This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Tirkkonen, Olav; Khosravirad, Saeed R.; Baracca, Paolo; Zhou, Liang; Parts, Ulo; Korpi, Dani; Uusitalo, Mikko A.

Optimized Survival Mode to Guarantee QoS for Time-critical Services

Published in:
2021 IEEE International Conference on Communications Workshops, ICC Workshops 2021 - Proceedings

DOI:
[10.1109/ICCWorkshops50388.2021.9473635](https://doi.org/10.1109/ICCWorkshops50388.2021.9473635)

Published: 01/07/2021

Document Version
Peer reviewed version

Please cite the original version:
Tirkkonen, O., Khosravirad, S. R., Baracca, P., Zhou, L., Parts, U., Korpi, D., & Uusitalo, M. A. (2021). Optimized Survival Mode to Guarantee QoS for Time-critical Services. In *2021 IEEE International Conference on Communications Workshops, ICC Workshops 2021 - Proceedings* [9473635] (IEEE international conference on communications workshops). IEEE. <https://doi.org/10.1109/ICCWorkshops50388.2021.9473635>

© 2021 IEEE. This is the author's version of an article that has been published by IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Optimized Survival Mode to Guarantee QoS for Time-critical Services

Olav Tirkkonen^{1,4}, Saeed R. Khosravirad², Paolo Baracca³, Liang Zhou⁴, Ulo Parts⁴,
Dani Korpi⁵ and Mikko A. Uusitalo⁵

¹ Department of Communications and Networking, Aalto University, Finland

² Nokia Bell Labs, Murray Hill, NJ, USA

³ Nokia Bell Labs, Stuttgart, Germany

⁴ Inalambrica Oy, Helsinki, Finland

⁵ Nokia Bell Labs, Espoo, Finland

e-mail: olav.tirkkonen@aalto.fi, firstname.lastname@nokia-bell-labs.com

Abstract—We consider time critical transmissions for wireless industrial IoT services, where information should not be older than a survival time in the millisecond order, and extreme service availability is targeted. With non-zero survival time, a feedback based survival mode is possible, where the network incorporates additional robustness if the previous transmission was not received. We consider the tradeoff between reliability of normal mode and survival mode transmission, and analyze the effect of feedback errors on these. We formulate an optimization to minimize average resource usage, guaranteeing time critical quality of service (QoS), and show numerical results in scenarios with typical system assumptions. For a user with a Rayleigh fading channel, average signal-to-noise ratio 10 dB, and control channel error probability 10^{-3} , optimization based on judiciously choosing survival and normal mode reliability targets can reduce resource usage needed to guarantee QoS with a factor of 30.

I. INTRODUCTION

The next generation of industrial control systems is widely anticipated to shift from the traditional fieldbus and Ethernet based wired solutions to wireless alternatives. This will reduce bulk and cost of installation, while enabling a highly flexible and dynamic environment of production stations that could seamlessly re-arrange according to production requirements [1], [2]. For wireless technologies, this has resulted in new requirements of sub-ms extreme low latency and “cable-like” ultra-high reliability [3], bringing about a great deal of research activities in the recent years on new technologies to enable the so-called ultra-reliable and low latency communications (URLLC) [4], [5], [6], [7], [8].

In the context of wireless motion control of robots and actuators, admittedly, the more distinct aspect of the quality of service (QoS) requirements is the new notion of survival time [3], [9]. For such applications with periodic packet arrival pattern, survival time refers to the time that the application may continue without an anticipated data packet. Table I shows three examples of such applications (see [3] for more elaborate examples) with the corresponding survival time. Here, service availability is defined as the percentage of time that the QoS requirements—including end-to-end latency and survival time—are satisfied for the link. The first two services in Table I can tolerate a survival time equivalent to the

transfer interval (TI), i.e., inverse of packet arrival period, while the third application can survive even with up to three consecutive packets not making it to the destination within the latency budget. In some applications, such as remote control of a harbor crane, the survival time can be as large as six consecutive transfer intervals [10].

The immediate impact of introducing survival time as a QoS requirements of the wireless link is a shift in design paradigm from typical link reliability—i.e., minimizing packet error rate (PER)—to service availability—i.e., minimizing chance of burst errors. Demonstrably, for a wireless medium that changes over time, nine nines of service availability translates to a less stringent link reliability figure. The exact link reliability requirement depends on the rate of variations and temporal correlation in the channel fade, and the survival time budget. Specifically, in presence of a reliable feedback channel that promptly reports the occurrence of packet failure, the relaxation on link reliability requirement can be more meaningful. An intelligent wireless scheduler can then differentiate between survival mode, i.e., a mode where the last packet has failed, and a normal mode of operation and take advantage of such relaxed PER requirement to increase the overall resource utilization efficiency. Hence, the main research questions this paper addresses are: first, what is the impact of feedback channel unreliability on service availability; and second, how much spectral efficiency gain is obtainable from decoupled scheduling strategies in the normal mode and survival mode?

Analysis of service availability for periodic traffic has recently gained attention in the literature. In [11], the statistics of service availability time is characterized in the absence of wireless channel statistics and channel state information. The work in [12] presents an extensive simulation analysis of wireless closed-loop control applications. Impact of several scheduling schemes are simulated and compared in [12], suggesting a conservative link-adaptation for a link in survival mode. Exploiting dual connectivity [13] and network coding [14] have also been reported as means for limiting consecutive errors and improving service availability. In a closely related line of research, the notion of age-of-information (AoI) has

TABLE I
QoS CHARACTERISTICS FOR APPLICATIONS WITH PERIODIC TRAFFIC PATTERN [3].

Service outage probability	E2E latency	Message size [byte]	Transfer interval	Survival time	# of UEs	Service area	Application
$10^{-7} - 10^{-5}$	< transfer interval	50	$500 \mu s$	$500 \mu s$	≤ 20	$50 m \times 10 m \times 10 m$	Motion control
$10^{-8} - 10^{-6}$	< transfer interval	40	1 ms	1 ms	≤ 50	$50 m \times 10 m \times 10 m$	Motion control
$10^{-8} - 10^{-6}$	< transfer interval	N/A	$\leq 1 ms$	$3 \times$ transfer interval	2-5	$100 m \times 30 m \times 10 m$	Wired-2-wireless 100 Mbit/s link replacement

been studied extensively in the literature, e.g., see [15], [16], [17]. AoI characterizes the freshness of the information at the receiver end of a communication link by measuring the elapsed time since the freshest packet was generated at the transmitter end. Therefore, the notion of AoI can be coupled with survival time and service availability from Table I as follows: communication service is deemed available if the age of the freshest packet at the receiver is less than the sum of the end-to-end latency and survival time budgets.

The main contribution of this work is to characterize service availability as a function of link reliability in normal mode and survival mode of operation in presence of feedback channel unreliability. To this end, we derive bounds on link reliability in each mode of operation. Moreover, for an assumed probability of error of the feedback channel, we optimize the average spectral efficiency with respect to PER in survival and normal mode of operation.

This paper is organized as follows: We present the system model in Section II, and analyze the effect of control channel errors on error probability requirements in Section III. In Section IV, we address the two-mode link adaptation problem and optimize the error probabilities to minimize average resource usage. Section V concludes the paper.

II. SYSTEM MODEL

We consider a downlink wireless system with a fixed population of U user equipment (UEs). A message of fixed size B bits is to be transmitted to each user in each TI of duration T . The communication rate of the users is thus $R = B/T$. The survival time of the system is $(M - 1)T$, with $M > 1$ being a small integer indicating the number of consecutive lost packets that leads to communication service outage for the application. For example, when $M = 2$, the system can survive one packet failure, but if there are two consecutive packet failures, the application suffers from service outage. The targeted maximum *probability of service outage* is denoted by P_{SO} .

A. Survival Protocol to Control Burst Errors

To ensure service availability, link adaptation operates in two modes, a *normal mode*, and a *survival mode*. The system enters into the survival mode after a failed packet transmission, and returns to normal mode after a successful survival mode transmission.

To enable this, an acknowledged mode is used; there is a feedback channel where the users send acknowledgements (ACK) or negative acknowledgements (NACK) after successful or unsuccessful reception of a packet, respectively. The ACK/NACK is assumed to arrive within the transfer interval, and is thus available at the transmitter before the transmission of the next packet. In contrast to conventional radio link control, failed packets are not retransmitted, however, ACK/NACK instead affects the transmission mode of the next packet with fresh data. The system transitions to survival mode if the base station receives a NACK, or there is missing ACK/NACK feedback.

We assume that link adaptation is based on maintaining target error probabilities for packet transmission: P_n for normal mode transmissions, and P_s for survival mode transmissions. For this, we assume that the transmitter has perfect knowledge of the statistics of channel quality of the users: in practice, that can be estimated by using techniques like the ones proposed in [18]. We assume that the packet error probabilities represent the total probability of failed reception, which includes both possible errors in downlink control channel reception, as well as in the decoding of the payload data itself. To guarantee service survival, $P_s < P_n$, which is realized by consuming more resources for packet transmission in survival mode.

The ACK/NACK feedback is transmitted over an uplink control channel, which has an error probability P_{control} , typically in the order of $10^{-2}, \dots, 10^{-4}$, see [19]. As a consequence, there is a probability P_{N2A} that a NACK is interpreted as ACK (N2A), and a probability P_{A2N} for an ACK-to-NACK (A2N) error. These are not necessarily equal to P_{control} ; by tuning the parameters of control channel reception, P_{N2A} can be reduced at the cost of increasing P_{A2N} [20].

N2A is more damaging to service survival than A2N. A N2A event prevents the shift of state to survival mode, and thus jeopardizes survival. An A2N error, in converse, does not jeopardize survival, but increases resource consumption in the system, as the survival mode is used more often. The probabilities of entering and leaving the survival mode are

$$\begin{aligned} P_{n \rightarrow s} &= P_{A2N} + (1 - P_{A2N} - P_{N2A}) P_n \\ P_{s \rightarrow n} &= 1 - P_{A2N} - (1 - P_{A2N} - P_{N2A}) P_s. \end{aligned}$$

The steady state probability of survival mode transmissions is

TABLE II
PROBABILITY VARIABLES IN THE SYSTEM MODEL

P_{SO}	Probability of service non-availability
P_n	Packet-loss probability in normal mode
P_s	Packet-loss probability in survival mode
P_{N2A}	NACK-to-ACK error probability
P_{A2N}	ACK-to-NACK error probability
$P_{\text{Tx},s}$	Probability of survival mode transmission

thus

$$P_{\text{Tx},s} = \frac{P_{n>s}}{P_{n>s} + P_{s>n}} = \frac{P_{\text{A2N}} + (1 - P_{\text{A2N}} - P_{\text{N2A}}) P_n}{1 + (P_n - P_s)(1 - P_{\text{A2N}} - P_{\text{N2A}})} \quad (1)$$

Thus, if $P_n < P_{\text{A2N}}$, the normal mode error probability has little effect in transition to survival mode. The probabilities used for system modeling are collected to Table II.

B. Signal Quality Model

The users are served in a controlled environment where the effect of other use of the channels reserved for communication can be modeled in terms of a constant average interference power. There is mobility in the system, either the UE and/or some scatterers are mobile, resulting in fading channels, such that the instantaneous signal-to-interference-plus-noise-ratio (SINR) γ_u of users u is assumed to be distributed according to a small scale fading distribution, e.g., Rice fading in Line-of-Sight (LoS) situations, or Rayleigh fading in Non-LoS. For simplicity, we assume narrowband channels, such that the same γ_u characterizes the channel of user u across the whole bandwidth that can be used for communication. Furthermore, we assume block fading, such that the SINR during the whole transmission is γ_u . In indoor factory scenarios, the typical delay spreads are so short, as compared to typical system bandwidth, that the channels are often narrowband, see, e.g., indoor factory models in [21].

Link adaptation is based on estimated SINRs $\hat{\gamma}_u$. The SINR used for link adaptation is estimated either from an uplink transmission, or from a downlink transmission with feedback. Irrespectively of the method to acquire $\hat{\gamma}$, the channel γ during transmission differs from the estimated channel; even with perfect channel estimation, there is a delay τ between the time the channel is estimated, and the time of transmission. The uncertainty of the SINR during transmission is characterized by a distribution $f_\Gamma(\gamma | \bar{\gamma})$, with $\bar{\gamma}$ the expected SNR at the time of transmission given $\hat{\gamma}$, see, e.g., [22].

Assume, for example, that the channel is Rayleigh or Rice distributed. If the time development of the fading components follow Jakes' model, the SINR during transmission is non-centrally χ^2 distributed with two degrees of freedom:

$$f_\Gamma(\gamma | \bar{\gamma}) = \frac{1 + K}{e^{K\bar{\gamma}}} e^{-(1+K)\gamma/\bar{\gamma}} I_0 \left(2\sqrt{(K^2 + K)\frac{\gamma}{\bar{\gamma}}} \right) \quad (2)$$

Here, $I_0(\circ)$ is the modified Bessel function of first kind. The K -factor depends on the possible Rician factor of the underlying fading statistics, the channel correlation between the time of estimation and the time of transmission, and the relative fading state at the time of channel estimation.

C. Transmission Error Probability Model

In link adaptation, bandwidth w_u is allocated to the transmission of the B bits of the user in a TI, based on $\bar{\gamma}_u$. We assume a transmission error probability function $p(\bar{\gamma}, w, R)$ for the transmission of the RT bits in bandwidth w , given an estimate of the expected SINR $\bar{\gamma}$. This could be the true block error probability of an adaptable size codebook used transmission, or an ideal finite blocklength error probability. For concrete calculations, we shall invoke the result from [23], where it was shown that the saddle point approximation of the error probability of an ideal finite block length code in a block fading channel is given by the asymptotic error probability of infinite length codes:

$$p(\bar{\gamma}, w, R) = F_\Gamma(\theta(w, R) | \bar{\gamma}) \quad (3)$$

where $F_\Gamma(\gamma | \bar{\gamma})$ is the Cumulative Distribution Function (CDF) of $f_\Gamma(\gamma | \bar{\gamma})$, e.g., of (2), and

$$\theta(w, R) = 2^{R/w} - 1 \quad (4)$$

is a threshold SINR required for an ideal AWGN capacity reaching code to achieve spectral efficiency R/w . For the non-central χ^2 distribution of (2) we have

$$F_\Gamma(\theta | \bar{\gamma}) = 1 - Q_1 \left(\sqrt{2K}, \sqrt{2(1+K)\frac{\theta}{\bar{\gamma}}} \right) \quad (5)$$

where $Q_1(\circ, \circ)$ is the Marcum Q-function.

III. ANALYSIS OF PACKET ERROR PROBABILITIES

We start by analyzing requirements on target packet error probabilities P_n and P_s that arise from a required maximum service outage P_{SO} , and a control channel unreliability, reflected in a NACK-to-ACK probability P_{N2A} . For simplicity, we assume that consecutive error events in the system are not correlated, leaving an analysis of error correlations to future work. The effect of P_{N2A} on Hybrid-ARQ (HARQ) for URLLC was analyzed in [20]. The analysis here differs due to the presence of the survival mode.

With survival time $(M-1)T$, for given P_n, P_s, P_{N2A} , the service outage probability can be derived to be:

$$P_{\text{SO}} = P_n \left(P_{\text{N2A}} P_n + (1 - P_{\text{N2A}}) P_s \right)^{M-1} \quad (6)$$

This follows from the fact that after an initial erroneous transmission, represented by the first P_n , each consecutive transmission consists of a pair of a uplink control transmission selecting the transmission mode, and a failed transmission in the selected mode. As both the NACK-to-ACK probabilities and the packet loss probabilities are assumed uncorrelated, the equation follows.

This shows that there is a lower bound $P_{n,\min} = \sqrt[M]{P_{\text{SO}}}$ for P_n , given by the point when $P_s = P_n$. At this lower bound, there is no survival mode, and the ACK/NACK feedback becomes irrelevant. As long as $P_{\text{SO}} < 0.5$, it follows from (6) that if $P_s < P_n$, we have $P_n > P_{n,\min}$.

Furthermore, (6) reveals requirements on normal mode transmission reliability given a NACK-to-ACK error

Fig. 1. The upper bound on normal mode error probability as a function of P_{N2A} for given P_{SO} target when $M = 2$.

probability. As such errors prevent the use of the survival mode to guarantee system survival, stringent requirements on P_n arise. This leads to similar analysis as in [24] for HARQ. The role of P_s in (6) vanishes in the limit $P_s \rightarrow 0$. In this limit, (6) yields a bound on P_n ; the probability of a service outage event where NACK-to-ACK errors prevent entering survival should be bounded as

$$P_n^M P_{N2A}^{M-1} < P_{SO}. \quad (7)$$

Note that if $P_s > 0$, which holds in a wireless system where there is always some uncertainty, these are not the only events that contribute to the overall service outage probability, thus this is a true inequality. This equation immediately leads to the upper bound on normal mode error probability, which combined with the lower bound found above yields

$$\sqrt[M]{P_{SO}} \leq P_n < \sqrt[M]{\frac{P_{SO}}{P_{N2A}^{M-1}}}. \quad (8)$$

This characterizes the rather unsurprising fact that the smaller the P_{SO} and the larger the P_{N2A} is, the more reliability is required from the normal mode. The bound on normal mode P_n as a function of P_{N2A} for $M = 2$, when two consecutive packet losses are not acceptable, is plotted in Figure 1 for the maximum service outage probabilities $P_{SO} = 10^{-6}$ and 10^{-8} , pertinent for the services discussed in Table I.

Another way of phrasing (8) is

$$P_n = \alpha \sqrt[M]{\frac{P_{SO}}{P_{N2A}^{M-1}}}, \quad (9)$$

where α is a design constant taking values in the interval $\alpha_{\min} \leq \alpha < 1$, with $\alpha_{\min} = P_{N2A}^{1-1/M}$. If α is taken close to 1, we assume an infinitely reliable survival mode with $P_s \rightarrow 0$, while at the lower bound $\alpha_{\min}$, there is no survival mode.

Next, we analyze the effect of NACK-to-ACK errors on the survival mode in light of the bounds on P_n found above. If (6) is taken as a constraint on P_s and P_n given a P_{SO} requirement and a P_{N2A} , it follows that P_s is a decreasing function of P_n . Corresponding to the interval (8) we thus have

$$\sqrt[M]{P_{SO}} \geq P_s > 0. \quad (10)$$

Fig. 2. The upper bound on survival mode error probability as a function of P_{N2A} for given P_{SO} target when $M = 2$ and $\alpha = 1/2$.

From (6) we can, moreover, solve P_s as a function of P_n :

$$P_s = \frac{M \sqrt[M]{P_{SO}}}{1 - P_{N2A}} \cdot \frac{1}{M \sqrt[M]{P_n}} - \frac{P_{N2A}}{1 - P_{N2A}} P_n. \quad (11)$$

This directly shows how P_s shrinks with growing P_n . Using (9) in this, we get

$$P_s = \left(\alpha^{-\frac{1}{M-1}} - 1 \right) \frac{M \sqrt[M]{P_{SO} P_{N2A}}}{1 - P_{N2A}}. \quad (12)$$

This shows how P_s is *increasing* in P_{N2A} for all α and P_{SO} . In Figure 2, P_s is plotted against P_{N2A} for two values of P_{SO} of interest, when $M = 2$ and $\alpha = 1/2$.

The two figures 1 and 2, taken together, portray the tradeoff between P_n and P_s , characterized by the variable α , that a system designer has at hand. To capture intuition about this tradeoff, the ratio P_s/P_n is of interest. Combining (9) and (12), we get

$$\frac{P_s}{P_n} = \left(\alpha^{-\frac{M}{M-1}} - \alpha^{-1} \right) \frac{P_{N2A}}{1 - P_{N2A}}. \quad (13)$$

From this we see that the less reliable the control channel is, the less additional reliability we require from the survival channel, while according to (8), the more we require from normal transmissions. In the limit $P_{N2A} = 0.5$, survival mode becomes meaningless, one would have $P_n^M = P_s^M = P_{SO}$.

In normal operation of cellular systems, error probabilities in the order of tens of percents maximize system efficiency [25]. To maintain such error probabilities for QoS requirements depicted in Table I, extreme feedback channel and survival mode reliability is required. If the system cannot guarantee these at a reasonable cost, one has to have a more reliable normal transmission mode.

For chosen P_{SO} and P_{N2A} , the system designer has to select the parameter $\alpha \in [\alpha_{\min}, 1)$ to balance between the normal and survival mode reliabilities. In Figure 3, the P_n and P_s values as a function of α are plotted, for $P_{N2A} = 10^{-3}$. For this P_{N2A} , we have $\alpha_{\min} = 0.032$. The upper bounds for P_n in Figure 1 are reached when $\alpha \rightarrow 1$, while the values of P_s in Figure 2 can be found at the point $\alpha = 1/2$.

Fig. 3. P_n and P_s as functions of α for P_{SO} values of interest, $M = 2$ and $P_{N2A} = 10^{-3}$.

Fig. 4. Backoff values $\theta_{dB} - \bar{\gamma}_{dB}$ in dB scale for survival mode transmissions for different values of α , when $M = 2$, $P_{N2A} = 10^{-3}$ and $\bar{\gamma} = 10$ dB.

IV. ERROR PROBABILITY OPTIMIZATION

In link adaptation, the target error probabilities have to be translated to an amount of resources allocated for the transmission of the B bits to the users. As we assume that the SINR statistics of the users are known, link adaptation would operate as follows. First, for target error probability ϵ , the SINR threshold

$$\theta = F_{\Gamma}^{-1}(\epsilon) \quad (14)$$

is solved. Here $F_{\Gamma}^{-1}(\circ)$ is the inverse of the conditional CDF $F_{\Gamma}(\circ|\bar{\gamma})$.

In Figure 4, the survival mode backoff values $\theta_{dB} - \bar{\gamma}_{dB}$ in dB-scale are plotted for instantaneous SINRs distributed as in (2) with estimated mean SINR $\bar{\gamma} = 10$ dB, when the channel uncertainty is characterized by $K = 10$ or $K = 20$. The control channel reliability is given by $P_{N2A} = 10^{-3}$, survival time is characterized by $M = 2$, and service outage probabilities of interest for services in Table I are targeted. For both P_{SO} values and both K -values considered, one sees the infinite reliability requirement arising when $\alpha \rightarrow 1$. The difference between the backoff requirement between the two K -values is striking. These backoff results are comparable to results reported in [22] for ultra-reliable link adaptation.

Fig. 5. Resources used to communicate one bit of information with error probability given by α . QoS characterized by $M = 2$ and $P_{SO} = 10^{-6}$. Estimated SINR is $\bar{\gamma} = 10$ dB, SINR uncertainty characterized by $K = 10$, and $P_{N2A} = 10^{-3}$.

Once backoffs are known, one may find the amount of resources needed to communicate one bit at this threshold SINR from (4):

$$w(\theta) = 1 / \log_2(1 + \theta) \quad (15)$$

The average amount of resources per bit used to serve a user is then

$$w_{ave} = P_{Tx,s} w[F_{\Gamma}^{-1}(P_s)] + (1 - P_{Tx,s}) w[F_{\Gamma}^{-1}(P_n)] \quad (16)$$

where $P_{Tx,s}$ is the probability of using survival mode from (1). For given given QoS (M and P_{SO}), system assumption P_{N2A} , and user channel state information (CSI) $\bar{\gamma}, K$, both $P_{Tx,s}$, P_s and P_n become functions of α , and we have $w_{ave} = w_{ave}(\alpha)$.

In Figure 5, the amount of resources to communicate one bit in normal mode, survival mode, and the averaged resource usage with the survival mode usage probability are plotted, for parameters $M = 2$, $P_{SO} = 10^{-6}$, $\bar{\gamma} = 10$ dB, $K = 10$, and $P_{N2A} = 10^{-3}$. Starting from $\alpha_{min} = 0.032$, where there is no survival mode, the gap between the bandwidth needed for a bit in normal and survival mode increases, with the latter growing rapidly when $\alpha \rightarrow 1$, indeed going to infinity at $\alpha = 1$. The minimum average resource usage for these parameters is at $\alpha \approx 0.64$. At this point, more than $10\times$ the resources are needed for a survival mode transmission than a normal mode one, and the ratio $P_n/P_s \approx 700$.

Now P_s and P_n can be jointly optimized for given QoS (M and P_{SO}), system assumption P_{N2A} , and user CSI $\bar{\gamma}, K$, to minimize expected resource usage for a user. Using (1, 9, 12), the objective function (16) is an unconstrained function of $\alpha \in \mathcal{A} = [\alpha_{min}, 1)$, and the error probabilities minimizing average resource usage can be found by finding

$$\alpha^* = \min_{\alpha \in \mathcal{A}} w_{ave}(\alpha) \quad (17)$$

The problem can be solved with bisection line search. The resulting minimum average resource usages for $M = 2$, $\bar{\gamma} = 10$ dB and $P_{N2A} = 10^{-3}$ are plotted in Figure 6 as a function of the K -factor, for P_{SO} -values from Table I.

Fig. 6. Average resource usage to communicate a bit with QoS characterized by indicated P_{SO} and $M = 2$, as a function of K -factor of realized SINR uncertainty. Estimated SINR is $\bar{\gamma} = 10$ dB.

When $K = 0$, the SINR at the time of transmission is characterized by Rayleigh fading, with average SINR CSI. Then, for $P_{SO} = 10^{-8}$, more than 20 time-frequency resources are needed to communicate one bit with the targeted QoS, i.e., the spectral efficiency may become as low as 0.047 bps/Hz even for a user with average SINR 10 dB. The benefit from having more reliable CSI at the transmitter is extreme. When $K = 10$, for example, 0.57 resources are needed for a bit, and the spectral efficiency for transmissions achieving these extreme QoS targets is more than 1.7 bps/Hz.

To understand the benefits of survival mode optimization, results without survival mode, i.e., for $\alpha = \alpha_{\min}$, are plotted in Figure 6 as well. Note that in the limit $\alpha \rightarrow 1$, resource usage becomes infinite. The cost of not having an optimized survival mode is striking at $K = 0$, when survival mode is not optimized, one needs $32\times$ the resources to guarantee QoS, as compared to the optimized resource usage. For $K = 10$, this factor becomes 3.4, still showing a considerable gain.

V. CONCLUSION

We analyzed normal mode and survival mode transmissions to guarantee highly reliable transmissions within a survival time, when $M - 1$ transmissions are possible within a survival time, and M consecutive transmissions in error lead to service outage. We have analyzed the effect of control channel errors on performance, and optimized the error probabilities P_n and P_s in the two modes, with the objective to minimize the average resource usage. For using the results in a real system, flexible availability of resources is assumed, such that additional resources are available to serve a user once survival mode is entered. In future work we shall address the multiuser aspects of time critical transmissions to multiple users, as well as the effects of user SINR statistics on multiuser performance.

ACKNOWLEDGMENT

This work was supported in part by Business Finland funding for the project 5G VIIMA.

REFERENCES

- [1] H. Viswanathan and P. E. Mogensen, "Communications in the 6G era," *IEEE Access*, vol. 8, pp. 57 063–57 074, 2020.
- [2] V. C. Gungor and G. P. Hancke, "Industrial wireless sensor networks: Challenges, design principles, and technical approaches," *IEEE Trans. Industrial Electronics*, vol. 56, no. 10, pp. 4258–4265, 2009.
- [3] 3GPP, "Service requirements for cyber-physical control applications in vertical domains; Stage 1," Tech. Rep. TS 22.104, v. 17.4.0, Sep. 2020.
- [4] M. Weiner, M. Jorgovanovic, A. Sahai, and B. Nikolić, "Design of a low-latency, high-reliability wireless communication system for control applications," in *Proc. IEEE ICC*, 2014, pp. 3829–3835.
- [5] R. Adeogun, G. Berardinelli, P. E. Mogensen, I. Rodriguez, and M. Razzaghpour, "Towards 6G in-X subnetworks with sub-millisecond communication cycles and extreme reliability," *IEEE Access*, vol. 8, pp. 110 172–110 188, 2020.
- [6] N. Brahmi, O. N. C. Yilmaz, K. W. Helmersson, S. A. Ashraf, and J. Torsner, "Deployment strategies for ultra-reliable and low-latency communication in factory automation," in *IEEE GLOBECOM Workshops*, 2015, pp. 1–6.
- [7] V. N. Swamy, S. Suri, P. Rigge, M. Weiner, G. Ranade, A. Sahai, and B. Nikolić, "Cooperative communication for high-reliability low-latency wireless control," in *Proc. IEEE ICC*, 2015, pp. 4380–4386.
- [8] S. R. Khosravirad, H. Viswanathan, and W. Yu, "Exploiting diversity for ultra-reliable and low-latency wireless control," *IEEE Trans. Wireless Comm.*, in press.
- [9] 3GPP, "Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC)," Tech. Rep. TS 38.824, v. 2.0.1, Mar. 2019.
- [10] H. Kokkonen-Tarckanen & al., "Enabling safe wireless harbor automation via 5G URLLC," in *IEEE 5G World Forum (5GWF)*, 2019, pp. 403–408.
- [11] S. Samarakoon, M. Bennis, W. Saad, and M. Debbah, "Predictive ultra-reliable communication: A survival analysis perspective," *IEEE Comm. Lett.*, in press.
- [12] J. Demel, C. Bockelmann, and A. Dekorsy, "Burst error analysis of scheduling algorithms for 5G NR URLLC periodic deterministic communication," in *Proc. IEEE VTC Spring*, 2020, pp. 1–6.
- [13] J. Gebert and A. Wich, "Alternating transmission of packets in dual connectivity for periodic deterministic communication utilising survival time," in *Proc. EuCNC*, 2020, pp. 160–164.
- [14] S. Paris, P. Kela, D. Laselva, and Q. Zhao, "Addressing reliability needs of industrial applications in 5G NR with network coding," in *Proc. IEEE VTC Spring*, 2020, pp. 1–6.
- [15] S. Kaul, M. Gruteser, V. Rai, and J. Kenney, "Minimizing age of information in vehicular networks," in *IEEE Conf. on Sensor, Mesh and Ad Hoc Commun. and Networks*, 2011, pp. 350–358.
- [16] M. K. Abdel-Aziz, C. Liu, S. Samarakoon, M. Bennis, and W. Saad, "Ultra-reliable low-latency vehicular networks: Taming the age of information tail," in *Proc. IEEE GLOBECOM*, 2018, pp. 1–7.
- [17] X. Zhang, Q. Zhu, and H. V. Poor, "Analyses for age of information supporting URLLC over multimedia wireless networks," in *Proc. IEEE SPAWC*, 2020, pp. 1–5.
- [18] A. Brighente, J. Mohammadi, and P. Baracca, "Interference distribution prediction for link adaptation in ultra-reliable low-latency communications," in *Proc. IEEE VTC Spring*, 2020, pp. 1–7.
- [19] Nokia and Nokia Shanghai Bell, "NR PUCCH simulation results," 3GPP, Tech. Rep. Tdoc R4-1900092, Mar. 2019.
- [20] H. Shariatmadari, Z. Li, M. A. Uusitalo, S. Iraj, and R. Jäntti, "Link adaptation design for ultra-reliable communications," in *Proc. IEEE ICC*, 2016, pp. 1–5.
- [21] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," Tech. Rep. TS 38.901, v. 16.1.0, Dec. 2019.
- [22] U. Oruthota, F. Ahmed, and O. Tirkkonen, "Ultra-reliable link adaptation for downlink MISO transmission in 5G cellular networks," *Information*, vol. 7, no. 1, pp. 1–18, Mar. 2016.
- [23] P. Mary, J. Gorce, A. Unsai, and H. V. Poor, "Finite blocklength information theory: What is the practical impact on wireless communications?" in *IEEE GLOBECOM Workshops*, 2016, pp. 1–6.
- [24] H. Shariatmadari, S. Iraj, Z. Li, M. A. Uusitalo, and R. Jäntti, "Optimized transmission and resource allocation strategies for ultra-reliable communications," in *Proc. IEEE PIMRC*, 2016, pp. 1–6.
- [25] A. Ghosh, L. Jalloul, M. Cudak, and B. Classon, "Performance of coded higher order modulation and hybrid ARQ for next generation cellular CDMA systems," in *Proc. IEEE VTC Fall*, 2000, pp. 500–505.