






# Mission Effective Capacity—A Novel Dependability Metric: A Study Case of Multiconnectivity-Enabled URLLC for IIoT

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**Abstract**—Various industrial Internet of Things applications demand execution periods throughout which no communication failure is tolerated. However, the classical understanding of reliability in the context of ultra-reliable low-latency communication (URLLC) does not reflect on the time-varying characteristics of the wireless channel. In this article, we introduce a novel mission reliability and mission effective capacity metric that takes these phenomena medium into account, while specifically studying multiconnectivity (MC)-enabled industrial radio systems. We assume uplink short packet transmission with no channel state information at URLLC user (the transmitter) and sporadic traffic arrival. Moreover, we leverage the existing framework of dependability theory and provide closed-form expressions (CFEs) for the mission reliability of the MC system using the maximal-ratio combining scheme. We do so by utilizing the mean time to first failure, which is the expected time of failure occurring for the first time. Moreover, we also derive exact CFEs for second-order statistics, such as level crossing rate and average fade duration, showing how fades are distributed in fading channels with respect to time. Furthermore, the design throughput maximization problem under the mission reliability constraint is solved numerically through the cross-entropy method.

**Index Terms**—Dependable industrial radio systems, dependability theory, finite blocklength, IIoT, mean time to first failure, mission effective capacity, mission reliability, multiconnectivity.

## I. INTRODUCTION

THE main objective of Industry 4.0 or the fourth industrial revolution is to digitize industrial machinery toward automation of tasks with reduced human participation and decentralized manufacturing of products in a variety of industrial

practices [1]. This current development is projected to resolve the demand for enhanced production efficiency, greater product customization, and a shorter production period. Industry 4.0 is driven by the industrial Internet of Things (IIoT), a subset of IoT that utilizes industrial radio systems to link different components such as sensors and several other types of equipment with industrial management applications to allow real-time control of ubiquitous actuators and machines across the smart factory [2].

Several candidate channel codes, such as polar and low density parity check, were considered for high reliability transmission of ultra-reliable low-latency communication (URLLC) data [3], [4]. One of the main challenges of industrial radio systems lies in providing connectivity reliability guarantees, i.e., URLLC. Reliability as a key performance indicator (KPI) in the context of URLLC is regarded as the percentage of transmission being successful within a certain deadline [5]. However, this classical definition of reliability reflects neither the temporal distribution of the failures nor the distinct time duration needed for URLLC applications. Moreover, various applications demand a time span throughout which failure is not tolerated, together with other stringent requirements such as ultra-reliability and low latency. This time span is normally referred to as mission duration [6]. The current KPIs do not address these requirements. Besides, what requirements should be considered while designing industrial radio systems if they are to be integrated with highly dependable industrial applications? For example, does the industrial radio systems need to be defined and engineered to ensure optimum packet loss rates at a link level of, e.g.,  $10^{-9}$ , or are novel and more accurate performance metrics and design strategies required to distinguish, assess, and upgrade radio-access technologies (RAT) toward becoming industrial-grade for time-critical and highly dependable industrial applications [7]? Dependability theory assists in finding answers to these questions.

Dependability is an influential theory that encompasses key attributes of reliability, availability, safety, maintainability, and integrity [8]. However, only reliability and availability can be quantified as the probabilities of correct and continuous services. Dependability attributes are of utmost significance in industrial or vehicular wireless applications, where system failure can have severe repercussions. Such applications' inherent temporal dynamics pose the timeliness conditions determined by the environment in which they work. Therefore, the communication system should be efficient enough to transmit messages under temporal limits.

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Multiconnectivity (MC) can be utilized to achieve the quantifiable attributes of dependability. MC, as an enabler of URLLC, uses multiple communication paths simultaneously to attain ultra-reliability and low latency [9]. A wide range of diversity schemes are used to distinguish MC paths, such as spatial diversity, frequency diversity, or RAT diversity [10]. Therefore, MC is seen as a viable approach for designing dependable industrial radio systems.

### A. Related Work

In literature, only a few researchers leveraged the dependability theory to wireless communication concerning time aspects (see [6] and references therein). Recently, Höbner *et al.* [6] have brought forth the idea of mission reliability to wireless communication and provided the closed-form expression (CFE) of mean time to first failure (MTTFF) and an approximate CFE for mission reliability of a point-to-point system with multiple links using a selection combining scheme.

The uncertain traffic arrival is one of the impediments in ensuring URLLC, which is sporadic in nature [11]. The traffic produced by URLLC applications entails time-varying wireless channel service guarantees, which can engender major quality of service (QoS) violations owing to random environmental changes. Due to the wireless medium's random nature, deterministic QoS constraints are crucial to guarantee delay-sensitive services over wireless networks. Thus, in [12], Wu and Negi proposed to switch the framework from deterministic to statistical using the notion of effective capacity (EC). The EC model aims to characterize wireless channels in terms of functions that can be mapped to link-level QoS metrics, such as delay bound violation probability for measuring the link and physical layer characteristics in the presence of statistical QoS limitations. Thus, EC is defined as a measure of throughput that the random wireless channel can handle with a certain latency constraint. Recently, EC has been widely used in various settings to assess the tradeoff between reliability, latency, energy efficiency, and security [13]. In [14], the performance of EC that uses finite blocklength over multiple coherence blocks with decoding error has been analyzed within queuing constraints and provides the throughput–delay tradeoff for variable and fixed transmission rates. The work in [15] explores EC and QoS exponent over parallel channels under fading with statistical and instantaneous channel state information (CSI) at the transmitter with sporadic traffic arrivals.

### B. Contribution

None of the prior work related to EC in the technical literature takes temporal aspects of a wireless channel into accounts. Motivated by this, our novel work aims to advance a mathematical framework that underpins dependability theory for the performance analysis of dependable industrial radio systems and captures the time-varying characteristics of wireless channels under the notion of EC. Specifically, our main contributions are as follows.

- 1) We derive exact CFE for level crossing rate (LCR) and average fade duration (AFD) in an MC scenario using maximal ratio combining (MRC).
- 2) We derive the tractable CFEs for mission reliability and MTTFF at the finite blocklength (FBL) transmission regime. Then, we present a novel mission EC ( $M_{EC}$ )

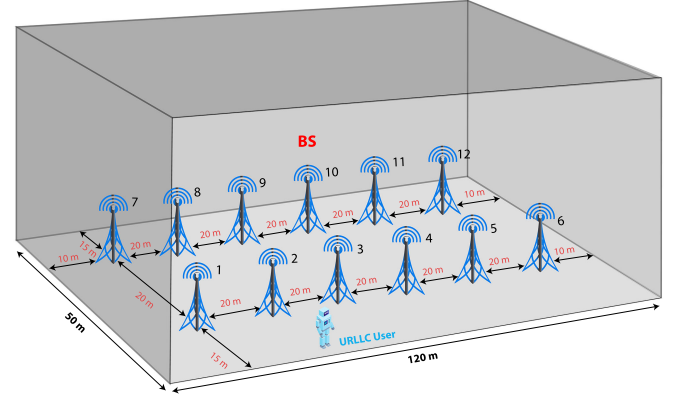


Fig. 1. System model. A URLLC user (the transmitter) is connected to  $N$  BSs, who perform MRC to add up received SNRs of all links.

metric elicited from dependability theory for MC-enabled URLLC networks. This novel metric reflects on the temporal aspects of a wireless channel. We also derive the mission reliability and mission EC ( $M_{EC}^{IBL}$ ) for the infinite blocklength regime as a special case.

- 3) We examine random traffic arrival by considering a Markovian source, which imposes serious challenges in ensuring URLLC.
- 4) The maximization of  $M_{EC}$  by considering the mission reliability constraint under a fixed transmission rate is solved numerically through the cross-entropy (CE) method.

The rest of this article is organized as follows. Section II introduces the system model and our main assumptions. Section III presents the performance metrics such as LCR, AFD, mission reliability, and MTTFF. Section IV provides the mission EC for FBL. Moreover, it also provides analysis of the source model, statistical QoS provisioning, and the mission EC maximization. Section V discusses the numerical results. Section VI concludes this article.

## II. SYSTEM MODEL

We assume a channel model for the indoor industrial factory (InF) subscenario, i.e., sparse clutter low base station (BS) height (InF-SL), where both the transmitter and the receiver are placed beneath the average height of the clutter, as illustrated in Fig. 1 [16]. We suppose an MC uplink setup, where a URLLC user is connected to  $N$  BSs, while communication failure may occur by virtue of multipath propagation. The URLLC user accumulates the generated data prior to transmission in a buffer. All BSs and the URLLC user are equipped with a single antenna. Each link undergoes quasi-static Rayleigh fading; thus, channel coefficients remain unchanged over a block interval and change independently for the subsequent block. The BSs in the InF scenario are deployed 20 m apart from each other,<sup>1</sup> and the propagation model amalgamates the pathloss, thus delineating the degradation in signal strength over distance. The pathloss

<sup>1</sup>Although the analytical results are evaluated in the context of the indoor factory scenario proposed by 3GPP in TR 38.901 [16], the derived analytical results and the numerical findings are not restricted to uniform position of BSs. The core findings remain valid, and proposed techniques are applicable for scenarios with arbitrarily BS locations.

is given under line of sight (LOS)  $PL_{LOS}$  and non-line-of-sight (NLOS)  $PL_{NLOS}$  situations. The  $PL_{LOS}$  for InF is given as [16]

$$PL_{LOS} = (31.84 + 21.5 \log_{10}(d_{3D}) + 19 \log_{10}(f_c)) Pr_{LOS} \quad (1)$$

where LOS probability is  $Pr_{LOS} = \exp(-\frac{d_{2D}(1-r)}{d_{clutter}})$ , while  $d_{2D}$  and  $d_{3D}$  (in meter) indicate the 2-D (i.e., distance on the ground) and 3-D distances between the URLLC user and the BS,  $d_{clutter}$  is typical clutter size,  $r$  represents the clutter density, and  $f_c$  denotes the carrier frequency (in gigahertz). Likewise,  $PL_{NLOS}$  for InF-SL is given as [16]

$$PL_{InF-SL} = 33 + 25.5 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) \quad (2)$$

$$PL_{NLOS} = \max(PL_{InF-SL}, PL_{LOS}) \times Pr_{NLOS} \quad (3)$$

where the NLOS probability is  $Pr_{NLOS} = (1 - Pr_{LOS})$ . Moreover, we consider CSI availability at the BSs only,<sup>2</sup> which is a common assumption. The URLLC user<sup>3</sup> does not know the channel states and transmits the data at a fixed transmission rate  $R$ . The aim is to enable the use of the redundant data received from multiple inputs. Many combining algorithms are known in the literature [18]; several of them combine the received inputs at the symbol level. Herein, we assume MRC scheme, and denote the received envelope at receivers as  $\gamma_{MRC}$ . The probability density function (PDF) and cumulative distribution function (CDF) of envelope  $\gamma_{MRC}$  are obtained by simple transformation of variables in [19, Proposition 3.1] as

$$f_{\Gamma_{MRC}}(\gamma) = \sum_{i=1}^N \bar{\Gamma}_i^{N-2} 2\gamma \exp\left(-\frac{\gamma^2}{\bar{\Gamma}_i}\right) \prod_{\substack{j=1 \\ j \neq i}}^N \frac{1}{\bar{\Gamma}_i - \bar{\Gamma}_j} \quad (4)$$

$$F_{\Gamma_{MRC}}(\gamma) = \sum_{i=1}^N \bar{\Gamma}_i^{N-1} \left(1 - \exp\left(-\frac{\gamma^2}{\bar{\Gamma}_i}\right)\right) \prod_{\substack{j=1 \\ j \neq i}}^N \frac{1}{\bar{\Gamma}_i - \bar{\Gamma}_j} \quad (5)$$

where  $\bar{\Gamma} = T_x - PL_{NLOS} - N_0$  is the received average SNR, while  $T_x$  and  $N_0$  are transmit power and receive noise power, respectively. It is essential to reduce the end-to-end delay for low-latency communication in industrial radio systems, thus motivating the transmission of short packets [3]. Therefore, we focus on the transmission of short packets by exploiting the seminal contribution of [20]. In this pioneering work, the authors derived the achievable rate at which short packets can be transmitted with error probability bound  $\epsilon \in [0, 1]$  as a function of the SNR and finite blocklength  $n$ . Using such a framework, we can guarantee with probability  $1 - \epsilon$  that the signal is received successfully if its received SNR  $|\gamma|^2$  is above a certain threshold  $\eta$ . Hence, the wireless channel is interpreted as a repairable component that conforms to the Gilbert–Elliot model [21]. Thus, we differentiate the two states by defining the random variable channel state as

$$Y(t)_{FBL} = \begin{cases} 0, & \text{if } \gamma < \sqrt{\eta}, \text{ "OFF," "failed"} \\ 1, & \text{if } \gamma \geq \sqrt{\eta}, \text{ "ON," "operational"} \end{cases} \quad (6)$$

<sup>2</sup>We assume the ideal case where perfect CSI at the receiver is available, which serves as an upper bound of the performance. Moreover, such an assumption allows us to concentrate our discussions on the dependability metric and framework introduced in this article [17].

<sup>3</sup>The system model with one URLLC user is a simple case, which we are considering as the first step in this analysis.

where  $\eta$  is the solution of [22, Eq. (8)]

$$\eta^{(j)} = 2^{R + \frac{1}{\sqrt{n}} \sqrt{1 - \frac{1}{(1+\eta^{(j-1)})^2}} \log_2 e Q^{-1}(\epsilon)} - 1 \quad (7)$$

where  $Q^{-1}(\cdot)$  is the inverse of the  $Q$ -function and  $e$  is the Euler's number. The superscript  $j$  represents the iteration index. Here, "operational" means communication with guarantee of error probability less than  $\epsilon$ ; otherwise, the system is in "failed" state. Note that (7) can be solved recursively for a given  $R$  and  $\epsilon$  by introducing a stopping criterion  $\eta_{\Delta}$ , e.g., until  $|\eta^{(i)} - \eta^{(i-1)}| < \eta_{\Delta}$  is satisfied, and using  $\eta^{(0)} = \infty$ . We denote the failure rate  $\lambda$  and the repair rate  $\mu$  as the transition rates between two-channel states. Although the PDF and the CDF are helpful in understanding how fades in the fading channel are distributed, they do not convey any information about the distribution of fades with respect to time. Conversely, the second-order statistics, i.e., AFD and LCR, carry this information. It is of paramount importance to characterize the AFD and the LCR precisely in designing URLLC networks because they impart exact manifestation of the rate of change of the signal with respect to time, which is beneficial in identifying failure events in URLLC networks [23].

### III. PERFORMANCE METRICS

#### A. Level Crossing Rate

The LCR,  $Q_{\Gamma}(\gamma)$ , by definition, is the rate at which the signal envelope exceeds the specified threshold level  $\gamma$  in a positive (or in a negative) direction per unit time; thus,  $Q_{\Gamma}(\gamma) = \int_0^{\infty} \dot{\gamma} f_{\Gamma, \dot{\Gamma}}(\gamma, \dot{\gamma}) d\dot{\gamma}$ , where  $\dot{\gamma}$  represents the time derivative of  $\gamma$ . Furthermore, Hadzi-Velkov *et al.* [24] showed that the time derivative of the  $i$ th channel envelope is independent of the envelope itself and follows zero-mean Gaussian distribution with variance  $\sigma_{\dot{\Gamma}_i}^2 = \pi^2 f^2 \sum_{i=1}^N \bar{\Gamma}_i$ , where  $f$  is the maximum Doppler frequency, as

$$f_{\dot{\Gamma}_i}(\dot{\gamma}) = \frac{1}{\sqrt{2\pi}} \sigma_{\dot{\Gamma}_i} \exp\left(-\frac{\dot{\gamma}^2}{2\sigma_{\dot{\Gamma}_i}^2}\right). \quad (8)$$

The joint PDF of  $\Gamma$  and  $\dot{\Gamma}$  is  $f_{\Gamma, \dot{\Gamma}}(\gamma, \dot{\gamma}) = f_{\Gamma}(\gamma) f_{\dot{\Gamma}}(\dot{\gamma})$  because the random process  $\Gamma$  and its time derivative  $\dot{\Gamma}$  are mutually independent [23]. Then, the LCR is given by

$$Q_{\Gamma}(\gamma) = \left( \sum_{i=1}^N \bar{\Gamma}_i^{N-2} \gamma \exp\left(-\frac{\gamma^2}{\bar{\Gamma}_i}\right) \prod_{\substack{j=1 \\ j \neq i}}^N \frac{1}{\bar{\Gamma}_i - \bar{\Gamma}_j} \right) f \sqrt{2\pi \sum_{i=1}^N \bar{\Gamma}_i}. \quad (9)$$

#### B. Average Fade Duration

The AFD,  $\bar{r}_f(\gamma)$ , is the average duration of fades for which the signal's envelope resides under the specified threshold. Mathematically, it is expressed as

$$\begin{aligned} \bar{r}_f(\gamma) &= \frac{F_{\Gamma_{MRC}}(\gamma)}{Q_{\Gamma}(\gamma)} \\ &= \frac{\sum_{i=1}^N \bar{\Gamma}_i^{N-1} \left(1 - \exp\left(-\frac{\gamma^2}{\bar{\Gamma}_i}\right)\right) \prod_{\substack{j=1 \\ j \neq i}}^N \frac{1}{\bar{\Gamma}_i - \bar{\Gamma}_j}}{\left( \sum_{i=1}^N \bar{\Gamma}_i^{N-2} \gamma \exp\left(-\frac{\gamma^2}{\bar{\Gamma}_i}\right) \prod_{\substack{j=1 \\ j \neq i}}^N \frac{1}{\bar{\Gamma}_i - \bar{\Gamma}_j} \right) f \sqrt{2\pi \sum_{i=1}^N \bar{\Gamma}_i}} \end{aligned} \quad (10)$$

whereas the average nonfade duration  $\bar{r}_n$  is obtained by exploiting the relationship  $\bar{r}_n(\gamma) = \frac{1}{Q_r(\gamma)} - \bar{r}_f(\gamma)$ . Then, the failure rate  $\lambda$  and the repair rate  $\mu$  can be characterized by reciprocal of  $\bar{r}_f(\sqrt{\eta})$  and  $\bar{r}_n(\sqrt{\eta})$  as  $\lambda = \frac{1}{\bar{r}_n(\sqrt{\eta})}$  and  $\mu = \frac{1}{\bar{r}_f(\sqrt{\eta})}$ , where  $f = \frac{vf_c}{c}$  with  $c$  and  $v$ , respectively, indicating the speed of light ( $3 \times 10^8$  (m/s)), and the relative velocity among transmitter, receiver, and scatterers.

Next, we concentrate upon the mission reliability metric, which has been recently introduced in [6] using the MTTF.

### C. Mission Reliability

The existing concept of reliability of future wireless system lacks temporal aspects; thus, it does not fit completely well when applied to practical time-varying wireless channels. In fact, by utilizing the toolset of dependability theory, the classical definition of reliability is quite compatible with the concept of availability [6]. Thus, by using the MTTF and mission duration  $\Delta T$  metrics, Höbner *et al.* [6] defined *mission reliability* as the probability of carrying failure-free transmission throughout the mission duration

$$R(\Delta T) = \Pr \{Y(\tau) = 1 \quad \forall \tau \in [0, \Delta T]\}$$

which reinforces the relation to failure-free operation over the period of mission duration. This metric is incompatible with the 3GPP reliability definition [6] that considers the average time required for packets to be delivered successfully. In fact, the 3GPP definition reflects steady-state channel availability. The fundamental difference between mission reliability and channel availability is discernible in [6], where instantaneous channel availability converges rapidly to steady-state channel availability  $A(t) = 0.99$ , which indicates that 1% outage probability is expected at any instant of time. On the contrary, mission reliability converges to zero as the random fading process does not allow failure-free operation for longer  $\Delta T$ , which stipulates the improvement of mission reliability and MTTF for different mission duration in the context of URLLC. Therefore, we introduce the mission reliability metric for finite blocklength next.

### D. Mission Reliability for Finite Blocklength

We define the mission reliability metric for finite blocklength as the probability of performing failure-free short packets transmission with a certain error probability  $\epsilon$  and blocklength  $n$  over the period of mission duration

$$R(\Delta T, n, \epsilon) = \Pr \{Y(\tau)_{\text{FBL}} = 1 \quad \forall \tau \in [0, \Delta T]\}.$$

This metric enlivens the association of short packet transmission to reliability guaranteed operation throughout the mission duration.

### E. Mean Time to First Failure

There is a close relationship between mission reliability and MTTF as the latter represents the average duration of a functional component before it fails for the first time. It is one of the widely known metrics in analyzing the reliability of technical systems, hardware systems, electronic devices, etc. However, it has been applied in wireless communication systems just recently in [6]. Due to its efficacy in time-based reliability analysis that is highly applicable to URLLC, we also use MTTF in the

scenario under discussion here. We determine the MTTF using an infinite integral or Laplace transform  $R_N^*(s)$  of the mission reliability function and set the Laplace parameter  $s = 0$ , i.e.,

$$\text{MTTF}_{\text{MRC}} = \int_0^\infty R_N(\tau) d\tau = R_N^*(0). \quad (11)$$

Since the MRC technique is assumed, so all connected links merge to a single unified link, and the CFE for the MTTF of a single component is [25]

$$\text{MTTF}_{\text{MRC}} = \frac{1}{\lambda}. \quad (12)$$

Thus, by utilizing the MTTF, the mission reliability is attained by leveraging the assumption that time to failure with constant failure rate  $\lambda$  follows exponential distribution [25], i.e.,

$$R_N(\Delta T)_{\text{FBL}} = \exp\left(-\frac{\Delta T}{\text{MTTF}_{\text{MRC}}}\right). \quad (13)$$

### F. Special Case

In this section, we focus on the transmission of infinitely large packets. Using the similar framework of dependability theory and the Gilbert–Elliot model, we differentiate the two states of the channel by introducing the random variable channel state as the signal is received successfully if its received SNR  $|\gamma|^2$  is below a certain threshold  $\Phi$ , i.e.,

$$Y(t)_{\text{IBL}} = \begin{cases} 0, & \text{if } \gamma < \sqrt{\Phi} = \sqrt{2^R - 1}, \text{ "OFF," "failed"} \\ 1, & \text{if } \gamma \geq \sqrt{\Phi} = \sqrt{2^R - 1}, \text{ "ON," "operational."} \end{cases} \quad (14)$$

Now, we attain the failure rate  $\lambda_{\text{IBL}}$  and repair rate  $\mu_{\text{IBL}}$ , introduced in Section III-B, for infinite blocklength regime as  $\lambda_{\text{IBL}} = \frac{1}{\bar{r}_n(\sqrt{\Phi})}$  and  $\mu_{\text{IBL}} = \frac{1}{\bar{r}_f(\sqrt{\Phi})}$ . We provide the mission reliability for infinitely long packet transmission of the considered system by substituting  $\lambda_{\text{IBL}}$  into (12) as

$$R_N(\Delta T)_{\text{IBL}} = \exp(-\Delta T \lambda_{\text{IBL}}). \quad (15)$$

*Remark 1:* When  $n$  approaches to  $\infty$ , (13) reduces to (15).

## IV. MISSION EFFECTIVE CAPACITY

In this section, we introduce the mission EC  $M_{\text{EC}}$  model to link the physical layer with QoS constraints. We provide the  $M_{\text{EC}}$  for FBL regimes. Then, we assume Markovian traffic arrival at the URLLC user and characterize the effective bandwidth (EB) under statistical QoS constraints such that we are able to capture the effects of latency and bursty traffic. For that purpose, we provide throughput maximization under mission reliability and latency constraints.

### A. Preliminaries

Let us assume that the transmission data are generated by random sources and accumulate in a buffer prior to transmission. We further assume that the buffer stationary queue length  $L$  is finite and the buffer overflow threshold is denoted by  $q$ . Hence, the probability of buffer overflow satisfies [26]

$$\lim_{q \rightarrow \infty} \frac{\ln \Pr\{L \geq q\}}{q} = -\theta \quad (16)$$

where  $\theta$  represents the decay rate. When  $q \rightarrow q_{\max}$ , we can approximate the buffer overflow probability using (16) as

$$\Pr\{L \geq q\} \approx \zeta e^{-\theta q} \quad (17)$$

where  $\zeta = \Pr\{L > 0\}$  denotes the probability that the buffer is nonempty. We assume  $\zeta = 1$ , meaning that buffer is always replenished with data. Note that  $\theta$  is also known as QoS exponent. A larger value of  $\theta$  results in stricter QoS limitations, whereas a smaller value of  $\theta$  implies looser QoS constraints [26]. Application requirement dictates the value of  $\theta$ . Furthermore,  $D$  represents the buffer queue delay in the steady state, whereas  $d_{\max}$  represents the maximum delay. Then, the delay violation probability is given as [12]

$$\Pr\{D \geq d_{\max}\} \approx \zeta e^{-\theta a(\theta) d_{\max}}. \quad (18)$$

Here,  $a(\theta)$  represents the EB, which characterizes the minimum constant service rate sustained by any random arrival process while satisfying the statistical queuing constraints. Let us assume that the sequence of nonnegative random arrival rates is given by  $\{a(k), k = 1, 2, 3, \dots\}$ , whereas  $B(t) \triangleq \sum_{k=1}^t a(k)$  represents the accumulated arrival process at time  $t$ . Then, the EB is given by [27]

$$a(\theta) \triangleq \lim_{t \rightarrow \infty} \frac{1}{\theta t} \ln \mathbb{E}\{e^{\theta A(t)}\}. \quad (19)$$

The dual concept of the EB is the EC, which measures the throughput supported by the wireless channel while satisfying the delay constraint requirement given by  $\theta$ . Let us assume that  $\{s[k], k = 1, 2, \dots\}$  represents the discrete-time stationary and ergodic stochastic service process, whereas  $S[t] \triangleq \sum_{k=1}^t s[k]$  represents the time-accumulated service process. Hence, the EC for a given QoS exponent is given by [12]

$$\begin{aligned} \text{EC}(\theta) &= -\lim_{t \rightarrow \infty} \frac{1}{\theta t} \ln \mathbb{E}\{e^{-\theta S[t]}\} \\ &\stackrel{(a)}{=} -\lim_{t \rightarrow \infty} \frac{1}{\theta t} \ln \mathbb{E}\{e^{-\theta R}\} = -\frac{\lambda(-\theta)}{\theta}. \end{aligned} \quad (20)$$

Step (a) arises from the maximum service rate  $R$  as the service process is dependent on the fading coefficients, which change independently every block. Meanwhile, for the ON-OFF model as in (6) and (14), we have that [27, Ch.7]

$$\begin{aligned} \text{EC} &= -\frac{1}{\theta} \ln \left( \frac{1}{2} (V_{11} + V_{22} e^{\theta R} \right. \\ &\quad \left. + \sqrt{(V_{11} + V_{22} e^{\theta R})^2 + 4(V_{11} + V_{22} - 1)e^{\theta R}}) \right). \end{aligned} \quad (21)$$

Next, we apply dependability theory on EC and define it as a function of mission reliability for FBL.

### B. Mission Effective Capacity for FBL

Many industrial applications use short packets for transmission to cope with the low-latency requirements of URLLC systems. Thereby, we leverage the dependability theory to define mission EC  $M_{\text{EC}}^{\text{fb}}$  for FBL transmissions. The novel dependability metric  $M_{\text{EC}}$  is capable of capturing the temporal aspects of the time-varying wireless channel. It also provides the failure-free communication throughout the mission duration.

**Definition 1:** Under finite blocklength, the  $M_{\text{EC}}$  metric sustains the maximum constant arrival rate by the reliability-guaranteed wireless channel (with an error probability  $\epsilon$ ) throughout the mission duration while maintaining the delay constraint  $\theta$ .<sup>4</sup>

Note that in our model,  $V_{11} = 1 - w$ ,  $V_{22} = w$ , and  $V_{11} + V_{22} = 1$  [14]; hence,  $w = R_N(\Delta T)$ , and (20) becomes

$$\begin{aligned} M_{\text{EC}} &= -\frac{1}{n\theta} \ln (1 - w + w \exp(-\theta nR)) \\ &= -\frac{1}{n\theta} \ln \left[ 1 - \exp\left(-\frac{\Delta T}{\text{MTTFF}_{\text{MRC}}}\right) (1 - \exp(-\theta nR)) \right]. \end{aligned} \quad (22)$$

**Remark 2:** As  $n$  approaches  $\infty$ , (22) converges to

$$M_{\text{EC}}^{\text{IBL}} = -\frac{1}{\theta} \ln \left[ 1 - \exp\left(-\Delta T \lambda_{\text{IBL}}\right) (1 - \exp(-\theta R)) \right] \quad (23)$$

which is the mission EC for IBL  $M_{\text{EC}}^{\text{IBL}}$ ; it is a measure of throughput supported by the failure-free wireless channel throughout the mission duration while satisfying the delay constraint  $\theta$ . Hence,  $w = R_N(\Delta T)_{\text{IBL}}$ .

Our goal is to obtain the maximum average arrival rate of a Markovian source that supports a particular fading channel, given that the QoS requirement is satisfied in (16). The QoS requirements are ensured when the EB of the arrival process equals  $M_{\text{EC}}$  of the service process [26]. Therefore,

$$a(\theta, r) = M_{\text{EC}}. \quad (24)$$

Next, we adopt a Discrete Markov process to capture the characteristics of machine-type devices (MTDs) traffic, e.g., burstiness and short packet transmissions [29], [30].

### C. Discrete Markov Source

This model describes a discrete-time data arrival, which is modeled as a discrete-time Markov chain. During ON-state data arrives at  $r$  bits/block, while no arrivals occur during the OFF state. The transition probability matrix  $\mathbf{J}$  for this source is  $\mathbf{J} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$ , where  $p_{11}$  indicates the probability of staying in the OFF state from one block to another. Similarly,  $p_{22}$  is the probability of staying in the ON state, while the transition probabilities are  $p_{21} = 1 - p_{22}$  and  $p_{12} = 1 - p_{11}$ . The probability of the ON state in the steady state is  $P_{\text{ON}} = \frac{1 - p_{11}}{2 - p_{11} - p_{22}}$ . The EB for this two-state (ON-OFF) model is given by [27]

$$a(\theta, r) \stackrel{(a)}{=} \frac{1}{\theta} \ln (1 - S + S e^{\theta r}) \quad (25)$$

where (a) comes from using  $p_{11} = 1 - S$  and  $p_{22} = S$ . Hence,  $P_{\text{ON}} = S$  becomes the measure of burstiness at the source and characterizes the variation of the arrival rates. It is relevant to model different MTDs traffic patterns. The maximum average arrival rate is  $\bar{r}_{\max} = r P_{\text{ON}}$ . By using (24), we obtain the average arrival rate that supports failure-free transmissions at given SNR  $\gamma$ ,  $\theta$ ,  $R$ ,  $f$ , and  $\Delta T$ , as follows:

$$M_{\text{EC}} = \frac{1}{\theta} \ln (1 - S + S e^{\theta r})$$

<sup>4</sup>The EC is applicable to describe queuing behavior of URLLC, only for those URLLC applications which have flexible latency requirements such as scalable URLLC and broadband URLLC [28]. But for extreme URLLC, EC may not be the most suitable metric.

$$r = \frac{1}{\theta} \ln \left( \frac{1}{S} \exp(\theta M_{EC}) - (1 - S) \right). \quad (26)$$

Then, we get  $\bar{r}_{\max}$  in terms of  $\theta$ ,  $R$ ,  $f$ , and  $\Delta T$ , for discrete-time Markov source as

$$\bar{r}_{\max} = \frac{S}{\theta} \ln \left( \frac{1}{S} \exp(\theta M_{EC}) - (1 - S) \right).$$

Later, we will see that large arrival rates are not served by wireless fading channels, thus increasing the queue length and delay of the network. This effect can be minimized by maximizing  $M_{EC}$ , which also enhances the maximum average arrival rate  $\bar{r}_{\max}$  since the latter is an increasing function of  $M_{EC}$ . Therefore, the problem of maximizing the  $M_{EC}$  with respect to fixed positive  $R > 0$  under the mission reliability constraint is presented next.

#### D. Mission Effective Capacity Maximization

We consider the fixed  $R$ , where CSI is only available at BSs, while the URLLC user does not have information about channel states. Hence, the URLLC user transmits data at a fixed rate, which maximizes the  $M_{EC}$  up to an optimal point and then diminishes. It is pertinent to observe that the optimal point under the constraint of target mission reliability, which is given by  $\sigma \in [0, 1]$ . Therefore, the optimization problem is designed as

$$\begin{aligned} \arg \max_R \quad & M_{EC} \\ \text{s.t.} \quad & R_N(\Delta T) \geq \sigma. \end{aligned}$$

We can observe that the objective function (23) is quasi-concave, and the constraint function (15) is concave with respect to the optimization variable, e.g.,  $R$  [31]. However, due to underlying complexity of expression (23) and space limitations, we omit the proof, instead numerically illustrate the quasi-concavity in Fig. 2. Obtaining a closed-form solution for this optimization problem requires strenuous efforts considering its complexity. Thereby, we resort to a numerical solution.

The optimization problem can be solved numerically through the CE method, as outlined in Algorithm 1. The CE algorithm starts generating a set of random samples  $X_1, X_2, \dots, X_U$  utilizing the distribution function  $f(\cdot; v)$  with mean  $a_\mu$  and variance  $a_\sigma^2$ , i.e.,  $v = [a_\mu, a_\sigma^2]$ , while determining the threshold  $\gamma$  as the  $(1 - z) - \text{quantile}$  from the performance values  $M_{EC}(X_1), \dots, M_{EC}(X_U)$ , where  $z$  represents the rarity parameter [32]. The elite samples are obtained from those samples whose performance is higher than threshold  $\gamma$  as  $M_{EC}(X_U) \geq \gamma$ . This creates a new parameterized distribution vector  $f(\cdot; v')$ , which minimizes the Kullback–Leibler divergence, i.e., CE and get closer to the target distribution  $f(\cdot; v^*)$ . The execution of this step performed in a single iteration. Based on these steps, the CE algorithm iteratively updates  $f(\cdot; v)$  to generate a family of PDFs  $f(\cdot; v_1), f(\cdot; v_2), \dots, f(\cdot; v^*)$  with the help of threshold values  $\gamma_1, \gamma_2, \dots, \gamma^*$  to obtain the optimal density function  $f(\cdot; v^*)$ . Finally, note that the convergence to the optimal solution is guaranteed.

#### V. NUMERICAL ANALYSIS

In this section, we analyze the  $M_{EC}$  in quasi-static Rayleigh fading for both IBL and FBL regimes in URLLC networks. We fix the position of the URLLC user in the indoor factory

#### Algorithm 1: CE Algorithm.

- 1: **Initialization:**  $\mu_0$  and  $\sigma_0^2$ , number of samples  $U$ , threshold  $\gamma$ , rarity parameter  $z$ , tolerance, number of iterations  $itr_n$  and maximum number of iterations  $max_n$
- 2: Set  $k = 0$
- 3: **while**  $(itr_n \leq max_n) \parallel ((\mu_{k+1} - \mu_k) \geq 10^{-6} \& (\sigma_{k+1}^2 - \sigma_k^2) \geq 10^{-6})$  **do**
- 4:   Generate  $U$  number of samples  $X_1, \dots, X_U$  from sampling distribution  $U(\mu_k, \sigma_k^2)$
- 5:   Compute constraint values as  $R_N(X_1), \dots, R_N(X_U)$
- 6:   **if**  $(R_N(X_1), \dots, R_N(X_U) \geq \sigma)$  **then**
- 7:     Compute outcomes values from (22)  $M_{EC}(X_1), \dots, M_{EC}(X_U)$
- 8:     Compute threshold as  $(1 - z)\text{quantile} = \gamma_k$  from outcomes values of the sample  $M_{EC}(X_1), \dots, M_{EC}(X_U)$
- 9:     Compute *Elite* samples vector, i.e., the samples that satisfied  $M_{EC}(X_U) \geq \gamma_k$
- 10:    Count elements of *Elite* samples vector =  $C$
- 11:    Update  $\mu_{k+1} = \frac{1}{C} \sum_{i=1}^C \text{Elite}_i$
- 12:    Update  $\sigma_{k+1}^2 = \frac{1}{C-1} \sum_{i=1}^C (\text{Elite}_i - \mu_{k+1})^2$
- 13:     $itr_n = itr_n + 1$
- 14:   **end if**
- 15: **end while**

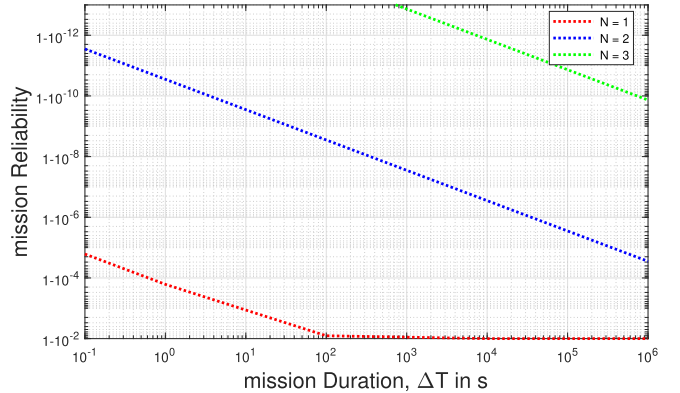


Fig. 2. Mission reliability  $R_N(\Delta T)$  for the FBL regime as a function of mission duration,  $\Delta T$ .

hall such that its coordinates are  $(x, y) = (48, 8)$ . Moreover, we set the rest of the system parameters as  $d_{\text{clutter}} = 10$ ,  $r = 30\%$ , BS antenna height,  $h_{BS} = 3$  m, URLLC user antenna height  $h_{USER} = 1$  m,  $f_c = 2$  GHz,  $f = 66.6$  Hz,  $T_x = 30$  dBm,  $N_0 = -130$  dB,  $\Delta T = 50$  s,  $\theta = 10^{-3}$ ,  $S = 0.5$ ,  $n = 500$  channel uses,  $\eta_\Delta = 10^{-4}$ , and  $\epsilon = 10^{-3}$ . Note that we consider four different configurations for simulations purpose, where  $N = 1$ ,  $N = 2$ ,  $N = 3$ , and  $N = 6$  correspond to the number of BSs in the network, i.e.,  $\{9\}$ ,  $\{8, 9\}$ ,  $\{7, 8, 9\}$ , and  $\{7, 8, 9, 10, 11, 12\}$ , respectively.

Fig. 2 shows the tradeoff between mission reliability  $R_N(\Delta T)$  for finite blocklength and mission duration ( $\Delta T$ ). We consider  $R = 6$  bpcu, and  $\theta = 10^{-4}$ . It can be seen that for mission duration  $\Delta T > 100$  s, only 99% mission reliability is achievable. Addition of another BS in the network enhances the mission reliability up to 99.99999% for  $\Delta T = 10^3$  s due to MC and

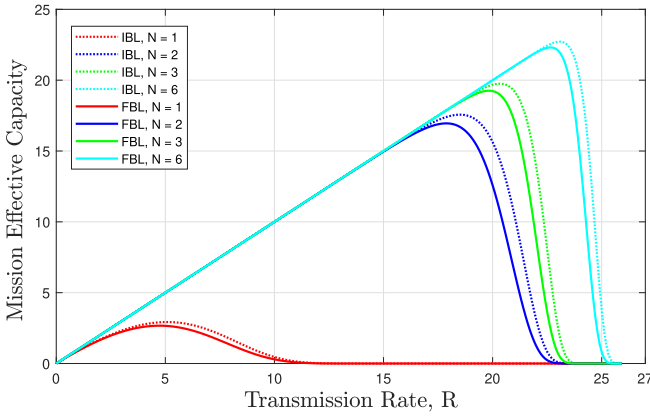


Fig. 3. Mission EC  $M_{EC}$  for IBL (bpcu) and FBL (bpcu) blocklength regimes as a function of transmission rate,  $R$  (bpcu).

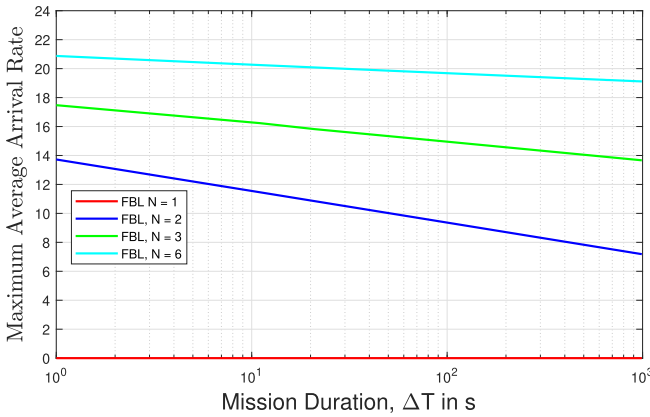


Fig. 4. Maximum average arrival rate  $\bar{r}_{max}$  (bps/frame) for FBL regime as a function of mission duration,  $\Delta T$ .

high received average SNRs of the corresponding channels in the indoor InF setup. It is also noticeable that mission reliability diminishes as the mission duration enhances due to the need to concurrently sustain this high reliability over a longer duration.

In Fig. 3, we demonstrate the mission EC  $M_{EC}$  as a function of fixed transmission rate  $R$  for IBL, and FBL assuming single connectivity ( $N = 1$ ), and MC ( $N > 1$ ), respectively. The envelope threshold is set to  $\sqrt{\Phi} = \sqrt{2^R - 1}$  for IBL and to  $\sqrt{\eta}$ , as specified in (7), for short packet transmission. We can observe that the system does not attain high  $M_{EC}$  for  $N = 1$ , but it can also degrade further, depending upon average received SNR  $\bar{\Gamma}$  of the corresponding link. Meanwhile,  $M_{EC}$  enhances by the inclusion of more BSs in the network, which means MC supports higher  $M_{EC}$ . Note that we present the IBL scenario as a benchmark scheme to illustrate the impact of short packet transmission. In fact, the performance gap between IBL and FBL is noticeable as the former considers not only infinitely large blocklength but also arbitrary small error probability. The rate in finite blocklength coding is penalized by the tolerable decoding error and by the size of the packet, which leads to a performance gap between finite and infinite coding. Moreover, with an increasing  $R$ ,  $M_{EC}$  also increases up to a maximal point, after which it sharply falls. Therefore, there is an optimal  $R$  that maximizes  $M_{EC}$ .

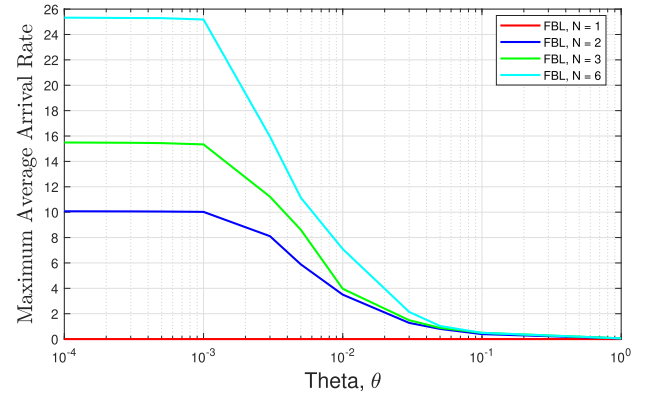


Fig. 5. Maximum average arrival rate  $\bar{r}_{max}$  (bps/frame) for the FBL regime as a function of the QoS exponent,  $\theta$ .

In Fig. 4, we fix the target mission reliability  $\sigma = 99.999\%$  and focus on the variation of the mission duration  $\Delta T$  over the optimal transmission rate  $R^*$ . The maximum average arrival rate  $\bar{r}_{max}$  diminishes with an increase in mission duration  $\Delta T$ , which is the duration of continuous failure-free operation due to the random fading process. It is discernible that using single connectivity can be detrimental for given network parameter values because long mission duration cannot be sustained due to fading in the wireless channel. A higher number of BSs can support the longer mission duration. In this case, longer mission duration indicates that communication with mission reliability of 99.999% can occur for long period of time without any failure.

Fig. 5 examines the impact of the QoS constraint  $\theta$  on the maximum average arrival rate  $\bar{r}_{max}$  for FBL. We set the mission reliability indicator  $\sigma = 99.999\%$  and consider transmission over an optimal  $R^*$ . We notice a degradation in the  $\bar{r}_{max}$  when stricter buffer constraints are imposed. Consequently, it is observed that a lower  $\bar{r}_{max}$  can be tolerated for stringent delay requirements ( $\theta \gg 0$ ). Considering the transmission of short packets, higher  $\bar{r}_{max}$  cannot be supported for  $\theta \geq 0.1$  irrespective of further addition of BSs in the network, but it raises  $\bar{r}_{max}$  for  $\theta < 0.1$ . Notice that as  $\theta \rightarrow 0$ , which implies longer delays,  $M_{EC}$  will converge to capacity, which in this case is a fixed rate  $R$ .

In Fig. 6, we analyze the maximum average arrival rate  $\bar{r}_{max}$  as a function of the target mission reliability in the FBL regime for different number of BSs. It is worth noticing that for the ultra-reliable region, i.e.,  $\sigma > 99.9\%$ , or stringent mission reliability requirement,  $\bar{r}_{max}$  along with optimal rate become very small for single connectivity; thus, it is impossible to operate in the ultra-reliable region. However, small throughput is achievable for  $\sigma < 90\%$ , and this particular result can be applied to those industrial applications, which demand only low latency. MC enhances the throughput even in the ultra-reliable region for the mission duration of 50 s. These results can be utilized for many URLLC applications, which operate on short packets transmission and demand flexible latency and stringent reliability requirement of 99.999%, such as automated guided vehicle, process automation, tactile Internet, mobile robots, and virtual/augmented reality. The MC scheme is favorable even with high bursty traffic for all these applications.

Fig. 7 shows the delay violation probability as a function of mission duration,  $\Delta T$ , for IBL and FBL. We assume delay

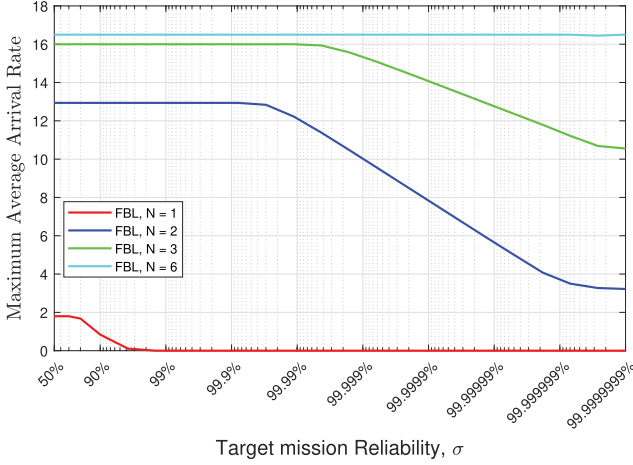


Fig. 6. Maximum average arrival rate  $\bar{r}_{\max}$  (bps/frame) for the FBL regime as a function of target mission reliability,  $\sigma$ .

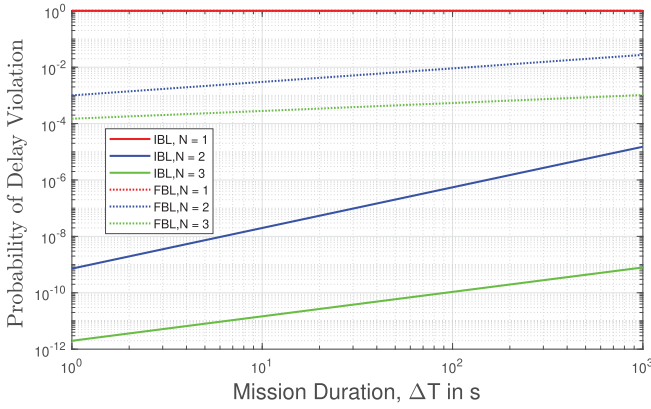


Fig. 7. Delay violation probability for IBL and FBL regimes as a function of mission duration,  $\Delta T$ .

threshold  $d_{\max} = 15$  and  $\theta = 10^{-1}$  for IBL, while  $d_{\max} = 500$  and  $\theta = 10^{-3}$ , as aforementioned, that throughput converges to zero for  $\theta \geq 0.1$  and  $d_{\max}$  should be at least equal to  $n$  for FBL. The larger values of the delay threshold indicate that the system is able to sustain longer delay, which, consequently, reduces the delay violation probability. Besides the stringent QoS requirement, i.e.,  $\theta = 1$ , also decreases the delay violation. Moreover, increment in mission duration  $\Delta T$  maximizes the probability delay violation, since the wireless channel cannot maintain longer mission duration  $\Delta T$  due to the fading process. To overcome this, MC is utilized, which minimizes the delay violation probability even for longer mission duration.

## VI. CONCLUSION

In this article, we investigated the statistical QoS provisioning of the MC-enabled industrial radio systems under mission reliability and latency constraints by introducing the mission EC metric for both IBL and FBL regimes. The performance metric

mission reliability captures the time-varying characteristics of a wireless channel, while MTTF provides the expected time until the first communication failure occurs. This is of paramount importance since various industrial applications demand the execution period during which no failure is tolerated. Using MRC, we adopted the robust framework of dependability theory to provide exact CFEs of the mission reliability and MTTF for FBL and IBL. We considered the InF-SL scenario, where a URLLC user accumulates the sporadic traffic arrivals in a buffer prior to transmission to  $N$  BSs. Moreover, we assumed fixed  $R$  with CSI availability only at BSs. The CFEs for second-order statistics, i.e., LCR and AFD, have also been derived, which show the fading distribution with respect to the time. A throughput maximization problem under the mission reliability constraint was formulated and tackled through the CE method. Furthermore, simulation results show that it is not desirable to operate with single connectivity to achieve ultra-reliable and low latency. The higher throughput can be achieved at a mission reliability of 99.999% and the  $\bar{r}_{\max} = 10.5$  bps/frame is obtained if at least two BSs are connected, and for almost  $\bar{r}_{\max} = 10.5$  bps/frame, a mission reliability of 99.999999% is achievable if three BSs are connected in the InF-SL setup. It is also observed that throughput experiences reduction when stringent QoS requirements are imposed. Finally, multiuser setups and the integration of advanced technologies such as intelligent reflecting surface to further improve end-to-end dependability will be studied in a future work.

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