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right\}^{-1}\\ &-\left\|\sqrt{\mathcal{P}_{\text{total}}(r_k)}\boldsymbol{x}_k^n+\sum_{i=1,i\neq k}^{K+1}\sqrt{\mathcal{P}_{\text{total}}(r_i)}\boldsymbol{x}_i^n+\boldsymbol{n}_k\right.\\ &-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n-\boldsymbol{x}_k^n\Big\|^2\left.\left.\left\{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right\}^{-1}\right\}\right]\\ \le &\ \frac{1}{2}\log_2\left[\frac{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]+\frac{(\log_2 e)}{n}\\ &\times\left\{\mathbb{E}\left[\left\|\sqrt{\mathcal{P}_{\text{total}}(r_k)}\boldsymbol{x}_k^n\right\|^2+\left\|\sum_{i=1,i\neq k}^{K+1}\sqrt{\mathcal{P}_{\text{total}}(r_i)}\boldsymbol{x}_i^n-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\right.\right.\right.\\ &\times\mathbf{I}_n\Big\|^2+\|\boldsymbol{n}_k\|^2\Big]\left\{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right\}^{-1}\\ &-\mathbb{E}\left[\left\|\sqrt{\mathcal{P}_{\text{total}}(r_k)}\boldsymbol{x}_k^n\right\|^2+\left\|\sum_{i=1,i\neq k}^{K+1}\sqrt{\mathcal{P}_{\text{total}}(r_i)}\boldsymbol{x}_i^n\right.\right.\\ &-\mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n\Big\|^2+\|\boldsymbol{n}_k\|^2+\|\boldsymbol{x}_k^n\|^2\Big]\left.\left\{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right\}^{-1}\right\}\\ = &\ \frac{1}{2}\log_2\left[\frac{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\\ &-(\log_2 e)\left[\frac{\mathcal{P}_k\left[\mathcal{P}_{\text{total}}(r_k)+1\right]}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\end{aligned}\tag{58}$$

which is Eq. (54), completing the proof for Theorem 2. ■

Remarks on Theorem 2: While it is infeasible to derive the exact closed-form expression for the channel capacity $C(r_k,\mathcal{P}_k)$ in terms of the mutual information for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks in the finite blocklength regime, Theorem 2 yields the accurate upper-bound for the mutual information $I(\boldsymbol{x}_k^n,\boldsymbol{y}_k^n)$ derived in Eq. (54) as an accurate approximation for the channel capacity $C(r_k,\mathcal{P}_k)$ given by Eq. (52), which provides with practically very useful designing guidance for engineering, modeling, and evaluating our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks in the finite blocklength regime.

D. The Channel Dispersion Modeling for the THz Band Communications in the Finite Blocklength Regime

Generally speaking, it is challenging to derive the closed-form expression of the channel dispersion for the nano-communications schemes in the THz band using FBC. However, leveraging some mathematical manipulations, we can obtain the tight upper-bound for the channel dispersion $V(r_k,\mathcal{P}_k)$ for our proposed statistical delay and error-rate bounded QoS provisioning schemes in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks as summarized in the following theorem.

Theorem 3: The upper-bound on the *channel dispersion* $V(r_k,\mathcal{P}_k)$ for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks is given as follows:

$$V(r_k,\mathcal{P}_k)\le 8n(\log_2 e)^2\left[\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right].\tag{59}$$

Proof: To derive the upper-bound on the channel dispersion $V(r_k,\mathcal{P}_k)$, we need to proceed with the following two steps.

Step 1. We start with variance of the modified information density $\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n)$ as in the following equation:

$$\begin{aligned}V(r_k,\mathcal{P}_k) &= \text{Var}\left[\boldsymbol{i}(\boldsymbol{x}_k^n;\boldsymbol{y}_k^n)\right]\\ &=\frac{1}{n}\text{Var}\left[\log_2\left(\frac{P_{Y_k^n|X_k^n}(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n)}{Q_{Y_k^n}(\boldsymbol{y}_k^n)}\right)\right]\\ &\le\frac{2}{n}\Big\{\text{Var}\left[\log_2\left(P_{Y_k^n|X_k^n}(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n)\right)\right]\\ &\quad+\text{Var}\left[\log_2\left(Q_{Y_k^n}(\boldsymbol{y}_k^n)\right)\right]\Big\}\end{aligned}\tag{60}$$

where Var$[\cdot]$ represents the variance operation.

Step 2. We can apply the Poincará inequality to derive the following equation:

$$\begin{aligned}&\text{Var}\left[\log_2\left(P_{Y_k^n|X_k^n}(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n)\right)\right]\\ &\qquad\le\mathbb{E}\left[\left\|\nabla\log_2\left(P_{Y_k^n|X_k^n}(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n)\right)\right\|^2\right]\end{aligned}\tag{61}$$

where ∇ is the Nabla operator. Then, to calculate the function $\nabla \log_2 \left(P_{Y_k^n|X_k^n}\left(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n\right)\right)$, we have

$$\begin{aligned}
&\nabla \log_2 \left(P_{Y_k^n|X_k^n}\left(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n\right)\right) \\
&= \frac{(\log_2 e)}{P_{Y_k^n|X_k^n}\left(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n\right)} \nabla P_{Y_k^n|X_k^n}\left(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n\right) \\
&= \frac{(\log_2 e)}{P_{Y_k^n|X_k^n}\left(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n\right)} \sum_{m=1}^{M} \left\{ \frac{1}{M}\left[2\pi\left(N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right)\right]^{-\frac{n}{2}} \right. \\
&\quad \left. \times \nabla \exp\left\{-\frac{\|\boldsymbol{y}_k^n - \mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n - \boldsymbol{x}_k^n(m)\|^2}{2\left[N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}\right\}\right\} \\
&= \frac{(\log_2 e)}{P_{Y_k^n|X_k^n}\left(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n\right)} \sum_{m=1}^{M} \left\{ \frac{1}{M}\left[2\pi\left(N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right)\right]^{-\frac{n}{2}} \right. \\
&\quad \times \left(\boldsymbol{x}_k^n(m) + \mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n - \boldsymbol{y}_k^n\right) \\
&\quad \left. \times \exp\left\{-\frac{\left\|\boldsymbol{y}_k^n - \mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n - \boldsymbol{x}_k^n(m)\right\|^2}{2\left[N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}\right\}\right\} \\
&= (\log_2 e)\left\{\mathbb{E}\left[\boldsymbol{x}_k^n|\boldsymbol{y}_k^n\right] + \mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n - \boldsymbol{y}_k^n\right\} \qquad (62)
\end{aligned}$$

where $\boldsymbol{x}_k^n(m)$ is the encoded signal from message $m \in \mathcal{M}$ with length n at nano transmitter k. Let us define:

$$\widehat{\boldsymbol{x}}_k^n \triangleq \mathbb{E}\left[\boldsymbol{x}_k^n|\boldsymbol{y}_k^n\right]. \qquad (63)$$

Accordingly, using the average power constraint given in Eq. (11), we can obtain the following equation:

$$\begin{aligned}
&\mathrm{Var}\left[\log_2\left(P_{Y_k^n|X_k^n}\left(\boldsymbol{y}_k^n|\boldsymbol{x}_k^n\right)\right)\right] \\
&\quad \le (\log_2 e)^2 \mathbb{E}\left[\left\|\widehat{\boldsymbol{x}}_k^n + \mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\mathbf{I}_n - \boldsymbol{y}_k^n\right\|^2\right] \\
&\quad \le 2(\log_2 e)^2 \left\{\mathbb{E}\left[\|\widehat{\boldsymbol{x}}_k^n\|^2\right] + \mathbb{E}\left[\left\|\boldsymbol{y}_k^n - \mathbb{E}\left[I_k^{(l)}(\boldsymbol{r})\right]\right\|^2\right]\right\} \\
&\quad = 2(\log_2 e)^2 \left\{n\mathcal{P}_k + n\left[N_{I_k^{(l)}}(\boldsymbol{r}) + N_k(r_k)\right]\right\} \\
&\quad = 2n(\log_2 e)^2 \left[\mathcal{P}_k + N_{I_k^{(l)}}(\boldsymbol{r}) + N_k(r_k)\right]. \qquad (64)
\end{aligned}$$

Similarly, we can derive the function $\mathrm{Var}\left[\log_2\left(Q_{Y_k^n}\left(\boldsymbol{y}_k^n\right)\right)\right]$ as follows:

$$\mathrm{Var}\left[\log_2\left(Q_{Y_k^n}\left(\boldsymbol{y}_k^n\right)\right)\right] \le 2n(\log_2 e)^2\left[\mathcal{P}_k + N_{I_k^{(l)}}(\boldsymbol{r}) + N_k(r_k)\right]. \qquad (65)$$

Therefore, plugging Eqs. (64) and (65) back into Eq. (60), we get:

$$V(r_k,\mathcal{P}_k) \le 8n(\log_2 e)^2\left[\mathcal{P}_k + N_{I_k^{(l)}}(\boldsymbol{r}) + N_k(r_k)\right] \qquad (66)$$

which is Eq. (59), completing the proof for Theorem 3. ■

Remarks on Theorem 3: The upper-bound on the channel dispersion $V(r_k,\mathcal{P}_k)$ given by Eq. (59) in Theorem 3 is important to derive the maximum achievable coding rate $R(n, r_k, \mathcal{P}_k)$ specified by Eq. (19) and the ϵ-effective capacity $EC_\epsilon(\theta_k)$ defined by Eq. (51), respectively, and to further solve the joint optimization problem for resource allocations to support our proposed statistical delay and error-rate bounded QoS provisioning for mURLLC over FBC-EH 6G THz wireless nano-networks which are to be investigated in Section IV-B.

IV. Joint Optimal Resource Allocation for Our Proposed Statistical Delay and Error-Rate Bounded QoS Provisioning for mURLLC Over FBC-EH 6G THz Wireless Nano-Networks

In this section, we derive the optimal resource allocation policies for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks.

A. The Set of EH Constraints in the THz Band

1) Transmit Power Constraint: Due to the limitation of the energy harvested at the nanogenerator, we can derive the minimum required energy, denoted by $\mathcal{P}_{\min}$, for transmitting one data packet at each self-powered nano device as follows:

$$\mathcal{P}_{\min} = \zeta_k\mathcal{P}_k + \mathcal{P}_{\text{circuit}} \qquad (67)$$

where ζ_k is the reciprocal of drain efficiency of power amplifier and $\mathcal{P}_{\text{circuit}}$ consists of two components, i.e., power consumption of the transmitter circuit and the receiver circuit, which is independent of the transmission distance. Then, we can derive the relationship between harvested energy after n_{cyc} cycles and the minimum required energy for transmitting a data packet with length n as follows:

$$\frac{1}{2}C_{\text{cap}}\left[V_{\text{cap}}(n_{\text{cyc}})\right]^2 \ge n\left(\zeta_k\mathcal{P}_k + \mathcal{P}_{\text{circuit}}\right). \qquad (68)$$

Plugging Eq. (14) into Eq. (68), we have

$$\frac{1}{2}C_{\text{cap}}\left\{V_g\left[1-\exp\left(-\frac{n_{\text{cyc}}\Delta Q}{V_g C_{\text{cap}}}\right)\right]\right\}^2 \ge n\left(\zeta_k\mathcal{P}_k + \mathcal{P}_{\text{circuit}}\right). \qquad (69)$$

Accordingly, we can derive a lower bound on the number of cycles n_{cyc} for self-powered nano devices as in the following in equation:

$$n_{\text{cyc}} \ge -\frac{C_{\text{cap}}V_g}{\Delta Q}\log\left[1-\sqrt{\frac{2n}{C_{\text{cap}}V_g}\left(\zeta_k\mathcal{P}_k + \mathcal{P}_{\text{circuit}}\right)}\right]. \qquad (70)$$

According to Eq. (70), to guarantee the effective value of a lower bound on n_{cyc}, we have

$$\sqrt{\frac{2n}{C_{\text{cap}}V_g}\left(\zeta_k\mathcal{P}_k + \mathcal{P}_{\text{circuit}}\right)} \le 1. \qquad (71)$$

Correspondingly, we can derive an upper-bound on the transmit power $\mathcal{P}_k$ for the self-powered nano transmitter k as follows:

$$\mathcal{P}_k \le \frac{C_{\text{cap}}V_g}{2n\zeta_k} - \frac{\mathcal{P}_{\text{circuit}}}{\zeta_k}. \qquad (72)$$

2) Energy Harvesting Rate Constraint: To derive the EH rate constraint, first we need to calculate the energy consumption rate, denoted by λ_{ec}, of each self-powered nano device as follows:

$$\lambda_{\text{ec}} < \mathcal{P}_k n C(r_k, \mathcal{P}_k). \tag{73}$$

As a result, the energy consumption rate λ_{ec} should not be greater than the energy harvesting rate λ_{eh} given in Eq. (16), i.e., $\lambda_{\text{ec}} \leq \lambda_{\text{eh}}$. Then, using Eq. (16) and (73), we can derive an upper-bound on the transmit power $\mathcal{P}_k$ for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks as follows:

$$\mathcal{P}_k \leq \frac{V_g \Delta Q}{nC(r_k, \mathcal{P}_k) t_{\text{cyc}}} \left[\exp\left(-\frac{\Delta Q n_{\text{cyc}}}{V_g C_{\text{cap}}}\right) - \exp\left(-\frac{2\Delta Q n_{\text{cyc}}}{V_g C_{\text{cap}}}\right)\right]. \tag{74}$$

B. Joint Optimal Resource Allocation for Our Proposed Statistical Delay and Error-Rate Bounded QoS Provisioning for mURLLC Over FBC-EH 6G THz Wireless Nano-Networks

The function of ϵ-effective capacity $EC_\epsilon(\theta_k)$ depends on the transmit power $\mathcal{P}_k$ and blocklength n. To maximize the ϵ-effective capacity $EC_\epsilon(\theta_k)$ while guaranteeing the EH constraints among self-powered nano devices for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks, we can formulate the optimization problem $\mathbf{P_1}$ subject to the EH constraints given by Eqs. (72) and (74) as follows:

$$\mathbf{P_1} : \arg \max_{\{n, \mathcal{P}_k\}} EC_\epsilon(\theta_k) \tag{75}$$

$$\text{s.t.: } \mathbf{C1:} R(n, r_k, \mathcal{P}_k) \approx C(r_k, \mathcal{P}_k) - \sqrt{\frac{V(r_k, \mathcal{P}_k)}{n}} Q^{-1}(\epsilon_k); \tag{76}$$

$$\mathbf{C2:} \mathcal{P}_k \leq \min\left\{\frac{C_{\text{cap}} V_g}{2n\zeta_k} - \frac{P_{\text{circuit}}}{\zeta_k}, \frac{V_g \Delta Q}{nC(r_k, \mathcal{P}_k) t_{\text{cyc}}} \times \left[\exp\left(-\frac{\Delta Q n_{\text{cyc}}}{V_g C_{\text{cap}}}\right) - \exp\left(-\frac{2\Delta Q n_{\text{cyc}}}{V_g C_{\text{cap}}}\right)\right]\right\}; \tag{77}$$

$$\mathbf{C3:} \mathcal{P}_k \geq \frac{1}{(r_k)^{-\eta} G 10^{\frac{\xi_k}{10}} S(f)} \left[\frac{\gamma_{\text{th}}\left(N_k(r_k) + N_{I_k^{(l)}}(\boldsymbol{r})\right)}{\left(\frac{c}{4\pi f r_k}\right) e^{-\frac{\alpha_{\text{abs}} r_k}{2}}}\right]^2; \tag{78}$$

$$\mathbf{C4:} \mathcal{P}_k > 0. \tag{79}$$

Equivalently, we can derive a minimization problem $\mathbf{P_2}$ as follows:

$$\mathbf{P_2} : \arg \min_{\{n, \mathcal{P}_k\}} \mathbb{E}_{r_k} \left\{\epsilon_k + (1 - \epsilon_k) \exp\left\{-\theta_k n \left[C(r_k, \mathcal{P}_k) - \sqrt{\frac{V(r_k, \mathcal{P}_k)}{n}} Q^{-1}(\epsilon_k)\right]\right\}\right\} \tag{80}$$

subject to the same constraints given in **C2**, **C3**, and **C4** which are specified by Eqs. (77), (78), and (79), respectively, in optimization problem $\mathbf{P_1}$. In order to solve the minimization problem $\mathbf{P_2}$, we define an utility function $F(n, r_k, \mathcal{P}_k)$ as follows:

$$F(n, r_k, \mathcal{P}_k) \triangleq nR(n, r_k, \mathcal{P}_k). \tag{81}$$

Then, by plugging Eq. (81) back into Eq. (80), we can rewrite the ϵ-effective capacity as follows:

$$EC_\epsilon(\theta_k) \triangleq -\frac{1}{\theta_k} \log\left(\mathbb{E}_{r_k}\left[\epsilon_k + (1 - \epsilon_k) e^{-\theta_k F(n, r_k, \mathcal{P}_k)}\right]\right). \tag{82}$$

We can formulate a new maximization problem $\mathbf{P_3}$, which is equivalent to $\mathbf{P_2}$, for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks as follows:

$$\mathbf{P_3} : \arg \max_{\{n, \mathcal{P}_k\}} F(n, r_k, \mathcal{P}_k) \tag{83}$$

subject to the same constraints given in **C2**, **C3**, and **C4** which are specified by Eqs. (77), (78), and (79), respectively, in optimization problem $\mathbf{P_1}$. To analyze the monotonicity of problem $\mathbf{P_3}$, we investigate the first-order derivative of the function $F(n, r_k, \mathcal{P}_k)$ with respect to the blocklength n when $\epsilon_k \in (0, 0.5)$ as follows:

$$\begin{aligned}\frac{\partial F(n, r_k, \mathcal{P}_k)}{\partial n} &= \frac{\partial nC(r_k, \mathcal{P}_k)}{\partial n} - \frac{\partial\left[\sqrt{nV(r_k, \mathcal{P}_k)} Q^{-1}(\epsilon_k)\right]}{\partial n} \\ &= C(r_k, \mathcal{P}_k) - \frac{\sqrt{V(r_k, \mathcal{P}_k)} Q^{-1}(\epsilon_k)}{2\sqrt{n}} \\ &= R(n, r_k, \mathcal{P}_k) + \frac{\sqrt{V(r_k, \mathcal{P}_k)} Q^{-1}(\epsilon_k)}{2\sqrt{n}} > 0. \end{aligned} \tag{84}$$

As a result, the optimization problem $\mathbf{P_3}$ specified by Eq. (83) is a monotonically increasing function of blocklength n when the error probability $\epsilon_k \in (0, 0.5)$. Then, the theorem that follows bellow characterizes the concavity of the optimization problem $\mathbf{P_3}$ with respect to the transmit power $\mathcal{P}_k$.

Theorem 4: Let the error probability be $\epsilon_k \in (0, 0.5)$ for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks and define the minimum blocklength, denoted by $n_{\min}$, as the function of ϵ_k, $\mathcal{P}_k$, $\mathcal{P}_{\text{total}}(r_k)$, $N_{I_k^{(l)}}(\boldsymbol{r})$, and $N_k(r_k)$ as follows:

$$n_{\min} \triangleq \frac{2\left[Q^{-1}(\epsilon_k)\right]^2 \left[\mathcal{P}_k + N_{I_k^{(l)}}(\boldsymbol{r}) + N_k(r_k)\right]}{\left[\mathcal{P}_{\text{total}}(r_k)\right]^4}. \tag{85}$$

If the blocklength n satisfies following condition for $n_{\min}$ given by Eq. (85):

$$n > n_{\min}, \tag{86}$$

then the optimization problem $\mathbf{P_3}$ specified by Eq. (83) is *strictly concave* with respect to the transmit power $\mathcal{P}_k$.

Proof: To prove this theorem, we need to proceed with the following two steps.

Step 1. We take the first-order derivative over the utility function $F(n, r_k, \mathcal{P}_k)$ specified in Eq. (81) with respect to the transmit power $\mathcal{P}_k$ as follows:

$$\begin{aligned}\frac{\partial F(n,r_k,\mathcal{P}_k)}{\partial \mathcal{P}_k} &= \frac{\partial\left[nC(r_k,\mathcal{P}_k)-\sqrt{nV(r_k,\mathcal{P}_k)}Q^{-1}(\epsilon_k)\right]}{\partial \mathcal{P}_k}\\ &= \frac{\partial[nC(r_k,\mathcal{P}_k)]}{\partial \mathcal{P}_k}-\frac{\partial\left[\sqrt{nV(r_k,\mathcal{P}_k)}Q^{-1}(\epsilon_k)\right]}{\partial \mathcal{P}_k}\\ &= \frac{n\mathcal{P}_{\text{total}}(r_k)}{2(\log 2)\left[\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}\\ &\quad -n(\log_2 e)\left[\frac{\mathcal{P}_{\text{total}}(r_k)+1}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\\ &\quad -\frac{\sqrt{2n}(\log_2 e)Q^{-1}(\epsilon_k)}{\sqrt{\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}}.\end{aligned} \tag{87}$$

Step 2. We take the second-order derivative of the function $F(n, r_k, \mathcal{P}_k)$ with respect to the transmit power $\mathcal{P}_k$ as follows:

$$\begin{aligned}\frac{\partial^2 F(n,r_k,\mathcal{P}_k)}{\partial \mathcal{P}_k^2} &= \frac{\sqrt{2n}(\log_2 e)Q^{-1}(\epsilon_k)}{2\left[\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]^{\frac{3}{2}}}\\ &\quad -\frac{n\left[\mathcal{P}_{\text{total}}(r_k)\right]^2}{2(\log 2)\left[\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]^2}.\end{aligned} \tag{88}$$

Applying the fact of $\mathcal{P}_{\text{total}}(r_k) < 1$ into Eq. (88), we get:

$$\begin{aligned}&\frac{\partial^2 F(n,r_k,\mathcal{P}_k)}{\partial \mathcal{P}_k^2}\\ &= \frac{\sqrt{2n}(\log_2 e)Q^{-1}(\epsilon_k)}{2\left[\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]^{\frac{3}{2}}}\\ &\quad -\frac{n\left[\mathcal{P}_{\text{total}}(r_k)\right]^2}{2(\log 2)\left[\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]^2}\\ &\le \frac{\sqrt{2n}(\log_2 e)Q^{-1}(\epsilon_k)}{2\left[\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]^{\frac{3}{2}}}\\ &\quad -\frac{n\left[\mathcal{P}_{\text{total}}(r_k)\right]^2}{2(\log 2)\left[\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]^2}\\ &= \frac{\sqrt{2n}Q^{-1}(\epsilon_k)\sqrt{\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}-n\left[\mathcal{P}_{\text{total}}(r_k)\right]^2}{2(\log 2)\left[\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]^2}\\ &= \frac{\left(\sqrt{nn_{\min}}-n\right)\left[\mathcal{P}_{\text{total}}(r_k)\right]^2}{2(\log 2)\left[\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]^2}\end{aligned} \tag{89}$$

where $n_{\min}$ is given by Eq. (85). Applying the condition: $n > n_{\min}$ specified by Eq. (86) into Eq. (89), which implies that $(\sqrt{nn_{\min}} - n) < 0$, and thus we can obtain the following equation:

$$\frac{\partial^2 F(n,r_k,\mathcal{P}_k)}{\partial \mathcal{P}_k^2} < 0. \tag{90}$$

Therefore, we complete the proof for Theorem 4. ■

Remarks on Theorem 4: Theorem 4 implies that if the finite blocklength is lower-bounded by the minimum blocklength $n_{\min}$ given by Eq. (85), then there exists the unique optimal power allocation policy that maximizes the ϵ-effective capacity in the THz band in the finite blocklength regime. Note that $n_{\min}$ is proportional to noise and interference power, and the decoding error probability ϵ_k but inversely proportional to the total received power $\mathcal{P}_{\text{total}}(r_k)$. These observations are expected because the noisier and more interfered channels warrant the longer coding blocklength for the more powerful channel-coding schemes' error-control performance. Then, the theorem that follows bellow derives the closed-form expressions for the optimal resource (transmit power) allocation strategies for our proposed schemes.

Theorem 5: **If** the blocklength $n > n_{\min}$, which is given by Eq. (85), for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks, **then** depending on whether the SINR falls into the high-SINR, medium-SINR, and low-SINR regimes, the optimal transmit power policies are given by the following three claims, respectively.

Claim 1. If the SINR falls into a high-SINR regime, which is defined as follows:

$$\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k) \gg N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k), \tag{91}$$

then the optimal power allocation policy for the high-SINR regime, denoted by $\mathcal{P}_k^{\text{OPT,H}}$, at nano transmitter k is given as follows:

$$\begin{aligned}\mathcal{P}_k^{\text{OPT,H}} = \frac{n}{2}\Bigg\{Q^{-1}(\epsilon_k)+\Bigg\{&\left[Q^{-1}(\epsilon_k)\right]^2+(\log 2)(\lambda_1-\lambda_2)\\ &+n\left[\frac{\mathcal{P}_{\text{total}}(r_k)+1}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\Bigg\}^{\frac{1}{2}}\Bigg\}^{-2}.\end{aligned} \tag{92}$$

Claim 2. If the SINR falls into a low-SINR regime, which is defined as follows:

$$\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k) \ll N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k), \tag{93}$$

then the optimal power allocation policy for the low-SINR regime, denoted by $\mathcal{P}_k^{\text{OPT,L}}$, at nano transmitter k is given as follows:

$$\begin{aligned}\mathcal{P}_k^{\text{OPT,L}} = &\frac{2nQ^{-1}(\epsilon_k)}{\left\{(\log 2)\left(\lambda_2-\lambda_1\right)-\frac{2n+n\mathcal{P}_{\text{total}}(r_k)}{2\left[N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}\right\}^2}\\ &-N_{I_k^{(l)}}(\boldsymbol{r})-N_k(r_k).\end{aligned} \tag{94}$$

Claim 3. If the SINR falls into the medium-SINR regime between the high-SINR and low-SINR regimes specified by Eqs. (91) and (93), respectively, **then** the optimal power allocation policy for the medium-SINR regime, denoted by $\mathcal{P}_k^{\text{OPT,M}}$, at nano transmitter k is given as follows:

$$\mathcal{P}_k^{\text{OPT,M}} = \frac{n}{2}\Bigg\{Q^{-1}(\epsilon_k)+\Bigg\{\left[Q^{-1}(\epsilon_k)\right]^2+(\log 2)\left(\lambda_1-\lambda_2\right)$$

$$+n\left[\frac{\mathcal{P}_{\text{total}}(r_k)+1}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]\Bigg\}^{\frac{1}{2}}\Bigg\}^{-2}-\frac{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}{\mathcal{P}_{\text{total}}(r_k)}. \quad (95)$$

Proof: To derive the closed-form solutions to the optimization problem $\mathbf{P_3}$, we can formulate its Lagrange function, denoted by J, as follows:

$$J=n\left[C(r_k,\mathcal{P}_k)-\sqrt{\frac{V(r_k,\mathcal{P}_k)}{n}}Q^{-1}(\epsilon_k)\right]+\lambda_1\left(\mathcal{P}_k^{\max}-\mathcal{P}_k\right)+\lambda_2\left(\mathcal{P}_k-\mathcal{P}_k^{\min}\right) \quad (96)$$

where λ_1 and λ_2 are the Lagrange multipliers associated with the EH constraints **C2** and **C3** which are specified by Eqs. (77) and (78), respectively, in optimization problem $\mathbf{P_1}$. Then, we can obtain the following Karush-Kuhn-Tucker (KKT) conditions:

$$\begin{cases}\frac{\partial J}{\partial \mathcal{P}_k}=\frac{n\mathcal{P}_{\text{total}}(r_k)}{2(\log 2)\left[\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}-n(\log_2 e)\\ \quad\times\left[\frac{\mathcal{P}_{\text{total}}(r_k)+1}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]-\frac{\sqrt{2n}(\log_2 e)Q^{-1}(\epsilon_k)}{\sqrt{\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}}-\lambda_1+\lambda_2\\ \quad=0;\\ \lambda_1,\lambda_2>0.\end{cases} \quad (97)$$

Using the first part of Eq. (97), we can obtain the following equation:

$$\frac{n\mathcal{P}_{\text{total}}(r_k)}{2\left[\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}-\frac{\sqrt{2n}Q^{-1}(\epsilon_k)}{\sqrt{\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}}=(\log 2)\left(\lambda_1-\lambda_2\right)+n\left[\frac{\mathcal{P}_{\text{total}}(r_k)+1}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]. \quad (98)$$

To derive the optimal power allocation policy for nano transmitter k, we prove **Claim 1**, **Claim 2**, and **Claim 3**, respectively, for this theorem as follows.

Claim 1. Considering the high-SINR regime, we have $\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)\gg N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)$. Since $\mathcal{P}_{\text{total}}(r_k)<1$, we can obtain:

$$\mathcal{P}_k\gg N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k). \quad (99)$$

As a result, we can convert Eq. (98) in the high-SINR regime into the following equation:

$$\frac{n}{2\mathcal{P}_k}-\frac{\sqrt{2n}Q^{-1}(\epsilon_k)}{\sqrt{\mathcal{P}_k}}=(\log 2)\left(\lambda_1-\lambda_2\right)+n\left[\frac{\mathcal{P}_{\text{total}}(r_k)+1}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]. \quad (100)$$

By solving Eq. (100), we obtain the optimal power allocation policy $\mathcal{P}_k^{\text{OPT,H}}$ for the high-SINR regime as given in Eq. (92).

Claim 2. In the low-SINR regime, we have $\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)\ll N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)$. As a result, we can convert Eq. (98) in the low-SINR regime into the following equation:

$$\frac{n\mathcal{P}_{\text{total}}(r_k)}{2\left[N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}-\frac{\sqrt{2n}Q^{-1}(\epsilon_k)}{\sqrt{\mathcal{P}_k+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}}=(\log 2)\left(\lambda_1-\lambda_2\right)+n\left[\frac{\mathcal{P}_{\text{total}}(r_k)+1}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]. \quad (101)$$

By solving Eq. (101), we can obtain the optimal power allocation policy $\mathcal{P}_k^{\text{OPT,L}}$ for the low-SINR regime as given in Eq. (94).

Claim 3. If the SINR falls into the medium-SINR regime between the high-SINR and low-SINR regimes, specified by Eqs. (91) and (93), respectively, then using Eq. (98), we can obtain the following equation:

$$\frac{n\mathcal{P}_{\text{total}}(r_k)}{2\left[\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)\right]}-\frac{\sqrt{2n\mathcal{P}_{\text{total}}(r_k)}Q^{-1}(\epsilon_k)}{\sqrt{\mathcal{P}_k\mathcal{P}_{\text{total}}(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}}=(\log 2)\left(\lambda_1-\lambda_2\right)+n\left[\frac{\mathcal{P}_{\text{total}}(r_k)+1}{N_{I_k^{(l)}}(\boldsymbol{r})+N_k(r_k)}\right]. \quad (102)$$

By solving the above Eq. (102), we can obtain the optimal power allocation policy for the medium-SINR regime $\mathcal{P}_k^{\text{OPT,M}}$ as given in Eq. (95). Therefore, we complete the proof for Theorem 5. ■

Remarks on Theorem 5: Conditioning on blocklength n being lower-bounded by n_{min} and depending on whether the SINR falling into which one of the three high-regime, medium-regime, or low-regime, Theorem 5 derives the three closed-forms solutions for the three corresponding optimal transmit power policies, respectively, for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks.

To ensure the optimality of the resource allocation strategies (policies) for the optimization problem $\mathbf{P_3}$, we also need to update the Lagrange multipliers λ_1 and λ_2 through iteration. In this paper, we employ the gradient projection method [50] to achieve the renewal of shadow prices due to its faster convergence towards a local extremum compared with other nongradient methods. To simplify the expressions for the Lagrange multipliers which are to be used in **Algorithm 1**, we define the following two new variables:

$$\begin{cases}\mathcal{P}_k^{\max}\triangleq\min\left\{\frac{C_{\text{cap}}V_g}{2n\zeta_k}-\frac{P_{\text{circuit}}}{\zeta_k},\frac{V_g\Delta Q}{nC(r_k,\mathcal{P}_k)t_{\text{cyc}}}\left[\exp\left(-\frac{\Delta Q n_{\text{cyc}}}{V_g C_{\text{cap}}}\right)-\exp\left(-\frac{2\Delta Q n_{\text{cyc}}}{V_g C_{\text{cap}}}\right)\right]\right\};\\ \mathcal{P}_k^{\min}\triangleq\frac{1}{(r_k)^{-\eta}G10^{\frac{\xi_k}{10}}S(f)}\left[\frac{\gamma_{\text{th}}\left(N_k(r_k)+N_{I_k^{(l)}}(\boldsymbol{r})\right)}{\left(\frac{c}{4\pi f r_k}\right)e^{-\frac{\alpha_{\text{abs}}r_k}{2}}}\right]^2.\end{cases} \quad (103)$$

Algorithm 1 FBC-EH Based Joint Optimal Resource Allocation Policy's Implementation Algorithm

Input: $a, b, B, K, t_{\text{cyc}}, \Delta Q, V_g, C_{\text{cap}}, L_{\max}, P_{\text{circuit}}, \lambda$, and γ_{th}
Initialization: $l = 0$ and $\mathcal{P}_k^{(0)} = \overline{\mathcal{P}}$
for $l = 1, l \leq L_{\max}$ **do**
  Step 1:
  Calculate the energy consumption rate by using Eq. (73)
  if $n > n_{\min}$ **then**
    if $\mathcal{P}_k \mathcal{P}_{total}(r_k) \gg N_{I_k^{(l)}}(\boldsymbol{r}) + N_k(r_k)$ **then**
      Calculate the transmit power $\mathcal{P}_k^{(l)}$ that maximize the function $F(n, r_k, \mathcal{P}_k)$ in the high-SINR regime by using Eq. (92)
    else if $\mathcal{P}_k \mathcal{P}_{total}(r_k) \ll N_{I_k^{(l)}}(\boldsymbol{r}) + N_k(r_k)$ **then**
      Calculate the transmit power $\mathcal{P}_k^{(l)}$ that maximize the function $F(n, r_k, \mathcal{P}_k)$ in the low-SINR regime by using Eq. (94)
    else
      Calculate the transmit power $\mathcal{P}_k^{(l)}$ that maximize the function $F(n, r_k, \mathcal{P}_k)$ by using Eq. (95)
    end if
  end if
  Step 2:
  Determine $n^{(l)}$ to increase the FBC-based ϵ-effective capacity $EC_\epsilon^{(l)}(\theta_k)$
  if $l = L_{\max}$ **then**
    $\mathcal{P}_k^{\text{OPT}} \leftarrow \mathcal{P}_k^{(l)}$ and $n_k^{\text{OPT}} \leftarrow n_k^{(l)}$, $\forall \mathcal{P}_k^{\text{OPT}} \in \left\{\mathcal{P}_k^{\text{OPT,H}}, \mathcal{P}_k^{\text{OPT,M}}, \mathcal{P}_k^{\text{OPT,L}}\right\}$
  end if
  Update the Lagrange multipliers $\lambda_1^{(l)}$ and $\lambda_2^{(l)}$ as specified by Eq. (104)
  $l \leftarrow (l + 1)$
end for

We further denote by l the number of current iteration and also let $\lambda_1^{(l)}$ and $\lambda_2^{(l)}$ be the Lagrange multipliers at the lth iteration, respectively. Consequently, the Lagrange multipliers $\lambda_1^{(l)}$ and $\lambda_2^{(l)}$ can be updated as follows:

$$\begin{cases} \lambda_1^{(l+1)} = \left[\lambda_1^{(l)} + \tau_1 \left(\mathcal{P}_k^{\max} - \mathcal{P}_k\right)\right]^+; \\ \lambda_2^{(l+1)} = \left[\lambda_2^{(l)} + \tau_2 \left(\mathcal{P}_k - \mathcal{P}_k^{\min}\right)\right]^+, \end{cases} \tag{104}$$

where $[a]^+ = \max\{a, 0\}$ and τ_1 and τ_2 are the positive step sizes, and $\mathcal{P}_k^{\max}$ and $\mathcal{P}_k^{\min}$ are given by Eq. (103). Define $L_{\max}$ as the maximum iteration number. Denote by $n^{(l)}$, $\mathcal{P}_k^{(l)}$, and $EC_\epsilon^{(l)}(\theta_k)$ the blocklength, transmit power, and ϵ-effective capacity at the lth iteration, respectively. Define n_k^{OPT} as the optimal blocklength and also we define $\mathcal{P}_k^{\text{OPT}} \in \left\{\mathcal{P}_k^{\text{OPT,H}}, \mathcal{P}_k^{\text{OPT,M}}, \mathcal{P}_k^{\text{OPT,L}}\right\}$ as the general notation of the optimal power allocation policy for nano transmitter k in the THz band. To solve the optimization problem $\mathbf{P_1}$, we develop the FBC-EH based optimal resource allocation policy as shown in **Algorithm 1** for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks.

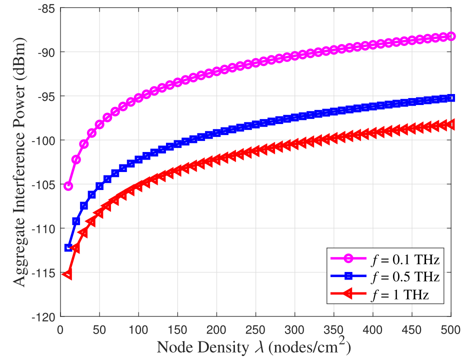

Fig. 3. The aggregate interference power (dBm) vs. node density λ in the THz band.

V. Performance Evaluations

We use MATLAB-based simulations to validate and evaluate our proposed FBC-EH based 6G THz wireless nano-networks under statistical delay and error-rate bounded QoS provisioning. Throughout our simulations, we set the bandwidth $B = 1$ THz, the radius of the THz-band covered region $a = 5$ m, the radius of the blind area $b = 5$ mm, the reference temperature $T_0 = 310K$, and the SINR threshold $\gamma_{\text{th}} = 10$ dB. In light of the state-of-the-art in molecular-electronics, we set the total signal energy to be 500 pJ, which is independent of the power spectral distribution. For our proposed THz-band FBC-EH-based nano-communication schemes, we set the generator voltage $V_g = 0.42$ V, total capacitance $C_{\text{cap}} = 176$ μF, the amount of electric charge per cycle $\Delta Q = 3.63$ nC, and the average time between vibrations $t_{\text{cyc}} = 0.02$ sec [45], [46].

Figure 3 plots the aggregate interference power as a function of the nano node density λ for our proposed schemes. We can observe from Fig. 3 that the aggregate interference first increases and finally converges to a certain value as the node density λ increases. This implies that compared to the interference, the effect of molecular absorption noise is of the secondary importance for our proposed THz-band wireless nano-networks as $K \to \infty$. Fig. 3 also shows that given the same node density λ, the aggregate interference decreases at higher frequency f. This implies that the path loss is proportional to the square of frequency f and the absorption coefficients are usually larger at higher frequency in the THz band.

Setting the frequency $f = 1$ THz, using Eq. (20), Fig. 4 plots the SINR $\gamma_k^{(l)}(\boldsymbol{r})$ as a function of the transmission distance r_k for our proposed schemes. We can observe from Fig. 4 that the SINR $\gamma_k^{(l)}(\boldsymbol{r})$ first decreases and then converges to a certain value as the transmission distance r_k increases. This implies that with a shorter transmission distance, we have a lower path loss, which leads to a larger value of the SINR. Fig. 4 shows that the SINR $\gamma_k^{(l)}(\boldsymbol{r})$ decreases as the node density λ increases, indicating that the node density is limited for the practical applications of wireless nano-networks.

Using Eqs. (52) and (54), Fig. 5 depicts the channel capacity $C(r_k, \mathcal{P}_k)$ with different blocklengths n in the THz band

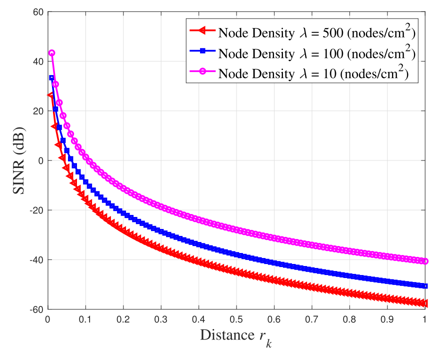

Fig. 4. The SINR (dB) vs. transmission distance r_k in the THz band in the finite blocklength regime.

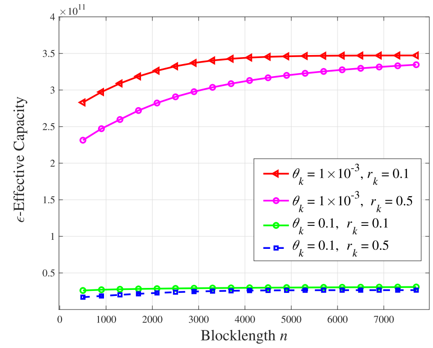

Fig. 7. The ϵ-effective capacity $EC_\epsilon(\theta_k)$ vs. blocklength n in the THz band in the finite blocklength regime.

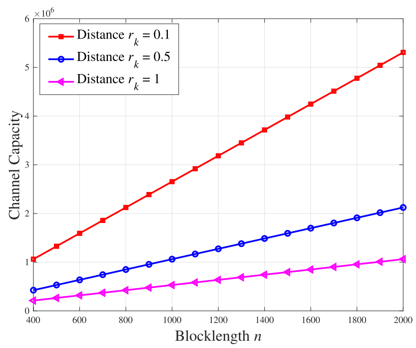

Fig. 5. The channel capacity $C(r_k, \mathcal{P}_k)$ vs. blocklength n in the THz band in the finite blocklength regime.

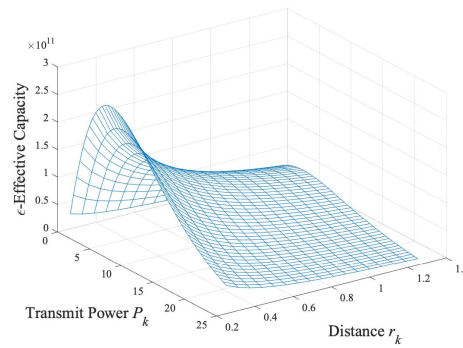

Fig. 8. The ϵ-effective capacity $EC_\epsilon(\theta_k)$ vs. transmit power $\mathcal{P}_k$ and transmission distance r_k in the THz band in the finite blocklength regime.

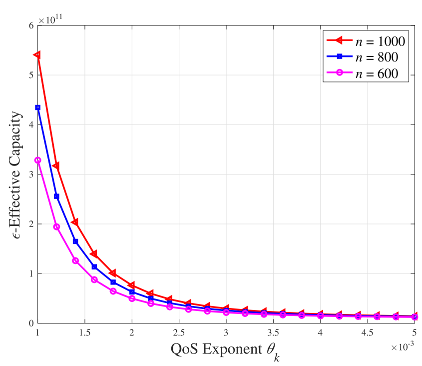

Fig. 6. The ϵ-effective capacity $EC_\epsilon(\theta_k)$ vs. QoS exponent θ_k in the THz band in the finite blocklength regime.

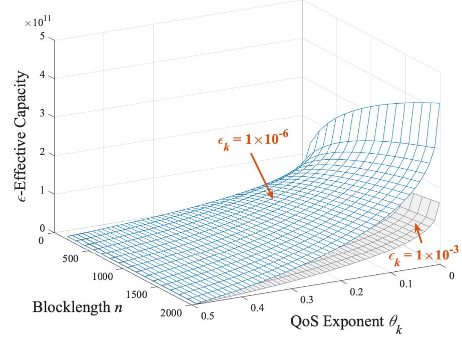

Fig. 9. The ϵ-effective capacity $EC_\epsilon(\theta_k)$ vs. blocklength n and QoS exponent θ_k in the THz band in the finite blocklength regime.

for our proposed schemes. As shown in Fig. 5, the channel capacity $C(r_k, \mathcal{P}_k)$ increases as the blocklength n increases. Fig. 5 also shows that the channel capacity $C(r_k, \mathcal{P}_k)$ decreases as the transmission distance r_k increases.

Given different blocklengths n, Fig. 6 depicts the ϵ-effective capacity $EC_\epsilon(\theta_k)$ as a function of QoS exponent θ_k in the THz band for our proposed schemes. We can observe from Fig. 6 that the ϵ-effective capacity $EC_\epsilon(\theta_k)$ decreases as the QoS exponent θ_k increases. We can also observe that the gaps among each curve decrease as the QoS exponent θ_k increases. Fig. 6 also shows that the ϵ-effective capacity $EC_\epsilon(\theta_k)$ increases as the blocklength n increases.

Setting the frequency $f = 1$ THz and node density $\lambda = 100$ nodes/cm^2, Fig. 7 plots the ϵ-effective capacity $EC_\epsilon(\theta_k)$ as a function of the blocklength n in the THz band using FBC. We can observe from Fig. 7 that the ϵ-effective capacity $EC_\epsilon(\theta_k)$ increases as the blocklength n increases and will converge to a certain value as $n \to \infty$. Fig. 7 also shows that the value of the ϵ-effective capacity $EC_\epsilon(\theta_k)$ depends on the transmission distance r_k.

Figure 8 depicts the ϵ-effective capacity $EC_\epsilon(\theta_k)$ as a function of both transmit power $\mathcal{P}_k$ (pJ) and transmission distance r_k in the THz band. We can observe from Fig. 8 that there exists an optimal transmit power $\mathcal{P}_k^{\rm OPT}$ that maximizes the ϵ-effective capacity $EC_\epsilon(\theta_k)$. Fig. 8 also shows that the optimal transmit power $\mathcal{P}_k^{\rm OPT}$ depends on the transmission distance r_k. With the increase of the transmission distance, the value of the optimal transmit power $\mathcal{P}_k^{\rm OPT}$ decreases in order to achieve the maximum ϵ-effective capacity $EC_\epsilon(\theta_k)$.

In addition, setting the frequency $f = 0.1$ THz and the transmission distance $r_k = 0.5$, Fig. 9 plots the ϵ-effective capacity $EC_\epsilon(\theta_k)$ as a function of both blocklength n and QoS exponent θ_k for our proposed schemes. We can observe from Fig. 9 that a smaller QoS exponent θ_k achieves a larger value of ϵ-effective capacity $EC_\epsilon(\theta_k)$ in the THz band. This implies that a smaller QoS exponent $\theta_k \to 0$ and a larger QoS exponent $\theta_k \to \infty$ set an upper bound and lower bound on the ϵ-effective capacity, respectively.

VI. Conclusions

We have developed optimal resource allocation policies to maximize the ϵ-effective capacity in the THz band over EH-based wireless nano-networks in the finite blocklength regime for statistical delay and error-rate bounded QoS provisioning. In particular, we have established EH-based THz-band nano-communication system models in the finite blocklength regime. Then, we have analyzed the THz-band aggregate interference, channel capacity, and channel dispersion functions using FBC. Considering statistical delay and error-rate bounded QoS provisioning, we have formulated and solved the ϵ-effective capacity maximization problem for our proposed statistical delay and error-rate bounded QoS provisioning in supporting mURLLC over FBC-EH based 6G THz wireless nano-networks. Simulation results have been included, which validate and evaluate our proposed schemes in the THz band over wireless nano-networks.

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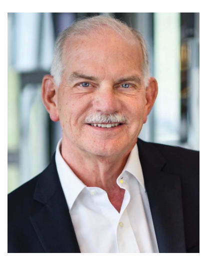

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