Statistical Delay and Error-Rate Bounded QoS Provisioning Over Massive-MIMO Based 6G Mobile Wireless Networks

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***Abstract*—The sixth generation (6G) mobile wireless networks are expected to provide a wide range of *massive ultra-reliable and low-latency communications* (mURLLC) for multimedia transmissions, which require extremely stringent delay and error-rate bounded *quality of services* (QoS). Massive multiple-input and multiple-output (MIMO) communication has been recognized as one of the promising techniques to support mURLLC thanks to its advantages in the beamforming gain and spatial multiplexing, etc. On the other hand, finite blocklength coding (FBC) based small packets communication technique has recently shown to be able to support the statistical delay and error-rate bounded QoS provisioning. However, how to achieve the *statistical delay and error-rate bounded QoS provisioning* through massive MIMO techniques has not been sufficiently studied. In this paper, we propose to apply the ϵ-effective capacity into massive MIMO communications to achieve the statistical delay and error-rate bounded provisioning for mURLLC traffic transmissions. First, we develop the FBC based scheme over a Nakagami-m fading wireless channel. Then, using the developed FBC based system model, we derive a closed-form expression for ϵ-effective capacity of massive MIMO communications, representing the maximum packet's arrival rate that a wireless channel can support under a given stringency of delay requirement and a constrained decoding error-rate. Finally, we use numerical analyses to validate and evaluate our proposed statistical delay and error-rate bounded QoS provisioning scheme over massive MIMO communication networks.**

***Index Terms*—Sixth generation (6G) wireless networks, massive multiple-input and multiple-output (MIMO), ϵ-effective capacity, statistical delay and error-rate bounded quality-of-service (QoS).**

I. Introduction

ALTHOUGH the fifth generation (5G) wireless networks have been deployed over the world, the demands of multimedia applications cannot be served satisfactorily due to the constrained wireless resources (i.e., transmit power and spectrum bandwidth). To serve these rapid growing, large volume, and wide range variety of mobile multimedia applications, wireless network researches have been shifted toward the upcoming sixth generation (6G) wireless communication networks. One of the main challenges in 6G wireless networks is how to satisfy stringent quality of service (QoS) requirements of ultra-reliable and low-latency communications (URLLC) for massive users (i.e., mURLLC) to support multimedia service transmissions. To serve massive mobile users, massive multiple-input and multiple-output (massive MIMO) communication has been proposed as a promising technique in 6G wireless networks. This is because using massive antennas, we are able to point the main beam of signal waves toward the targeted mobile user, serve more users through spatial multiplexing, and mitigate the mutlipath effect via different antenna's spatial diversity. Moreover, the finite blocklength coding (FBC) scheme has been developed for mURLLC transmissions, where senders encode the message with short packets (i.e., packets with small numbers of bits) to reduce the transmission latency while mitigating the decoding error rate.

The studies on massive MIMO communications and FBC schemes have attracted significant attentions. The work of [1] proposed the FBC based statistical QoS provisioning schemes which leverage the age-of-information as the key performance metrics in mURLLC communications. The authors of [2] derived optimal resource allocation policies for the Terahertz band wireless nano-communications to jointly mitigate the packet's transmission delay and error rate under the FBC scheme. The authors of [3] developed a cell-free massive MIMO communication system, for which they proposed max-min power control algorithms to optimize individual user's uplink and downlink throughputs.

However, how to integrate the statistical QoS provisioning with massive MIMO communications remains as an open problem. To address this problem, in this paper we first establish an FBC based statistical QoS provisioning system model over the Nakagami-m fading wireless channel. We propose to characterize the statistical delay and error rate bounded QoS provisioning by ϵ-effective capacity. Then, we

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apply this developed statistical QoS provisioning system model into massive MIMO communications, where we conduct the uplink training to estimate the channel gain and then transmit the downlink payload data using the estimated channel. In the end, we derive a closed-form expression for ϵ-effective capacity of massive MIMO communications.

The rest of this paper is organized as follows. Section II describes the FBC based statistical QoS provisioning system model. Section III derives a closed-form expression for ϵ-effective capacity of massive MIMO communications using the FBC scheme. Section IV confirms our derived the analytical results of massive MIMO communications. This paper concludes with Section V.

Notations: Denote by $\mathbb{E}[\cdot]$ the expectation of a random variable. Denote by $\mathbb{E}_{\gamma}[\cdot]$ the expectation with respect to the random variable γ if there are more than one random variables. The capital boldface letter, e.g., $\mathbf{X}$, denotes a matrix and the lower-case boldface letter, e.g., $\mathbf{x}$, denotes a vector. Denote by $\Pr\{\cdot\}$ the probability of an event.

II. System Models

A. Integrating Effective Capacity with Finite Blocklength Coding Theories Using ϵ-Effective Capacity

Let K be the total number of mobile users in the wireless cell, and let k be the index of a mobile user, $\forall k \in \{1, 2, \ldots, K\}$. Previous works [4–8] used the important performance *effective capacity* to measure the maximum packet's constant arrival rate that the time-varying wireless channel can support in order to guarantee the stringency of a statistical delay-bounded QoS requirement, specified by the QoS exponent θ_k, where θ_k is the exponential decaying rate of the packet delay violation probability [5, Eq. (2)] for the kth mobile user.

Since effective capacity theory only focuses on the delay guarantee, to support the stringent statistical delay and error-rate bounded QoS provisioning for mURLLC, we propose to also use the FBC scheme, which is an emerging and powerful solution in wireless networks, to encode the message. Using the FBC scheme, terminals send messages using packets with small numbers of bits to achieve low latency transmissions while mitigating the packets decoding error rate for reliable transmissions. We consider a wireless fading channel, which uses input blockcode set $\mathcal{A}$ and output blockcode set $\mathcal{B}$. We define a (q, W, ϵ)-code as follows [9]:

- Define W as the cardinality of a message space $\mathcal{W} = \{c_1, \cdots, c_W\}$.
- An encoder is a mapping: $\mathcal{W} \mapsto \mathcal{A}^q$, where $\mathcal{A}^q$ is the set of codewords with length q. At the receiver end, a decoder produces an estimate of the original message by observing the channel output, according to a function: $\mathcal{B}^q \mapsto \widehat{\mathcal{W}}$, where $\mathcal{B}^q$ is the set of received codewords with length q and $\widehat{\mathcal{W}}$ is the estimation of $\mathcal{W}$.
- The decoding error rate, denoted by ϵ, is defined as $\epsilon \triangleq \Pr\{c_w \neq \widehat{c}_w\}$, where $c_w \in \mathcal{W}$, $\widehat{c}_w \in \widehat{\mathcal{W}}$.

Thus, the triple-variable (q, W, ϵ) represents that a source with the cardinality W can successfully transmit messages with a probability of success $(1-\epsilon)$ over q channel uses.

To integrate the effective capacity with the FBC scheme, we propose to employ the *ϵ-effective capacity*, which measures the maximum packet's arrival rate that a wireless channel can support under a given QoS exponent and a given decoding error-rate. Let ϵ_k and $\mathcal{P}_k$ be the decoding error rate and the transmit power, respectively, for the kth mobile user. Denote by $EC_k(\theta_k, \epsilon_k, \mathcal{P}_k)$ the ϵ-effective capacity for the kth mobile user, which characterizes both statistical delay and error-rate bounded provisionings under the power allocation $\mathcal{P}_k$. We define the ϵ-effective capacity $EC_k(\theta_k, \epsilon_k, \mathcal{P}_k)$ as follows [1, Definition 5]:

Definition 1: For a (q, W, ϵ)-code, the ϵ-effective capacity $EC_k(\theta_k, \epsilon_k, \mathcal{P}_k)$ for the kth mobile user is defined as the maximum constant arrival rate for a given service process considering the delay decaying rate θ_k and the non-vanishing decoding error rate ϵ_k, subject to statistical delay and error-rate bounded QoS constraints, respectively, which is given as follows:

$$\begin{aligned} EC_k(\theta_k, \epsilon_k, \mathcal{P}_k) = -\frac{1}{q\theta_k} \log \Bigg\{ \mathbb{E}_{\zeta_k}\left[\epsilon_k\left(\frac{\zeta_k \mathcal{P}_k}{N_0}\right)\right] \\ + \mathbb{E}_{\zeta_k}\left[1 - \epsilon_k\left(\frac{\zeta_k \mathcal{P}_k}{N_0}\right)\right] e^{-\theta_k \log_2 W} \Bigg\} \end{aligned} \tag{1}$$

where ζ_k is the wireless channel fading for the kth mobile user and N_0 is the additive white Gaussian noise (AWGN). Define $\gamma_k \triangleq \frac{\zeta_k \mathcal{P}_k}{N_0}$ as the signal-to-noise ratio (SNR) of the kth mobile user. In Eq. (1), $\epsilon_k\left(\frac{\zeta_k \mathcal{P}_k}{N_0}\right) = \epsilon_k(\gamma_k)$ is given by:

$$\epsilon_k(\gamma_k) \approx Q\left(\frac{C(\gamma_k) - \frac{\log_2 W}{q}}{\sqrt{V(\gamma_k)/q}}\right) \tag{2}$$

where $Q(\cdot)$ is the Q-function. In Eq. (2), $C(\gamma_k)$ and $V(\gamma_k)$ are the channel capacity and channel dispersion, respectively, which are given by [9]:

$$C(\gamma_k) = \log_2(1+\gamma_k) \text{ and } V(\gamma_k) = 1 - \frac{1}{(1+\gamma_k)^2}. \tag{3}$$

B. The ϵ-Effective Capacity of Nakagami-m Fading Channel

Assuming that the wireless channel fading follows the Nakagami-m distribution where the probability density function (pdf), denoted by $P_Z(\zeta_k)$, is given by:

$$P_Z(\zeta_k) = \frac{\zeta_k^{m-1}}{\Gamma(m)} \left(\frac{m}{\overline{\zeta}}\right)^m \exp\left(-\frac{m}{\overline{\zeta}}\zeta_k\right) \tag{4}$$

where m is the fading parameter of the Nakagami-m distribution, $\overline{\zeta}$ is the average of ζ_k, $\forall k$, and $\Gamma(\cdot)$ is the Gamma function.

Theorem 1: If the wireless channel follows the Nakagami-m distribution, whose pdf is given by Eq. (4), then we obtain a closed-form expression for the ϵ-effective capacity of the kth mobile user under the (q, W, ϵ)-code using the FBC scheme, which is given by Eq. (5) at the top of the next page.

$$
\begin{aligned}
&EC_k(\theta_k, \epsilon_k, \mathcal{P}_k)\\
&=\begin{cases}
-\dfrac{1}{q\theta_k}\log\left\{Q\left(\sqrt{q}\left[\log_2\left(1+\dfrac{\overline{\zeta}\mathcal{P}_k}{N_0}\right)-\dfrac{\log_2 W}{q}\right]\right)+\left[1-Q\left(\sqrt{q}\left[\log_2\left(1+\dfrac{\overline{\zeta}\mathcal{P}_k}{N_0}\right)-\dfrac{\log_2 W}{q}\right]\right)\right]W^{-\frac{\theta_k}{\log 2}}\right\}, \text{ if } \dfrac{\overline{\zeta}\mathcal{P}_k}{N_0}\gg 1\\
-\dfrac{1}{q\theta_k}\log\left\{Q\left(\sqrt{\dfrac{q}{2}}\left[(\log_2 e)\left(\dfrac{\overline{\zeta}\mathcal{P}_k}{N_0}\right)^{\frac{1}{2}}-\dfrac{\log_2 W}{q}\left(\dfrac{\overline{\zeta}\mathcal{P}_k}{N_0}\right)^{-\frac{1}{2}}\right]\right)\right.\\
\qquad\left.+\left[1-Q\left(\sqrt{\dfrac{q}{2}}\left[(\log_2 e)\left(\dfrac{\overline{\zeta}\mathcal{P}_k}{N_0}\right)^{\frac{1}{2}}-\dfrac{\log_2 W}{q}\left(\dfrac{\overline{\zeta}\mathcal{P}_k}{N_0}\right)^{-\frac{1}{2}}\right]\right)\right]W^{-\frac{\theta_k}{\log 2}}\right\}, \text{ if } 0<\dfrac{\overline{\zeta}\mathcal{P}_k}{N_0}<1
\end{cases}
\end{aligned}
\tag{5}
$$

III. ϵ-Effective Capacity for Massive MIMO Communications

A. Channel Estimations for Massive MIMO Communications

Suppose that there are M_T antennas on the BS and there are M_R antennas for each mobile user, where $M_T \gg M_R$. Denote by $\mathbf{g}_{k,t} \in \mathbb{C}^{M_R\times 1}$ the channel gain between the kth mobile user and the tth antenna on the massive antenna equipped BS and denote by $d_{k,t}$ the distance between the mobile user k and the tth antenna on the BS. We give $\mathbf{g}_{k,t}$ as follows [10, Eq. (2.19)]

$$\mathbf{g}_{k,t} = \sqrt{\beta_k}\mathbf{h}_{k,t} \tag{6}$$

where $\beta_k \approx [\lambda/(4\pi d_{k,1})]^2$ is the large-scale fading coefficient assuming that the distance between two antennas on the BS is small comparing with the distance between a mobile user and the BS, $\mathbf{h}_{k,t} \in \mathbb{C}^{M_R\times 1}$ indicates the effect of small-scale fading between all antennas on the kth mobile user and the tth antenna on the BS, and λ is the wavelength. We consider that each coherence interval is divided into two phases: 1) *uplink training* to estimate the channel gain information and 2) *downlink payload data transmission* to download the data.

1) Uplink Training: Denote by $\tau_{\text{ul,p}}$ the number of samples for the uplink pilot signal, where we assume that $\tau_{\text{ul,p}} \geq M_R$. Define $\boldsymbol{\phi} = [\phi_1, \cdots, \phi_{\tau_{\text{ul,p}}}] \in \mathbb{C}^{1\times\tau_{\text{ul,p}}}$ as an orthogonal pilot training sequence satisfying $\|\boldsymbol{\phi}\|^2 = 1$, where $\|\cdot\|$ is the Euclidean norm. The pilot signal sending from the kth mobile user to the BS is denoted by $\mathbf{x}_{\text{p},k} = \sqrt{\tau_{\text{ul,p}}}\boldsymbol{\phi}$. In the training phase, we assign M_R orthogonal pilot sequences to M_R antennas of mobile user k, and both mobile user k and the BS know these pilot sequences. Let ρ_{ul} be the transmit power over uplink and $\mathbf{W}_{\text{p}} \in \mathbb{R}^{M_R\times\tau_{\text{ul,p}}}$ be the AWGN matrix. The received pilot signal, denoted by $\mathbf{Y}_{k,t}^{(\text{p})} \in \mathbb{C}^{M_R\times\tau_{\text{ul,p}}}$, at the tth antenna of the BS, is given by

$$\mathbf{Y}_{k,t}^{(\text{p})} = \sqrt{\rho_{\text{ul}}}\mathbf{g}_{k,t}\mathbf{x}_{\text{p},k} + \mathbf{W}_{\text{p}} = \sqrt{\tau_{\text{ul,p}}\rho_{\text{ul}}}\mathbf{g}_{k,t}\boldsymbol{\phi} + \mathbf{W}_{\text{p}}. \tag{7}$$

Applying the de-spreading scheme [10, Section 3.1.2] to the received pilot signal, the BS performs a de-spreading operation by correlating its received signals with the pilot signal. Denote by $\overline{\mathbf{y}}_{k,t}^{(\text{p})} \in \mathbb{C}^{M_R\times 1}$ the received signal after the de-spreading operation, which is given by

$$\overline{\mathbf{y}}_{k,t}^{(\text{p})} = \mathbf{Y}_{k,t}^{(\text{p})}\boldsymbol{\phi}^H = \sqrt{\tau_{\text{ul,p}}\rho_{\text{ul}}}\mathbf{g}_{k,t} + \overline{\mathbf{w}}_{\text{p}} \tag{8}$$

where $(\cdot)^H$ denotes the Hermitian transpose, $\overline{\mathbf{w}}_{\text{p}} \triangleq \mathbf{W}_{\text{p}}\boldsymbol{\phi}^H \in \mathbb{R}^{M_R\times 1}$, and each element of $\overline{\mathbf{w}}_{\text{p}}$ follows the Gaussian distribution $\mathcal{N}(0,1)$. Let $\mathbf{G}_k = [\mathbf{g}_{k,1}, \mathbf{g}_{k,2}, \cdots, \mathbf{g}_{k,M_T}] \in \mathbb{C}^{M_R\times M_T}$ be the channel gain matrix between all antennas on the kth mobile user and all antennas on the BS. Let $\widehat{\mathbf{G}}_k = [\widehat{\mathbf{g}}_{k,1}, \widehat{\mathbf{g}}_{k,2}, \cdots, \widehat{\mathbf{g}}_{k,M_T}] \in \mathbb{C}^{M_R\times M_T}$ be the estimated channel gain matrix, indicating the estimation of $\mathbf{G}_k$. Using the minimum mean-square error (MMSE) estimation, we obtain the estimated channel gain $\widehat{g}_{k,t}^{(j)}$ as follows [10, Eq. (3.7)] [3, Eq. (4)]:

$$
\begin{aligned}
\widehat{g}_{k,t}^{(j)} &= \mathbb{E}\left[g_{k,t}^{(j)}\middle|\overline{y}_{k,t}^{(\text{p},j)}\right]\\
&= \frac{\mathbb{E}\left[\overline{y}_{k,t}^{(\text{p},j)*}g_{k,t}^{(j)}\right]}{\mathbb{E}\left[\left|\overline{y}_{k,t}^{(\text{p},j)}\right|^2\right]}\overline{y}_{k,t}^{(\text{p},j)} = \frac{\sqrt{\tau_{\text{ul,p}}\rho_{\text{ul}}}\beta_k}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k}\overline{y}_{k,t}^{(\text{p},j)}
\end{aligned}
\tag{9}
$$

where $(\cdot)^*$ denotes the conjugate, and $\widehat{g}_{k,t}^{(j)}$ and $\overline{y}_{k,t}^{(\text{p},j)}$ are the jth element of $\widehat{\mathbf{g}}_{k,t}$ and $\overline{\mathbf{y}}_{k,t}^{(\text{p})}$, respectively. Plugging each element of $\overline{\mathbf{y}}_{k,t}^{(\text{p})}$ given by Eq. (8) into Eq. (9), the channel estimation $\widehat{\mathbf{g}}_{k,t}$ is given by:

$$\widehat{\mathbf{g}}_{k,t} = \frac{\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k}\mathbf{g}_{k,t} + \frac{\sqrt{\tau_{\text{ul,p}}\rho_{\text{ul}}}\beta_k}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k}\overline{\mathbf{w}}_{\text{p}} \tag{10}$$

2) Downlink Payload Data Transmission: In the downlink payload data transmission, the BS treats the channel estimation $\widehat{\mathbf{g}}_{k,t}$ as the true channel to transmit the data packet to the mobile user k. Let q_k be symbol intended to the mobile user k, satisfying $\mathbb{E}[|q_k|^2] = 1$. Let $\mathbf{x} = [x_1, x_2, \cdots, x_{M_T}]^{\intercal} \in \mathbb{C}^{M_T\times 1}$ be the weighted symbol transmitted from all antennas of the BS, where $(\cdot)^{\intercal}$ is the transpose. Let $\mathcal{P}_{\text{BS}}$ be the total transmit power from the massive MIMO BS to all mobile users. Each element $x_t, \forall t$, of $\mathbf{x}$ is given by

$$x_t = \sqrt{\rho_{\text{dl}}}\sum_{k=1}^{K}(\boldsymbol{\eta}_{k,t})^{\frac{1}{2}}\,\widehat{\mathbf{g}}_{k,t}^{*}q_k, \tag{11}$$

where $\rho_{\text{dl}} = \frac{\mathcal{P}_{\text{BS}}}{K}$ is the downlink power for each mobile user, $\boldsymbol{\eta}_{k,t} \in \mathbb{R}^{1\times M_R}$ is power control coefficient for the kth mobile user, each element of $\boldsymbol{\eta}_{k,t}$, denoted by $\eta_{k,t}^{(j)}$, satisfies $\eta_{k,t}^{(j)} \in [0,1], \forall j$, and $(\cdot)^{\frac{1}{2}}$ is taking square root for each element. The received signal at the kth mobile user, denoted by $\mathbf{y}_k \in \mathbb{C}^{M_R\times 1}$, is given by $\mathbf{y}_k = \mathbf{G}_k\mathbf{x} + \mathbf{w}_k$, where $\mathbf{w}_k \in \mathbb{R}^{M_T\times 1}$ is the additive noise following $\mathcal{N}(0,1)$. Thus, each element $y_k^{(j)}, \forall j \in \{1,2\cdots,M_R\}$, of $\mathbf{y}_k$ is given by:

$$y_k^{(j)} = \sum_{t=1}^{M_T} g_{k,t}^{(j)} x_t + w_k^{(j)} = \sqrt{\rho_{\text{dl}}}\sum_{t=1}^{M_T} g_{k,t}^{(j)} (\boldsymbol{\eta}_{k,t})^{\frac{1}{2}}\, \widehat{\mathbf{g}}_{k,t}^{*} q_k + \underbrace{\sqrt{\rho_{\text{dl}}}\sum_{t=1}^{M_T}\sum_{u=1,u\neq k}^{K} g_{k,t}^{(j)} (\boldsymbol{\eta}_{u,t})^{\frac{1}{2}}\, \widehat{\mathbf{g}}_{u,t}^{*} q_u + w_k^{(j)}}_{\text{effective additive noise } n_k^{(j)}} \quad (12)$$

where $n_k^{(j)}$ is the *effective additive noise* of the kth mobile user on its jth antenna.

B. Average SNR for Massive MIMO Communications

Denote the SNR of the jth antenna on the kth mobile user under the BS power allocation $\mathcal{P}_{\text{BS}}$ by $\gamma_{k,(j)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}})$, and denote the received signal SNR of the kth mobile user on all antennas by $\boldsymbol{\gamma}_k^{\text{MIMO}}(\mathcal{P}_{\text{BS}}) = \left[\gamma_{k,(1)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}}),\cdots,\gamma_{k,(M_R)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}})\right]$. The key step to derive ϵ-effective capacity of massive MIMO communications is deriving the expression for $\gamma_{k,(j)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}})$. Using Eq. (12), $\gamma_{k,(j)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}})$ is given by [11, 12]

$$\gamma_{k,(j)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}}) = \frac{\text{Var}\left[\sqrt{\frac{\mathcal{P}_{\text{BS}}}{K}} q_k \sum_{t=1}^{M_T} g_{k,t}^{(j)} \sum_{i=1}^{M_R}\sqrt{\eta_{k,t}^{(i)}}\widehat{g}_{k,t}^{(i)*}\right]}{\text{Var}\left[\sqrt{\rho_{\text{dl}}}\sum_{t=1}^{M_T}\sum_{u=1,u\neq k}^{K} g_{k,t}^{(j)} (\boldsymbol{\eta}_{u,t})^{\frac{1}{2}}\, \widehat{\mathbf{g}}_{u,t}^{*} q_u\right]+1}. \quad (13)$$

To obtain the closed-form expression for $\gamma_{k,(j)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}})$, we further derive the numerator of Eq. (13) as

$$\begin{aligned}
&\text{Var}\left[\sqrt{\frac{\mathcal{P}_{\text{BS}}}{K}} q_k \sum_{t=1}^{M_T} g_{k,t}^{(j)} \sum_{i=1}^{M_R}\sqrt{\eta_{k,t}^{(i)}}\widehat{g}_{k,t}^{(i)*}\right] \\
&= \frac{\mathcal{P}_{\text{BS}}}{K}\mathbb{E}\left[\left|\sum_{t=1}^{M_T}\sum_{i=1}^{M_R} g_{k,t}^{(j)}\sqrt{\eta_{k,t}^{(i)}}\widehat{g}_{k,t}^{(i)*}\right|^2\right] \\
&\overset{(a)}{=} \frac{\mathcal{P}_{\text{BS}}}{K}\left(\frac{\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k}\right)^2\mathbb{E}\left[\left|\sum_{t=1}^{M_T}\sum_{i=1}^{M_R}\sqrt{\eta_{k,t}^{(i)}} g_{k,t}^{(j)} g_{k,t}^{(i)*}\right|^2\right] \\
&\quad + \frac{\mathcal{P}_{\text{BS}}}{K}\left(\frac{\sqrt{\tau_{\text{ul,p}}\rho_{\text{ul}}}\beta_k}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k}\right)^2\mathbb{E}\left[\left|\sum_{t=1}^{M_T}\sum_{i=1}^{M_R}\sqrt{\eta_{k,t}^{(i)}} g_{k,t}^{(j)} \overline{w}_{\text{p}}^{(i)*}\right|^2\right]
\end{aligned} \quad (14)$$

where $\overline{w}_{\text{p}}^{(i)}$ is the ith element of $\overline{\mathbf{w}}_{\text{p}}$, and (a) is obtained by using the identity of $\mathbb{E}[|X+Y|^2] = \mathbb{E}[|X|^2]+\mathbb{E}[|Y|^2]$ when X and Y are two independent random variables and $\mathbb{E}[Y]=0$. We further derive

$$\begin{aligned}
&\mathbb{E}\left[\left|\sum_{t=1}^{M_T}\sum_{i=1}^{M_R}\sqrt{\eta_{k,t}^{(i)}} g_{k,t}^{(j)} g_{k,t}^{(i)*}\right|^2\right] \\
&= \beta_k^2\sum_{t=1}^{M_T}\sum_{i=1}^{M_R}\mathbb{E}\left[\left(h_{k,t}^{(j)}\right)^2 \eta_{k,t}^{(i)}\left(h_{k,t}^{(i)}\right)^2\right] \\
&\quad + \beta_k^2\sum_{t=1}^{M_T}\sum_{i=1}^{M_R}\mathbb{E}\left[h_{k,t}^{(j)}\sqrt{\eta_{k,t}^{(i)}}h_{k,t}^{(i)}\sum_{(n,l)\neq(t,i)} h_{k,n}^{(j)}\sqrt{\eta_{k,n}^{(l)}}h_{k,n}^{(l)}\right].
\end{aligned} \quad (15)$$

Using the system model in Section II-B that the small-scale fading follows the Nakagami-m fading with average fading power $\overline{\zeta}$, we have $\mathbb{E}\left[h_{k,t}^{(i)}\right] = \overline{\zeta}$ and $\mathbb{E}\left[\left(h_{k,t}^{(i)}\right)^2\right] = \overline{\zeta}^2$. We further derive Eq. (15) by using $\mathbb{E}[XY] = \mathbb{E}[X]\mathbb{E}[Y]$ if X and Y are uncorrelated random variables as follows:

$$\mathbb{E}\left[\left|\sum_{t=1}^{M_T}\sum_{i=1}^{M_R}\sqrt{\eta_{k,t}^{(i)}} g_{k,t}^{(j)} g_{k,t}^{(i)*}\right|^2\right] = \beta_k^2\overline{\eta}M_T^2M_R^2\overline{\zeta}^4. \quad (16)$$

Similarly, we also derive the expectation in the last part of Eq. (14) as:

$$\begin{aligned}
\mathbb{E}\left[\left|\sum_{t=1}^{M_T}\sum_{i=1}^{M_R}\sqrt{\eta_{k,t}^{(i)}} g_{k,t}^{(j)} \overline{w}_{\text{p}}^{(i)*}\right|^2\right] &= \beta_k\overline{\eta}\sum_{t=1}^{M_T}\sum_{i=1}^{M_R}\mathbb{E}\left[\left(h_{k,t}^{(j)}\right)^2\right] \\
&= \beta_k\overline{\eta}M_TM_R\overline{\zeta}^2
\end{aligned} \quad (17)$$

and derive the first term of the denominator in Eq. (13) as

$$\begin{aligned}
&\text{Var}\left[\sqrt{\rho_{\text{dl}}}\sum_{t=1}^{M_T}\sum_{u=1,u\neq k}^{K} g_{k,t}^{(j)} (\boldsymbol{\eta}_{u,t})^{\frac{1}{2}}\, \widehat{\mathbf{g}}_{u,t}^{*} q_u\right] \\
&= \rho_{\text{dl}}\overline{\eta}M_TM_R(K-1)\mathbb{E}\left[\left(g_{k,t}^{(j)}\right)^2\left(\widehat{g}_{u,t}^{(i)*}\right)^2\right] \\
&\quad + \rho_{\text{dl}}\overline{\eta}M_T^2M_R(M_R-1)(K-1)^2\mathbb{E}\left[\left(g_{k,t}^{(j)}\right)^2\right]\left(\mathbb{E}\left[\widehat{g}_{u,t}^{(i)*}\right]\right)^2 \\
&= \rho_{\text{dl}}\overline{\eta}\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k\overline{\zeta}^2M_TM_R(K-1)(\tau_{\text{ul,p}}\rho_{\text{ul}}\overline{\zeta}^2+1) \\
&\qquad \times\mathbb{E}\left[\frac{\beta_u^2}{(1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u)^2}\right] \\
&\quad + \rho_{\text{dl}}\overline{\eta}\beta_k\overline{\zeta}^2M_T^2M_R(M_R-1)(K-1)^2\left(\mathbb{E}\left[\frac{\beta_u^{\frac{3}{2}}}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u}\right]\right)^2.
\end{aligned} \quad (18)$$

Then we give the expressions for $\mathbb{E}\left[\frac{\beta_u^2}{(1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u)^2}\right]$ and $\mathbb{E}\left[\frac{\beta_u^{\frac{3}{2}}}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u}\right]$ in the following Theorem.

Theorem 2: Assuming that mobile users are uniformly distributed within the wireless cell with inner radius $R_{\min}$ and outer radius $R_{\max}$, we have

$$\mathbb{E}\left[\frac{\beta_u^2}{(1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u)^2}\right] = \frac{\lambda^2}{16\pi^2(R_{\max}^2-R_{\min}^2)}(X_{\max}-X_{\min}) \quad (19)$$

and

$$\mathbb{E}\left[\frac{\beta_u^{\frac{3}{2}}}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u}\right] = \frac{\lambda^2}{16\pi^2(R_{\max}^2-R_{\min}^2)}\log\left(\frac{X_{\max}}{X_{\min}}\right) \quad (20)$$

where

$$\begin{cases} X_{\max} = \dfrac{\lambda^2}{16\pi^2(R_{\min}^2+\iota^2)+\tau_{\text{ul,p}}\rho_{\text{ul}}\lambda^2}; \\ X_{\min} = \dfrac{\lambda^2}{16\pi^2(R_{\max}^2+\iota^2)+\tau_{\text{ul,p}}\rho_{\text{ul}}\lambda^2}. \end{cases} \tag{21}$$

and ι is the height of massive MIMO antennas.

Proof: Assuming that mobile users are uniformly distributed within the wireless cell with inner radius $R_{\min}$ and outer radius $R_{\max}$ and defining the random variable of a mobile users' radius as R, the pdf of a user's radius, denoted by $p_R(r)$ is given by:

$$p_R(r) = \frac{2r}{R_{\max}^2 - R_{\min}^2} \tag{22}$$

Defining $X \triangleq \frac{\beta_u}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u}$, we derive the cumulative distribution function (cdf) of X, denoted by $P_X(x)$, as:

$$\begin{aligned} P_X(x) &= \Pr\left\{\frac{\lambda^2}{(4\pi)^2\left(R^2+\iota^2\right)+\tau_{\text{ul,p}}\rho_{\text{ul}}\lambda^2} \leq x\right\} \\ &\overset{(b)}{=} 1 - \frac{1}{R_{\max}^2 - R_{\min}^2}\left(\frac{\lambda^2(1-\tau_{\text{ul,p}}\rho_{\text{ul}}x)}{(4\pi)^2 x} - \iota^2\right) \end{aligned} \tag{23}$$

where (b) is obtained by using Eq. (22). Then, using Eq. (23), we have the pdf of X, denoted by $p_X(x)$, as follows:

$$p_X(x) = \frac{\partial P_X(x)}{\partial x} = \frac{\lambda^2}{16\pi^2 x^2(R_{\max}^2 - R_{\min}^2)}. \tag{24}$$

Therefore, we have:

$$\mathbb{E}\left[\frac{\beta_u^2}{(1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u)^2}\right] = \mathbb{E}\left[X^2\right] = \int_{X_{\min}}^{X_{\max}} x^2 p_X(x)dx \tag{25}$$

where $X_{\max}$ and $X_{\min}$ are given by Eq. (21). Plugging Eq. (24) into Eq. (25), we obtain Eq. (19). Similarly, we also have

$$\mathbb{E}\left[\frac{\beta_u^{\frac{3}{2}}}{1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_u}\right] \approx \mathbb{E}[X] = \int_{X_{\min}}^{X_{\max}} x p_X(x)dx, \tag{26}$$

and thus, we obtain Eq. (20), completing the proof of Theorem 2. ■

Plugging Eq. (19) and Eq. (20) into Eq. (18), we further derive Eq. (18) as:

$$\begin{aligned} &\text{Var}\left[\sqrt{\rho_{\text{dl}}}\sum_{t=1}^{M_T}\sum_{u=1,u\neq k}^{K} g_{k,t}^{(j)}\left(\boldsymbol{\eta}_{u,t}\right)^{\frac{1}{2}}\widehat{\mathbf{g}}_{u,t}^{*}q_u\right] \\ &= \rho_{\text{dl}}\overline{\eta}\beta_k\overline{\zeta}^{2}M_T M_R(K-1)\frac{\tau_{\text{ul,p}}\rho_{\text{ul}}(\tau_{\text{ul,p}}\rho_{\text{ul}}\overline{\zeta}^{2}+1)\lambda^2}{16\pi^2(R_{\max}^2-R_{\min}^2)} \\ &\qquad \times (X_{\max}-X_{\min}) \\ &\quad + \rho_{\text{dl}}\overline{\eta}\beta_k\overline{\zeta}^{2}M_T^2 M_R\frac{(M_R-1)(K-1)^2\lambda^4}{(4\pi)^4(R_{\max}^2-R_{\min}^2)^2}\left[\log\left(\frac{X_{\max}}{X_{\min}}\right)\right]^2. \end{aligned} \tag{27}$$

Therefore, the closed-form expression for $\gamma_{k,(j)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}})$ can be obtained by plugging Eq. (16) and Eq. (17) into Eq. (14), and then plugging Eq. (27) and Eq. (14) into Eq. (13). The average of SNR $\overline{\gamma}_k^{\text{MIMO}}(\mathcal{P}_{\text{BS}})$ can be obtained by

$$\begin{aligned} \overline{\gamma}_k^{\text{MIMO}}(\mathcal{P}_{\text{BS}}) &= \frac{1}{M_R}\sum_{j=1}^{M_R}\gamma_{k,(j)}^{\text{MIMO}}(\mathcal{P}_{\text{BS}}) \\ &= \frac{\mathcal{P}_{\text{BS}}\beta_k^3\tau_{\text{ul,p}}\rho_{\text{ul}}\overline{\eta}M_T M_R\overline{\zeta}^{2}}{K(1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k)^2}\left(1+\tau_{\text{ul,p}}\rho_{\text{ul}}\beta_k M_T M_R\overline{\zeta}^{2}\right) \\ &\times\left\{1+\frac{\mathcal{P}_{\text{BS}}\beta_k\overline{\eta}M_T M_R\overline{\zeta}^{2}(K-1)\lambda^2}{K(4\pi)^2(R_{\max}^2-R_{\min}^2)}\right. \\ &\times\left[\tau_{\text{ul,p}}\rho_{\text{ul}}\left(\tau_{\text{ul,p}}\rho_{\text{ul}}\overline{\zeta}^{2}+1\right)(X_{\max}-X_{\min})\right. \\ &\left.\left.+\frac{M_T(M_R-1)(K-1)\lambda^2}{(4\pi)^2(R_{\max}^2-R_{\min}^2)}\left[\log\left(\frac{X_{\max}}{X_{\min}}\right)\right]^2\right]\right\}^{-1}. \end{aligned} \tag{28}$$

C. Closed-Form Expression for ϵ-Effective Capacity in Massive-MIMO Communications

Replacing $\frac{\zeta\mathcal{P}_k}{N_0}$ in Eq. (5) by $\overline{\gamma}_k^{\text{MIMO}}(\mathcal{P}_{\text{BS}})$, we obtain a closed-form expression for ϵ-effective capacity $EC_k^{\text{BS}}(\theta_k, \epsilon_k, \mathcal{P}_{\text{BS}})$ if downloading a multimedia data using a massive MIMO BS, which is given by Eq. (29) at the bottom of the next page, where $\overline{\gamma}_k^{\text{MIMO}}(\mathcal{P}_{\text{BS}})$ is given by Eq. (28).

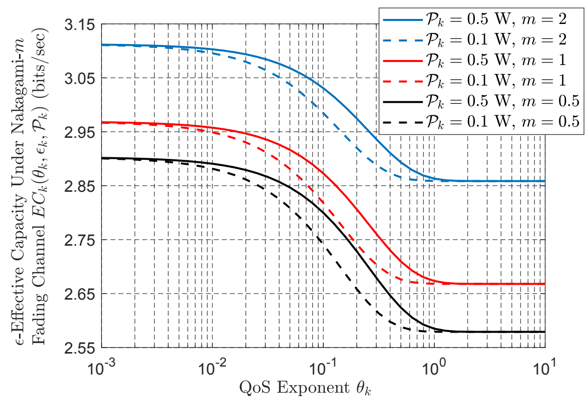

Fig. 1. The function of ϵ-effective capacity with respect to QoS exponent θ_k under different values of transmit power $\mathcal{P}_k$ and Nakagami-m parameter m.

IV. Performance Evaluations

Figure 1 plots the function of ϵ-effective capacity $EC_k(\theta_k, \epsilon_k, \mathcal{P}_k)$ with respect to QoS exponent θ_k under different transmit powers $\mathcal{P}_k = 0.1, 0.5$ and Nakagami-m parameters $m = 0.5, 1, 2$, respectively. We set other parameters as follows: length of a codeword $q = 500$, average SNR $\overline{\gamma} = 20$ dB, and channel fading range $\zeta_k = [0.1, 1]$. Fig. 1 shows that for the same Nakagami-m parameter, the ϵ-effective capacity increases as the transmit power allocation $\mathcal{P}_k$ increases. This is because a larger value of $\mathcal{P}_k$ yields a larger value of SNR for the same channel fading ζ_k and the same AWGN noise. We

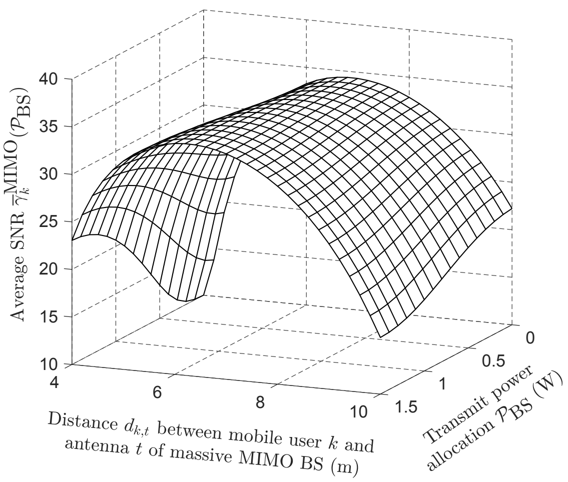

Fig. 2. The average SNR $\overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}})$ under different values of distance $d_{k,t}$ between the mobile user k and the tth antenna of massive MIMO BS and different values of transmit power allocation $\mathcal{P}_{\mathrm{BS}}$.

can also observe from Fig. 1 that for the same transmit power, ϵ-effective capacity increases as the Nakagami-m parameter increases. This is because m represents the channel quality, and thus, the larger m is, the larger $EC_k(\theta_k, \epsilon_k, \mathcal{P}_k)$ is.

In Fig. 2, we plot the average SNR of the kth mobile user $\overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}})$ under different values of distance $d_{k,t}$ between the mobile user k and the tth antenna of massive MIMO BS. We set $\lambda = 8$m, the range of massive MIMO BS transmit power allocation $\mathcal{P}_{\mathrm{BS}}$ as $[0, 1.5]$W, the range of distance $d_{k,t}$ as $[4, 10]$m. Fig. 2 shows that there exists an optimal distance $d_{k,t}$ which maximizes the average SNR, indicating that a mobile user can adjust its position to obtain a better wireless channel. We also observe from Fig. 2 that for small distance $d_{k,t}$, the average SNR is an increasing function of the allocated transmit power $\mathcal{P}_{\mathrm{BS}}$. However, for large distance $d_{k,t}$, the average SNR is a decreasing function of the allocated transmit power $\mathcal{P}_{\mathrm{BS}}$. This is implies that the interference among antennas of a mobile user has more impact when the value of distance $d_{k,t}$ is large.

V. Conclusions

To support the mURLLC using massive MIMO techniques over 6G wireless networks, we have proposed to use ϵ-effective capacity for massive MIMO communications to measure the maximum packet's arrival rate that a massive MIMO channel can support under a given delay decaying rate and a given decoding error-rate. We have set up an FBC based statistical QoS provisioning system model over the Nakagami-m fading wireless channel. Using the developed system model, we have derived a closed-form expression for ϵ-effective capacity of massive MIMO communications using FBC.

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$$
\begin{aligned}
&EC_k^{\mathrm{BS}}(\theta_k, \epsilon_k, \mathcal{P}_{\mathrm{BS}}) \\
&= \begin{cases}
-\dfrac{1}{q\theta_k}\log\left\{Q\left(\sqrt{q}\left[\log_2\left(1+\overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}})\right)-\dfrac{\log_2 W}{q}\right]\right)\right. \\
\qquad\left.+\left[1-Q\left(\sqrt{q}\left[\log_2\left(1+\overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}})\right)-\dfrac{\log_2 W}{q}\right]\right)\right]W^{-\frac{\theta_k}{\log 2}}\right\}, & \text{if } \overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}}) \gg 1 \\
-\dfrac{1}{q\theta_k}\log\left\{Q\left(\sqrt{\dfrac{q}{2}}\left[(\log_2 e)\left(\overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}})\right)^{\frac{1}{2}}-\dfrac{\log_2 W}{q}\left(\overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}})\right)^{-\frac{1}{2}}\right]\right)\right. \\
\qquad\left.+\left[1-Q\left(\sqrt{\dfrac{q}{2}}\left[(\log_2 e)\left(\overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}})\right)^{\frac{1}{2}}-\dfrac{\log_2 W}{q}\left(\overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}})\right)^{-\frac{1}{2}}\right]\right)\right]\right\}, & \text{if } 0 < \overline{\gamma}_k^{\mathrm{MIMO}}(\mathcal{P}_{\mathrm{BS}}) < 1
\end{cases}
\end{aligned}
\tag{29}
$$