Burst error analysis of scheduling algorithms for 5G NR URLLC periodic deterministic communication

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***Abstract*—Wireless industrial radio communication systems spawn a new set of requirements with focus on high reliability and low latency. These requirements were identified in the Industry 4.0 (I4.0) initiative as well as in 5th Generation (5G) mobile communication standardization in the form of Ultra Reliable Low Latency Communication (URLLC).**

Specifically Closed-Loop-Control (CLC) applications exhibit periodic deterministic communication with short packets. These applications require ultra low latency which bars the application of retransmissions to improve reliability. Also, many CLC applications are very sensitive to burst errors but can tolerate single packet loss. Therefore, we propose to shift the focus from sum-rate maximization to burst error minimization. As a first step, we perform an extensive burst error analysis of state of the art scheduling and Resource Allocation (RA) strategies. We show that any dynamic RA outperforms a static RA by a large margin.

***Index Terms*—5G, URLLC, Industry 4.0, closed loop control, scheduling, resource allocation, periodic deterministic traffic, reliability, latency**

I. Introduction

In 5th Generation (5G) Ultra Reliable Low Latency Communication (URLLC) new use cases for Machine-type-Communication (MTC) systems are identified which include factory automation and autonomous driving [1], [2]. In the realm of URLLC requirements factory automation in the form of Closed-Loop-Control (CLC) systems for Motion Control (MC) applications exhibit particularly high requirements with regards to low latency and high robustness against burst errors [2]. Especially, Motion Control (MC) applications with periodic deterministic communication behavior and short packets pose new challenging Quality-of-Service (QoS) requirements to wireless communication systems. These QoS constraints require new solutions for future 5th Generation New Radio (5G NR) communication systems for reliable and low latency communication [3].

One challenge addressing CLC applications is that they pose a strict low latency requirement on packet transmissions with real-time deadlines. Thus, at the application level, a packet is lost, not only if it cannot be received, but also, if it fails to arrive before the deadline. Further, a CLC application fails if it cannot receive a new packet after a given survival time [2]. In communication engineering, the Key Performance Indicator (KPI) is the Frame-Error-Rate (FER), that is an average measure, while in the automation domain it is Mean Time To Failure (MTTF) [4]. In [4] the authors proposed a method to obtain a relation between those KPIs. Further, they show that automation systems require extremely low FERs while not directly addressing robustness to burst errors.

In [2], the KPI is availability with a typical 99.999 % availability requirement. Availability is defined as the probability a communication system fulfills a set of QoS requirements at the application level, e.g. latency, reliability or survival time [2]. Low latency requirements prohibit retransmissions and a short survival time restricts the number of consecutive erroneous packets per link to a single packet. Here, we define burst errors as consecutive erroneous packets, i.e. if multiple consecutive packets are received erroneously on a single link. Typical use cases require a 99.999 % availability which results in a 10^{-5} maximum burst error rate. In order to boost availability, we propose to shift the focus from sum-rate maximization to burst error minimization [5].

We need accurate channel models and link abstraction to perform proper scheduling and Resource Allocation (RA) evaluations. The used link abstraction models need to be well suited for industrial environments. Industrial radio channel measurements reveal particularly harsh conditions for radio propagation [6], [7]. Furthermore, large scale and small scale fading contribute to burst errors and need to be taken into account [8]. Different strategies to meet URLLC requirements are discussed, e.g. fixed Modulation and Coding Scheme (MCS) setups [9]. The authors in [10] worked out a link abstraction model for industrial radio with short packets and low FER by using Mutual Information Effective SNR Mapping (MIESM). We rely on [10] and use MIESM for accurate system level simulations. This enables us to study scheduling and RA in frequency selective block fading channels with Orthogonal Frequency Division Multiplexing (OFDM) modulation [11].

Our main contribution is an evaluation how state of the art scheduling and RA strategies perform with respect to burst errors in scenarios with short packets, low latency and low FER requirements. Here, we conclude that it is important to shift the focus from sum-rate maximization to burst error minimization. We investigate the benefits and trade-

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offs between different scheduling and RA schemes. Further, recommendations for efficient RA for URLLC systems based on this KPI for different scenarios are devised. This does allow for QoS with MTTF in mind. We show that any dynamic RA outperforms a static RA by a large margin.

II. Channel model

The channel model in our work is composed of two components, namely large scale fading and small scale fading. First, we describe large scale fading effects such as our path loss model and shadowing effects [8], [12], [13]. Second, we incorporate these results in our small scale fading model that is described via link abstraction [10].

A. Link Budget

We consider large scale fading effects that impact propagation conditions. Here, we have both, deterministic and statistical, effects that degrade a received signal. We denote received signal power with transmit power P_t, speed of light c and carrier frequency f as

$$P_r(d) = P(f,1,2) - 10 \cdot \eta \cdot \log_{10}\left(\frac{d}{d_0}\right) + S \text{ [dBm]} \quad (1)$$

$$P(f,d,\eta) = P_t + G_t + G_r + 10\log_{10}\left(\frac{c^2}{(4\pi f)^2 \cdot d^\eta}\right) \text{ [dBm]} \quad (2)$$

where all values are in logarithmic units [12]. The path loss exponent η depends on channel conditions, e.g. Line-Of-Sight (LOS) or Non-Line-Of-Sight (NLOS). The reference received power $P_r(f,1,2)$ is defined at a reference distance $d_0 = 1\,\text{m}$ with $\eta = 2$. Also, we assume isotropic antennas at the transmitter and receiver, i.e. $G_t = G_r = 1$.

In (1), shadowing is expressed via S drawn from a Gaussian distribution with $\mu = 0$ and shadowing deviation σ_{SF} dependent on channel conditions [8], [13]. Shadowing is a large scale parameter that is more pronounced under NLOS conditions and changes slowly over time, thus we assume spatially correlated shadowing [8].

Received noise power can be expressed as

$$E\{|\text{n}|^2\} = \sigma_n^2 = N_0 = 30 \cdot \log_{10}(\kappa T B) \text{ [dBm]} \quad (3)$$

with bandwidth B, temperature T and Boltzmann constant κ [12]. Finally, we denote our link budget in terms of Signal-to-Noise-Ratio (SNR) as

$$\text{SNR} = P_r(d) - N_0 - F \quad (4)$$

where noise figure F is receiver dependent.

B. Fading

Industrial radio measurement campaigns [6], [13] show that all time-domain channel taps $\tilde{h}_i$, regardless if they are LOS or NLOS, are Rayleigh distributed. Also, the Power Delay Profile (PDP) $\boldsymbol{p}$ of the channel follows an exponential distribution with a delay spread σ_{RMS} in the range $40\,\text{ns}$ to $100\,\text{ns}$. Typically the maximum channel delay τ_{max} varies around $200\,\text{ns}$. We obtain the ith channel tap by $\tilde{h}_i = p_i \cdot \tilde{h}_{\text{R},i}$, $\tilde{h}_{\text{R},i} \in \mathcal{CN}(0,1)$. Finally, frequency-domain channel taps are obtained as $\boldsymbol{h} = \mathcal{F}_{N_{\text{FFT}}}\tilde{\boldsymbol{h}}$ with its elements $h_i \in \mathcal{CN}(0,1)$.

We assume that the Cyclic Prefix (CP) duration τ_{CP} is larger than the maximum channel delay τ_{max}. Thus, each subcarrier in our frequency-domain link model is affected by only one channel tap h_i. Furthermore, we assume perfect system synchronization, i.e. we assume zero time and frequency offsets.

We focus on short packets, thus we assume a block fading channel, i.e. the channel is constant over the duration of a frame which may span over multiple OFDM symbols. The channel covariance ρ for consecutive frames can be approximated as

$$\rho = \exp\left\{-23 \cdot \left(\frac{\Delta t v f_c}{c_0}\right)^2\right\} \quad (5)$$

depending on time difference Δt, carrier frequency f_c and relative velocity v between transmitter and receiver [14]. Channel covariance ρ quantifies how statistically dependent consecutive channel realizations are, i.e. $\rho = 1$ indicates that the channel did not change at all.

III. Link abstraction

We use the link model introduced in [10] that is similar to 5G NR. With Fig. 1 we show the idea how we transform available Channel State Information (CSI) in a system simulation into a characteristic FER to simulate packet loss.

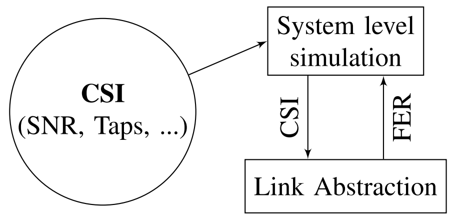

Fig. 1. Link abstraction concept

Usually, link abstraction is facilitated by transforming per-subcarrier Carrier-to-Noise-Ratios (CNRs)

$$\text{CNR}_i = |h_i|^2 \cdot \text{SNR} \quad (6)$$

for all occupied subcarriers into an effective Signal-to-Noise-Ratio SNR_{eff} such that SNR_{eff} indicates the equivalent SNR for a transmission over an Additive White Gaussian Noise (AWGN) channel [10].

A. Resources

We briefly describe the physical resources and link parameters that are available for our system level investigations. In Fig. 2 we depict a resource grid with a resource block set $\mathcal{S}$, $|\mathcal{S}| = N_{\text{FFT}}$ where each resource block comprises 12 subcarriers. Further, a Time-Division-Duplex (TDD) scheme allows for alternating uplink and downlink transmissions. A slot, or Transmission Time Interval (TTI), spans 6 OFDM symbols which refers to a minislot in 5G NR terminology [15]. For each slot, we assume an independent frequency-selective block fading channel, cf. Sec. II, per user. Moreover, a frequency-flat channel per resource block, cf. 5G NR [16], is assumed. Slots are equally sized and thus, each resource block conveys the same fixed number of complex symbols per slot. With a Frequency-Division-Multiplex (FDM) RA strategy whole resource blocks are allocated to a user [17]. We may assign an arbitrary subset $\mathcal{S}_a \subseteq \mathcal{S}$ with $|\mathcal{S}_a| = N_{\text{sc}}$ to a user for transmission in a slot. For Time-Division-Multiplex (TDM), we assume that a RA strategy may allocate the same number of symbols from each resource block to a user. Different users may be allocated different numbers of symbols per resource block depending on channel conditions.

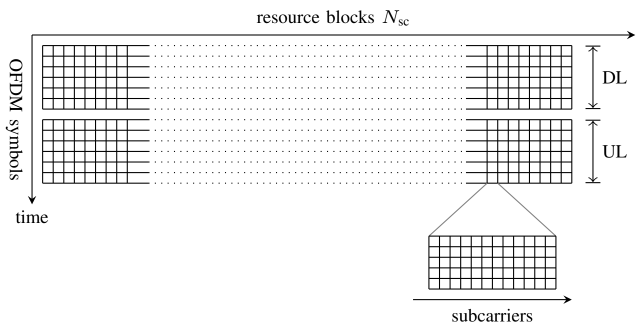

Fig. 2. Resource grid

In order to efficiently use resources, we assume Adaptive Modulation and Coding (AMC) with MCSs shown in Tab. I. We use a polar code from [10], similar to the one used in 5G NR control channels [18], and a modulation alphabet $\mathcal{A}$, $|\mathcal{A}| = 2^M$ with Quadrature Phase Shift Keying (QPSK) or 16-Quadrature Amplitude Modulation (QAM) gray mapping. A lower MCS index indicates a lower effective rate $R_{\text{eff}} = RM$ and thus higher robustness against errors.

From AWGN simulations we obtain FER over SNR curves that we use to obtain switch points between MCSs. We set a target FER T_{FER} that indicates a threshold and if not met causes the system to use a more robust MCS. While a more robust MCS is desirable from a reliability point of view, we need to consider multiple users which compete for shared resources. A more efficient R_{eff} for links with high SNR may enable to spend more resources on links with low SNR and in turn improve resilience to burst errors.

TABLE I

PROPERTIES OF USED MCS IS A SUBSET OF [10] FOR SHORT PACKETS

MCS index	0	1	2	3	4	5	6
Coderate R	1/8	1/6	1/4	1/3	1/2	1/3	1/2
Modulation	QPSK	QPSK	QPSK	QPSK	QPSK	16-QAM	16-QAM
R_{eff}	0.25	0.33	0.5	0.67	1.0	1.33	2.0
SNR [dB] for $T_{\text{FER}} = 0.1$	-4.90	-3.53	-1.62	-0.09	2.13	4.95	7.62

B. *Effective SNR Mapping*

The process of converting CSI into an effective SNR is called Effective SNR Mapping (ESM). The authors in [10] show that MIESM yields the highest accuracy among the investigated Effective SNR Mapping (ESM) methods. Also, only one adjustment factor β per coderate is sufficient. We consider one distinct adjustment factor β per coderate as shown in Tab. II.

TABLE II

CODERATES R WITH CORRESPONDING ADJUSTMENT FACTORS β

R	β
1/8	0.2989
1/6	0.3833
1/4	0.4816
1/3	0.5029
1/2	0.7770

For MIESM per-subcarrier CNRs are used to calculate

$$\text{SNR}_{\text{eff}} = \beta I^{-1}\left(\frac{1}{N_{\text{sc}}}\sum_{i=0}^{N_{\text{sc}}-1} I\left(\frac{\text{CNR}_i}{\beta}\right)\right) \tag{7}$$

where the function $I(\cdot)$ for MIESM depends on the chosen modulation alphabet $\mathcal{A}$ [10]. Since we assume a constant channel realization for the duration of a slot, it is sufficient to calculate SNR_{eff} over N_{sc} occupied subcarriers.

IV. SCHEDULING AND RESOURCE ALLOCATION

We split Scheduling and Resource Allocation (RA) into two sub-tasks as depicted in Fig. 3. Both, scheduling and RA work on a per TTI or slot basis. We assume an alternating *DUDU* TDD scheme [15] where half a slot is used for downlink and the other half for uplink communication, effectively comprising minislots as depicted in Fig. 2 [15]. We assume the channel to be constant for the duration of a slot. As mentioned before, we focus on burst error minimization in contrast to other works that focus on sum-rate maximization [5].

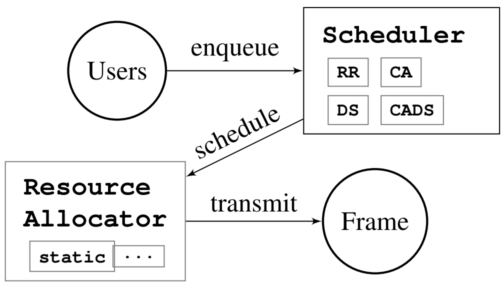

Fig. 3. Scheduling and RA processing chain

With Fig. 3 in mind, we briefly describe the scheduling and RA process for each slot.

- All users enqueue a new packet in the current slot.
- The scheduler assigns weights w_m to all user packets and thus, these packets are ordered in ascending weight order.
- The RA sequentially allocates resources to user packets in the given scheduler order.
- All allocated packets are transmitted in the current slot.

A. *Packet arrival model*

CLC applications exhibit periodic deterministic communication behavior with real-time deadlines [2]. We assume a deterministic packet arrival model with a set $\mathcal{U}$ of $|\mathcal{U}| = U$ active users. At the start of each communication cycle with duration T_{cycle} every user enqueues a new packet for transmission and expects a new packet for reception [4]. The cycle duration constitutes the real-time deadline for all packets, i.e. they are discarded and considered lost if not transmitted successfully within one cycle [15]. Also, the cycle duration equals the slot duration and they are aligned. We do not allow for packet segmentation over multiple slots because this would increase latency beyond their real-time deadline. Since each user has one new packet ready for transmission at the start of a slot, we do not allow for preemptive scheduling. We focus on MC applications with typical cycle times in the range $0.25\,\mathrm{ms}$ to $2\,\mathrm{ms}$ [2], [4]. Thus, retransmissions add a prohibitively high delay [15], [19]. Further, we assume that the number of information bits is identical for all packets in every cycle. We focus on downlink scheduling and note that uplink scheduling faces similar conditions and challenges. In practice, we need to consider signal processing times that add more delay before and after transmission over the air. If a communication system would support shorter latencies, this would be leveraged to reduce cycle duration T_{cycle} instead of re-transmissions [15].

B. Scheduling

The scheduler task is to determine the order in which resources are allocated to packets [5]. A scheduler computes weights w_u for all users in $\mathcal{U}$ and orders them in *ascending weight order* in each slot. Subsequently, a RA sequentially allocates resources to users. We focus on burst error minimization and thus, we consider the packet transmission success delay $N_{\text{sd},u} \in \mathbb{N}^0$ which quantifies the delay in number of slots since the last successful transmission, i.e. the current burst error length. A scheduler may use information on current CSI for each user for scheduling decisions. CSI is assumed to be constant for the duration of a slot. We do not permit re-transmissions, thus a scheduler cannot use information such as Head-of-Line Access Delay [20]. Here, we describe possible scheduling strategies.

a) Round Robin (RR): scheduling schedules packets user-by-user sequentially such that $w_u = u$. This implies that in case not enough resources for all users are available, the last user will always be dropped for the current cycle.

b) Channel Aware (CA): scheduling prefers packets for users with poor channel conditions in a slot to ensure these users receive as many resources as possible to reduce burst errors. The scheduler computes the weights $w_u = \text{CNR}_{\text{avg},u}$ according to (7) with $I(x) = x$, $\beta = 1$.

c) Sum-Rate (SR): scheduling prefers packets for users with superior channel conditions in a slot to ensure these users maximize sum data rate. The scheduler computes the weights $w_u = -\text{CNR}_{\text{avg},u}$ according to (7) with $I(x) = x$, $\beta = 1$.

d) Delay Sensitive (DS): scheduling prefers packets by users that experience a longer delay since the last successfully transmitted packet $w_u = -N_{\text{sd},u}$. This strategy addresses problematic burst error conditions.

e) Channel Aware Delay Sensitive (CADS): scheduling combines the CA and the DS strategy. The weights $w_u = -N_{\text{sd},u} + 1/(1 + \exp\{-\text{CNR}_{\text{avg},u}\})$ are calculated such that a larger $N_{\text{sd},u}$ always causes a user to take precedence over users with smaller $N_{\text{sd},u}$ and users with the same $N_{\text{sd},u}$ are ordered in ascending $\text{CNR}_{\text{avg},u}$ order.

C. Resource Allocation

We identify several RA strategies that we discuss shortly. A RA sequentially processes users in *ascending scheduler weight order*. First, it needs to determine the best MCS subject to available resources. Then these resources are allocated to the current user and the next user is processed. In general, two distinct approaches to multiplex users onto resources are possible [17]. With TDM we distribute packets over all N_{FFT} resource blocks in order to leverage frequency diversity. We outline our considered RA strategies briefly.

a) Static: RA does not consider any dynamic information but uses a static MCS_u. We assume MCS index 4 according to Tab. I [9].

b) Dynamic: RA uses (7) to compute $\text{SNR}_{\text{eff},u}$. Starting with the highest MCS its corresponding $\text{SNR}_{\text{eff},u}$ is calculated. If this MCS does not satisfy the FER threshold T_{FER}, the next lower MCS is considered. The current user MCS_u is determined as the highest MCS that satisfies T_{FER}.

c) Backoff: RA is an extension to dynamic RA. First, it determines $\text{MCS}_{d,u}$ according to the dynamic RA strategy. Then, it determines the used $\text{MCS}_u = \text{MCS}_{d,u} - 2N_{\text{sd},u}$ such that users with a packet transmission success delay are granted extra resources to minimize packet error probability for the next transmission.

d) Failsafe: RA is an extension to backoff RA. In case $N_{\text{sd},u} > 0$ it determines $\text{MCS}_u = 0$. Otherwise the dynamic RA strategy applies.

With MCS_u the number of required symbols is determined and allocated for the current user. In case sufficient resources are not available anymore in the current slot, no resources are allocated for the current user in the current slot.

On the other hand, we consider FDM to allocate resources to users such that we leverage multi-user diversity. In this case the RA strategy is to compute the number of required resource blocks N_{sc} for the highest MCS, then determine the set $\mathcal{S}_a$ of available resource blocks with the highest CNRs for the current user. Finally, compute $\text{SNR}_{\text{eff},u}$ for these resource blocks. If $\text{SNR}_{\text{eff},u}$ does not satisfy T_{FER} the next lower MCS is chosen until an MCS is found that satisfies T_{FER}. In that regard it is similar to the dynamic RA strategy.

V. Simulation Assumptions

We assume an industrial radio setup at $3.8\,\mathrm{GHz}$ and $100\,\mathrm{MHz}$ bandwidth with TDD which corresponds to 5G NR channels *n77* or *n78* [21]. We set $N_{\text{FFT}} = 135$ which corresponds to the number of resource blocks in 5G NR for a $100\,\mathrm{MHz}$ bandwidth and $60\,\mathrm{kHz}$ subcarrier spacing setup [17]. We expect a frequency flat channel over a resource block and further we consider the channel to be constant for the duration of one slot. Further, we assume a downlink scenario with a single antenna setup with a $24\,\mathrm{dBm}$ maximum transmit power

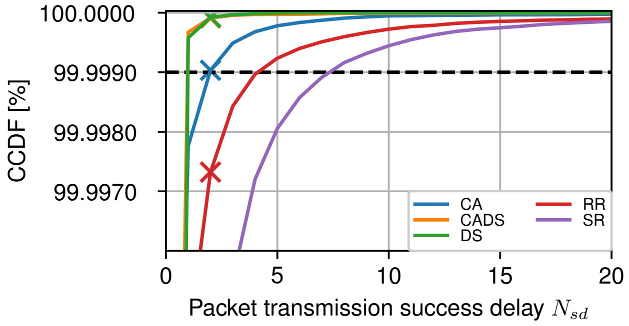

Fig. 4. Scheduling strategy impact for $M_u = 42$ users with FDM RA

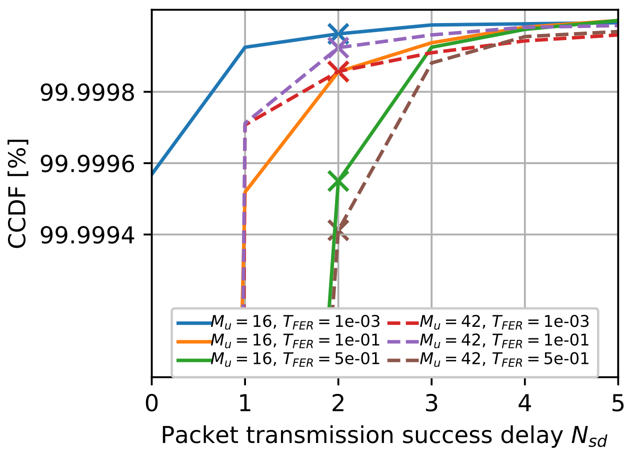

Fig. 5. Burst error probabilities for different target FERs with FDM RA

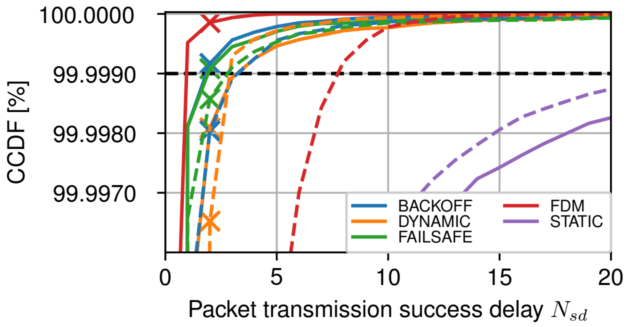

Fig. 6. Comparison of different RA strategies with perfect CSI [solid line] and 1 ms-delayed CSI [dashed line]

and a receiver noise figure $F = 9\,\mathrm{dB}$ [8]. Also, we suppose the room temperature to be at $T = 300\,\mathrm{K}$ for noise floor calculations. We expect NLOS conditions with large scale fading parameters $\sigma_{SF} = 8\,\mathrm{dB}$ shadowing deviation with $d_{corr} = 5\,\mathrm{m}$ correlation distance and a path loss exponent $\eta = 3$ which may occur frequently even at low distances for indoor scenarios [8]. In accordance with [6] we assume $\sigma_\tau = 46.8\,\mathrm{ns}$ and $\tau_{max} = 250\,\mathrm{ns}$ with an exponential power delay profile. We assume that all devices move at $v = 15\,\mathrm{km\,h^{-1}}$ velocity which determines the channel coherence time. We simulate 10^6 slots with M_u users and each user transmits one packet with $32\,\mathrm{byte}$ or $256\,\mathrm{bit}$ of information per slot.

VI. Numerical results

We investigate application level availability with Complementary Cumulative Distribution Function (CCDF) curves for packet transmission success delay N_{sd}. A CCDF is a cumulative distribution function that indicates the delay until the next successful packet transmission for all users in the system. Communication system availability is defined as the CCDF for length-2 burst errors that are marked with crosses in all result figures. We require availability above $99.999\,\%$, indicated with a dashed horizontal line. First, we use the FDM RA strategy in Fig. 4 for $M_u = 42$ and $T_{\text{FER}} = 10^{-1}$ with different scheduling strategies. The Sum-Rate (SR) strategy exhibits the poorest performance which highlights our proposed focus shift to burst error minimization. While the Channel Aware Delay Sensitive (CADS) strategy has a slight edge over the Delay Sensitive (DS) strategy, we conclude that only these two strategies enable us to meet URLLC requirements.

In Fig. 5, we consider different target FERs T_{FER} and number of user M_u for FDM at $20\,\mathrm{m}$ distance. We observe that lower T_{FER} slightly improves resilience against burst errors for $M_u = 16$ where sufficient resources for all users are available. For $M_u = 42$ resilience against burst errors decreases and a lower T_{FER} boosts this decrease. Thus, a target FER $T_{\text{FER}} = 10^{-1}$ may serve as a suitable reference. We conclude that a fully occupied system requires more aggressive MCS switch points in order to ensure that more users may be allocated. Though, a more aggressive MCS switch point is only a minor contributor to burst errors and the availability is always above $99.999\,\%$.

Next, we consider different RA strategies at $20\,\mathrm{m}$ distance with a target FER $T_{\text{FER}} = 10^{-1}$ shown in Fig. 6. With perfect CSI (solid), a FDM RA strategy outperforms all other strategies while the *FAILSAFE* and *BACKOFF* RA strategies yield similar performance. This picture changes in case of a $1\,\mathrm{ms}$ CSI delay (dashed), i.e. the RA uses CSI that was obtained earlier and thus, does not represent the current CSI. Most notably, the *FDM* RA strategy performance deteriorates significantly. Also, the *FAILSAFE* strategy yields the best performance in case of CSI delay while the *BACKOFF* strategy performance deteriorates more.

We note that any dynamic RA strategy outperforms the *STATIC* strategy in all cases by a large margin. In order to achieve above $99.999\,\%$ availability the FDM RA or a *FAILSAFE* strategy is necessary. CSI quality is critical to system performance and needs to be considered in future 5G NR releases for URLLC.

In Fig. 7 we investigate the impact of different distances between the Access Point (AP) and the devices on burst errors with a *FAILSAFE* RA. We observe that even at a distance of $25\,\mathrm{m}$ the communication system under investigation is unable

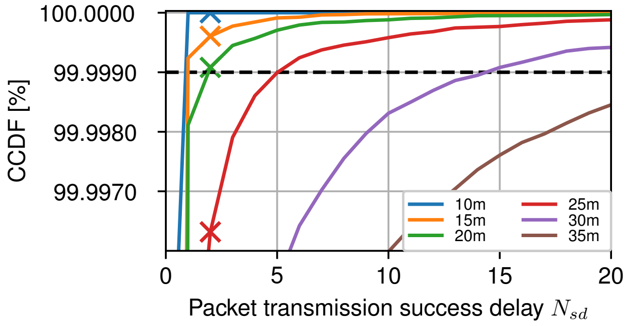

Fig. 7. *FAILSAFE* RA with users at different distances from the AP

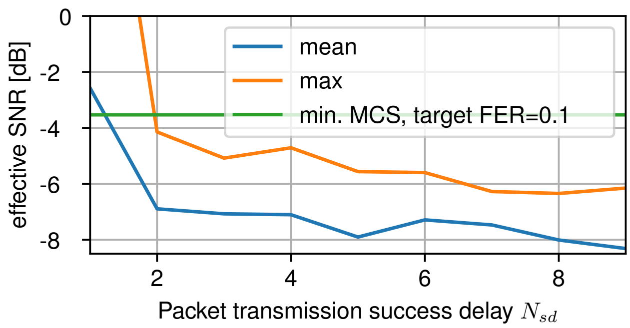

Fig. 8. Effective SNR over burst error length

to provide the required $99.999\,\%$ availability QoS.

We investigate the reasons for burst errors in Fig. 8. All users are placed at a $25\,\mathrm{m}$ distance from the AP with $T_{\mathrm{FER}} \in \{10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}\}$. We observe that burst errors of length 2 and above are solely caused by an effective SNR that even the MCS with the lowest effective rate cannot serve with an FER below 0.1. Therefore, we conclude that burst errors are dominated by fading and shadowing effects even if large link budgets are available.

VII. Conclusion

In this paper we analyzed periodic deterministic communication for Factory Automation (FA) with real-time constraints. We showed that aggressive MCS switch points have a minor effect on burst error probabilities. While FDM RA exhibit superior performance with perfect CSI knowledge, there performance deteriorates quickly and TDM RA becomes favorable. *STATIC* RA strategies are not suitable for URLLC unless surplus resources are available. A quick reaction to error events and subsequent error handling were shown to be beneficial to mitigate burst errors. We showed that URLLC communication is mainly limited by shadowing and fading. Such events cannot be mitigated by means of scheduling and RA by a single AP and thus multiple spatially separated cooperating APs are required.

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