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Communications Survival Strategies for Industrial Wireless Control

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***Abstract*—Industrial wireless control systems are mainly designed on the premise of time-sensitive ultra-reliable and low-latency communications (URLLC). With the introduction of *survival time* to the quality-of-service requirements of such systems, the design paradigm has evolved from the typical *link reliability*, i.e., minimizing packet error rate, to *service availability*, i.e., minimizing chance of burst errors which can cause loss of communication for longer than survival time. In this article, we address the implications of this evolution and present a set of survival time strategies that are designed to guarantee end-to-end dependable industrial wireless control. To ensure service availability, transmissions are divided to a normal and survival mode. The presented strategies include scheduling and link adaptation that are designed to target the differences between these modes of operation, traffic prioritization to enhance service availability for users in survival mode, and more efficient multi-node, multi-path and multi-carrier communications techniques.**

I. Introduction: Industrial Wireless Control

Automation and internet cloud computing are rapidly evolving to allow integration with artificial intelligence (AI), software automation and remote control with haptic feedback to improve quality of experience for the human in the loop, while increasing productivity of future cyberphysical systems. Such digital transformation in the cyberphysical and industrial space is a highly complicated endeavor. We are experiencing the next industrial revolution—Industry 4.0—with the main drivers being mining vast amounts of data, AI-enabled cloud computing, and dependable real-time wireless communications.

The wireless transformation will, in particular, reduce bulk and cost of installation, while enabling a highly flexible and dynamically re-configurable industrial environment. Such a vision covers various use cases, including industrial internet-of-things (IIoT), smart grid, mobility and traffic control, health care, entertainment and gaming. In manufacturing environments, thanks to time-sensitive wireless networking, production stations may be seamlessly re-arranged according to production requirements [1]. For this, wireless communication has to be as dependable as a wired connection, i.e., providing extremely high reliability, while guaranteeing anytime/everywhere service. This is the promise of fifth generation (5G), and beyond that of sixth generation (6G), mobile networks.

One of the most exciting recent advancements in wireless communications has been the order-of-magnitude reduction in the end-to-end (E2E) latency—from the tens of milliseconds achievable in long term evolution (LTE) technology, to a fraction of a millisecond with 5G new radio (NR). This promises a ground-breaking move to 1 millisecond round-trip latency, unleashing the potentials for tactile remote control [2]. Remote steering of real and virtual objects, and wireless control of

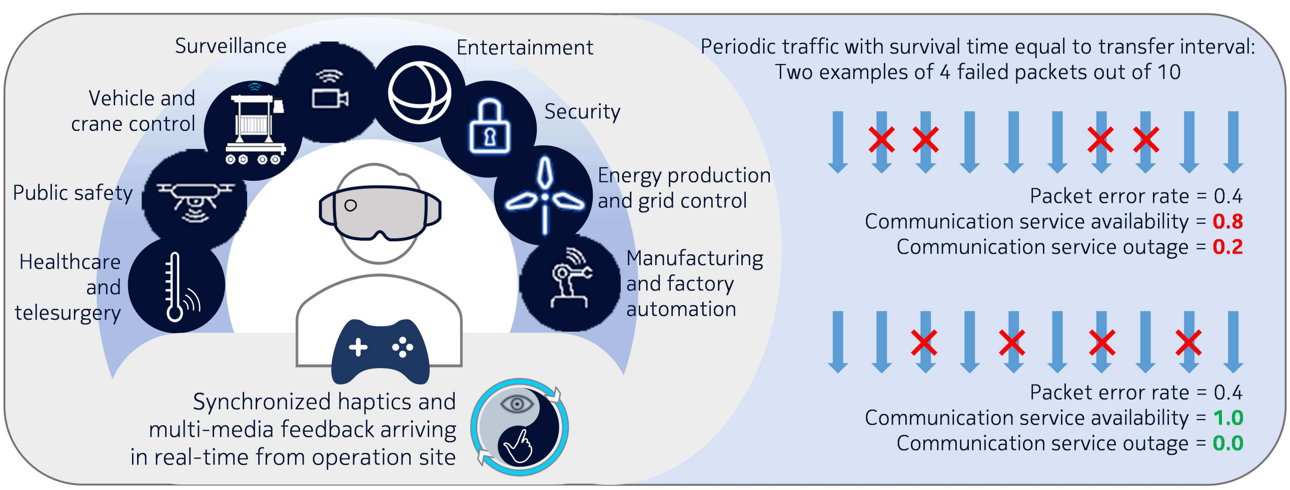

Figure 1: Wireless control with survival time constraint: a shared vision across multiple industries.

Table I: QoS characteristics for motion control and haptic feedback [6].

Communication service outage	E2E latency	Message size [byte]	Transfer interval	Survival time	number of devices	Service area	Application
$10^{-7} - 10^{-5}$	$<$ transfer interval	50	500 μs	500 μs	≤ 20	50 m $\times$ 10 m $\times$ 10 m	Motion control
$10^{-8} - 10^{-6}$	$<$ transfer interval	N/A	≤ 1 ms	3 $\times$ transfer interval	2–5	100 m $\times$ 30 m $\times$ 10 m	Wired-2-wireless 100 Mbps link replacement
10^{-8}	< 2 ms	250 to 2000	1 ms	1 ms	1	room	Motion control and haptic feedback
10^{-6}	< 20 ms	250 to 2000	1 ms	1 ms	$<$ 2 per 1000 km^2	national	Motion control and haptic feedback
10^{-8}	< 2 ms	50	2 ms	2 ms	> 2	100 m^2	Mobile Operation Panel: Haptic feedback data stream

machines with haptic feedback requires low round-trip latency to avoid creating cyber-sickness. 5G ultra-reliable low-latency communications (URLLC) will thus create a breakthrough in the evolution of a wide range of cyberphysical systems. Reliability and latency have attracted considerable research activity in recent years [3], while other new quality of service (QoS) characteristics for industrial wireless control have not received similar attention.

In this paper we address those new service requirements, namely survival time and service availability. We discuss how wireless channel dynamics impact those service requirements, and then, we present enabling strategies, using proper link adaptation and exploiting diversity, for the design of dependable communications in the era of industrial wireless control. Some of the presented strategies are inspired by earlier works in the literature (e.g., see [4], [5]). Accordingly, at the end of the paper, a detailed list of existing open problems and the envisioned future research directions are presented.

II. New QoS characteristics for wireless control

A. *Definitions*

3rd generation partnership project (3GPP) has introduced QoS requirements for industrial wireless control [6]. The distinctly novel aspect of these is the notion of survival time. For five example applications with periodic packet arrival pattern, Table I shows those requirements from [6]. The terminology is defined according to the interaction between the application and the wireless communications system, as follows [6]:

a) Transfer interval: the time difference between two consecutive packet transfers from the application to the wireless communications system. This corresponds to the concept of cycle time commonly used in the IIoT context [3].

b) E2E latency: the packet transfer time, measured at the communication interface, from the time the source transmission begins to the moment of successful reception.

c) Survival time: the time that an application may continue without an anticipated message (packets are typically anticipated due to the periodicity of the traffic pattern).

d) Communication service availability: the fraction of time the E2E communication service QoS requirements—including E2E latency and survival time requirements—are satisfied for the application. In Table I, communication service outage probability is presented, defined as the fraction of time those requirements are not satisfied.

Note that communication service outage probability for an application with zero survival time equals the packet error rate (PER). That is, service availability for zero survival time is equivalent to link reliability. Moreover, the survival time depends on the application. For motion control systems responsible of controlling moving parts of machines, e.g., printing machines or packaging machines, the survival time is comparable to the transfer interval. This also holds for motion control with haptic feedback, e.g., in case of robotic-aided telesurgery where the feedback provides haptic guidance for the patient body model. The strict survival time requirements are due to the high precision of operation that is vital in these use cases. In applications with less stringent operation accuracy, such as remote control of a harbor crane, the survival time can be as large as six consecutive transfer intervals [7].

B. *Implications of the New Service Requirements for 5G Systems*

The immediate impact of introducing survival time as a QoS requirement of the wireless link is a shift in design paradigm from typical link reliability—i.e., minimizing PER—to service availability—i.e., minimizing the chance of a burst of consecutive packet failures, as also noted by recent works on service availability in [4], [5]. For the case of survival time equal to one transfer interval, consecutive packet error rate (CPER) represents the communication service outage probability, which is calculated as the ratio of packet failures that last consecutively for longer than one transfer interval over the total transfer intervals. Eight nines of service availability translates into a less stringent link reliability figure, and makes it possible to react to, and even exploit, channel fading. The exact link reliability requirement depends on the rate of variations and temporal correlation in the channel fade, and the survival time budget.

Note that there is no direct relation between latency and survival time. Depending on the use case and service area, those may vary. For motion control applications within small areas, low E2E latency is achievable when physical distance allows, and is desirable as seen in the examples in Table I. For example, the controller node and the actuators of a motion control network can be located in the same room and can be connected to the same 5G base station, resulting in a short E2E link.

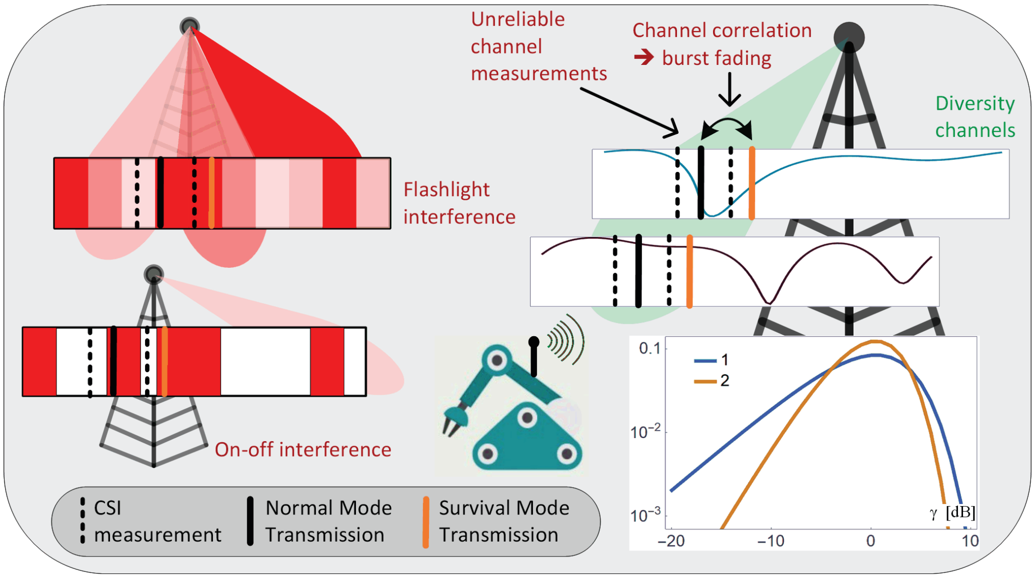

Figure 2: Factors causing channel state information unreliability and potential burst errors.

A two-way communication link, e.g., one that utilizes a feedback channel for acknowledging packet transmissions, can then take advantage of the small round trip time (RTT) to inform the scheduler of packet failures. Therefore, a failure in packet delivery within the E2E latency budget can trigger a transmission of the next packet with higher reliability in the following transfer interval. This is what we refer to as *survival mode strategies* in this paper, which is plainly motivated by the fact that cyberphysical applications can tolerate packet failures as long as the duration of consecutive failures is bounded by the survival time of the application. The network serves the user in what we refer to as *normal mode* of operation most of the time, providing the link with moderate reliability levels, but as it identifies a packet failure, the user enters *survival mode* of operation which requires a more reliable transmission.

However, as the distance between nodes increases (e.g., in case of a nation-wide mission critical network as depicted in Table I), the E2E latency naturally increases too. The E2E latency may become larger than the survival time. Each packet travels across multiple hops—including a wireless access link, wired or wireless backhaul, and network switches. The resulting RTT could become much larger than the survival time. In such a multi-hop scenario, the wireless access hop is frequently the least reliable. To guarantee service survival, we propose to adopt a survival mode strategy *per hop*, using wired/wireless acknowledgment feedback for the corresponding radio access technology (RAT) or backhaul technology for each hop. Note that the RTT for a hop depends on the chosen technology, with 5G RATs being capable of providing RTTs well within survival time requirements.

III. Channel State Information, Temporal Variation and Prediction

For wireless services with rapidly aging information, variability of channel state information (CSI) becomes an issue. In mobile broadband (MBB) services, errors in link adaptation (LA) caused by CSI variability are reliably corrected by automatic repeat request (ARQ) retransmissions, especially in the hybrid automatic repeat request (HARQ) form. For services with stringent latency and extreme service availability requirements, HARQ cannot be utilized as a last line of defense for providing reliability.

The quality of a channel can be represented by CSI characterizing the statistics of the signal to interference and noise ratios (SINRs) that the symbols comprising a data packet will experience. For robust transmissions, a small number of information bits per packet have to be used, such that the probability for correct reception is high. The dynamic range of SINRs experienced in a wireless system is dramatic, though. Even in indoor systems, dynamic ranges of up 60 dB can be experienced, for distances ranging between 10 and 100 m, and path loss parameters from [8]. For efficient resource usage, LA providing sufficiently reliable transmission rates should be used. To design industrial wireless control systems, a detailed understanding of processes causing CSI variability is needed.

The most important processes causing unreliable CSI in a wireless system are depicted in Fig. 2, where there is a wireless transceiver connected to a machine, being served by a base station at the right. At the left are two base stations using the same communication frequency as the service of interest, and thus causing interference. Without loss of generality, the interference scenarios in the figure are depicted for a downlink transmission towards the device.

In CSI measurements pertaining to SINR, there is uncertainty both in the wanted signal power, and in the interference power. Challenges in LA for time-sensitive networking arise from the crucial fact that CSI measurements invariably happen at a different time than the adapted transmission. This holds both for measurements of the wanted signal channel and for the interference. In a time division duplex (TDD) system, the wanted signal may be measured at the transmitter from a transmission in the opposite link direction, using channel reciprocity, while interference CSI has to be measured at the receiver, and fed back to the transmitter. Even if wanted signal measurements are performed at the transmitter, there is processing, and duplexing delay. In Fig. 2, the times of CSI measurements are indicated with dashed lines, and times of transmissions with solid lines. There are two conceptually different sources for CSI uncertainty: fading, and changes in interferer activity–the so-called flashlight effect.

A. Channel Fading

Both the wanted signal channel, and the interference channel experience fading. Time-selective fading is unavoidable in a mobile system, due to the motion of the transmitter, the receiver, or objects in the environment. In a multipath propagation environment, the signal power may rapidly decrease tens of dBs from a typical level, and equally rapidly increase back [9]. In Fig. 2, time-selective fading processes of two diversity branches are depicted, related to the wanted signal between the serving base station (BS) and the device. Two kinds of problems arise from temporal fading. First, as depicted in the upper fading process, the channel may be fading between the time of CSI measurement, and the time of transmission. Second, the fading states of consecutive transmissions are correlated, which may cause error bursts, detrimental in a system with extreme service availability.

In [10], the effect of CSI differences between measurement and transmission times on URLLC link adaptation was addressed, assuming Rayleigh fading channels with Jakes' temporal fading characteristics [9]. Despite channels between these time instances being highly correlated, e.g., with a correlation coefficient $\rho = 0.99$, the channel power may change orders of magnitude, if the instantaneous channel during measurement was weak. For conventional MBB, the long-term impact of this happening would be insignificant, but when compared to the extreme service availability targets discussed here, it is large. Industrial wireless control and URLLC change the notion of which probabilities can be deemed insignificant.

If there is diversity, e.g., from frequency selectivity, the probability that all diversity branches fade simultaneously is reduced. In the lower-right corner of Fig. 2, the statistics of the signal to noise ratio (SNR) of conventional Rayleigh fading with one and two diversity branches is plotted, for a channel with average SNR of 0 dB. The y-axis gives the probability that the instantaneous SNR γ is within 1 dB from the value on the x-axis. The tails of these distribution are fat towards $-\infty$, while falling exponentially towards $+\infty$. As a consequence, the average signal power is not a robust estimate of the wanted signal, while it does provide a rather robust estimate of interference power.

B. Flashlight Effect and On-Off Interference

When it comes to interference, changes in interferer actions become a far more important source of CSI unreliability than fading of channels. In Fig. 2, two kinds of effects causing interference variability are depicted. The upper left part depicts the beam domain flashlight effect [11] in a system where a high degree of beamforming is used to target transmission power to users. The interference experienced by victims becomes variable—if the intended receiver of the interfering transmission is in the same direction as the interference victim, interference is strong, while if the intended receiver is in another direction, the interference may be negligible. This can cause severe problems for LA. If interference is measured while flashlight interference points to another direction, while flashlight interference points towards the victim during data transmission, the SINR may drop considerably, and packets may be lost.

Another type of interference variability is depicted in the lower left part of Fig. 2. In this case, the interfering BS sometimes uses the frequency of the wanted signal, sometimes not. Such on-off activity would occur naturally in a scheduled system with finite buffer traffic. This may cause similar problems for LA as beam-domain flashlight interference. In systems serving MBB traffic with moderate multiple-input multiple-output (MIMO) dimensionality, flashlight and on-off interference does not to pose dramatic problems; HARQ is able to mitigate these problems [12]. In URLLC, the situation changes [10], and particularly so in 5G NR systems, where a high degree of beamforming is used [13]. When striving for URLLC in 5G NR systems, the flashlight and on-off interference effects are the most important source of SINR variability [13].

Temporal correlation characteristics of flashlight interference depends on the activity pattern of the interfering BSs. As opposed to multipath fading, for interference variability no law of nature either precludes or prevents such correlations. This further exacerbates the need to engineer reliable interference control schemes for industrial wireless control. One method to overcome the challenges posed by the flashlight effect is to stabilize interference in the network by avoiding directive transmissions altogether.

IV. Survival Mode Scheduling

In wireless systems schedulers are usually optimized for high bandwidth applications targeting to maximize system spectral efficiency. In MBB systems, LA usually targets first transmission PER of around 0.1, which provides good quality service together with HARQ and flexible modulation and coding scheme (MCS) selection. In industrial wireless control, the scheduler has to be designed to fulfill extreme service availability requirements. It is not sufficient to deliver packets successfully. Packets should be delivered within a transfer interval, and retransmissions may not be possible at all. Moreover, the envisioned services do not allow for bursts of consecutive packet losses, only one (or in some cases, a few) consecutive erroneous packets are allowed, bounded by survival time. Thus, the scheduler has to differentiate between a user that is in *survival mode*—that is to say, its latest packet has failed—and a user in normal mode. Optimization of resource allocation may be based on the following principles.

1) The scheduler should predict the CSI at the moment of transmission, based on CSI at the moment of channel estimation, and CSI history.

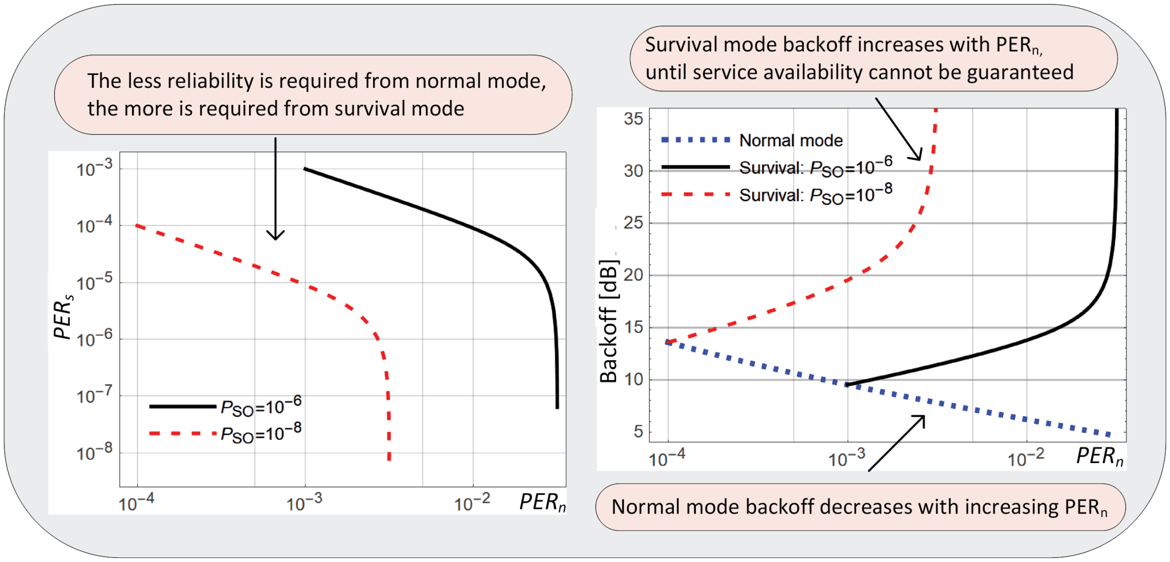

Figure 3: Tradeoff between normal and survival mode reliability.

2) A sufficient amount of resources should be scheduled to survival mode users.
3) The number of users in survival mode should be kept small.

Let us assume that scheduler in an orthogonal frequency-division multiple access (OFDMA) system knows the narrow-band CSI for each resource block for each user. Robust LA should be applied to fulfill service availability requirements. One simple way to implement this is to back off from the estimated CSI—i.e., the scheduler assumes that the channel will be worse than the estimated channel. The amount of back-off depends on the speed of variations in the channel and can be determined from CSI history. Changes in CSI caused by user motion is one factor which should be taken into account. As discussed in Sec. III, in fading channels, users with low instantaneous SINR as compared to their average SINR experience larger changes in channel quality. Thus, users with low relative SINR demand larger back-off.

Survival mode users should receive their immediate next packet successfully. To guarantee sufficient resources, the scheduler should favor survival mode users over normal mode ones. The survival mode users should never be in resource outage, i.e., in a situation where scheduled resources do not correspond to the amount demanded by the estimated CSI. Occasional packet failures of normal mode users do not necessarily destroy service availability. Such failures are part of normal mode performance, and are handled by sufficiently robust survival mode transmissions.

The scheduler may apply additional back-off to users in the survival mode to increase the probability of reception without errors. As a consequence of these LA methods, survival mode users will need relatively more resources. Therefore, the number of survival mode users should be kept small.

For this, an industrial wireless control system scheduler may control target normal and survival mode packet error probabilities PER$_n$ and PER$_s$. Actively changing the target PER is a useful option in modern wireless technologies—e.g., NR allows flexible transmission time interval (TTI) duration as small as a fraction of a millisecond [13]. In dynamic scheduling, transmission rate, determined as a MCS, may vary from TTI to TTI, and target PER may change with the same frequency. This divides system optimization into parts. Normal and survival mode could use different transmission schemes and scheduling strategies. The selected PER$_n$ defines the number of users that require survival mode operation to guarantee service availability.

In addition to these probabilities, communication service availability (see Table I) depends also on the probability of feedback errors, which are caused by errors in wireless control channels. These may prevent moving from normal to survival mode, or cause unnecessary survival mode transmissions. The former is more severe as it jeopardizes service availability. In contrast, the latter case increases the usage of system resources. Thus the feedback error probability is a design optimization parameter as well.

The relation between PER$_n$ and PER$_s$ at feedback error probability 10^{-3} is shown in the left part of Fig. 3, for two service availability targets, namely 6 nines and 8 nines, indicated by $P_{\rm SO} = 10^{-6}$ and $P_{\rm SO} = 10^{-8}$, respectively. The numbers are analytically derived, assuming independent and identically distributed channels across transfer intervals [4]. When normal mode error probability requirements are tightened, it is possible to relax the requirements for survival mode. The connection between PER$_n$ and PER$_s$ given a $P_{\rm SO}$ can be directly used to trade off the frequency of using survival mode vs the reliability of the normal mode transmissions. Optimization for a system key performance indicator (KPI) can be applied, e.g., finding the optimal survival mode frequency to minimize overall resource usage.

The balance between normal and survival mode target PER also determines the backoff which has to be used in LA. Backoff dependence in normal and survival mode for the two

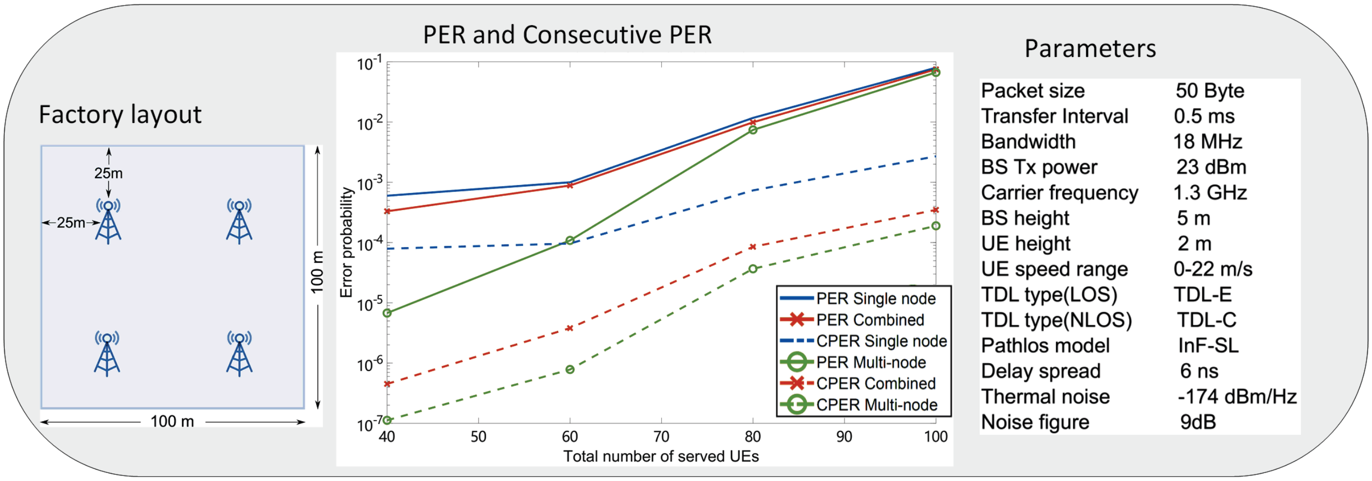

Figure 4: Simulation of multi-node transmission.

service availability targets is shown in the right side of Fig. 3. Normal mode backoff increases with decreasing PER_n. The survival mode operation ensures overall service availability and therefore the needed survival mode backoff increases with PER_n decreasing. Very high backoff values are not desirable as they demand many resources and decrease spectral efficiency.

V. Multi-node and Multi-path Transmission for Survival Mode

In addition to channel prediction for reliable LA, and using survival mode-specific scheduling, multi-node transmissions provide an efficient method to further improve survival mode reliability and to reduce the probability of burst errors. As discussed in Sec. III, once flashlight and on-off effects are avoided by proper co-channel interference mitigation, correlated fading between normal and survival mode transmissions become a dominant problem for burst-error performance. Using multi-point transmissions in survival mode effectively removes such correlated fading.

Accordingly, instead of receiving transmissions only from the serving BS, user equipments (UEs) in survival mode receive a superposition signal of transmissions from multiple BSs, combined over the air, for instance, using single-frequency network (SFN) transmission, of the type applied in digital video broadcasting-terrestrial (DVB-T) [14]. To guarantee that the transmissions from different nodes do not add up destructively for all frequencies, specific delays can be added to symbols transmitted from the different BSs to imitate the effect of a multi-path channel. In an orthogonal frequency-division multiplexing (OFDM) system, properly specifying delays from different BSs guarantees that signals from different BSs are constructively combined in multiple available resources without inter-symbol-interference. With OFDM, the delays can be applied in cyclic form to the symbol prior to cyclic prefix insertion—a technique known as cyclic delay diversity (CDD)—which helps avoid delay overhead inefficiencies.

SFN- and CDD-based multi-node transmission schemes require simpler transceiver implementation and less CSI precision than beamforming MIMO, and accordingly provides robustness for survival mode. UE receivers only need to measure and feedback the combined channel, instead of all channels from all transmitters.

Multi-node transmission introduces spatial diversity as the channels from different BS transmitters are independent assuming they are located far from each other. UEs experi-encing fading of the serving BS signal are protected against consecutive packet errors by the spatial diversity and power gain provided by multi-path transmissions. The power gain can be dramatic when the serving BS is in a deep fade. If multi-node transmission is only applied in survival mode, the extra power consumption is small considering the achieved performance gain. A similar multi-path impact can be achieved by deploying cooperative device-to-device relaying where in a first phase, the BS broadcasts the message to relay UEs, and in the second phase, the relay UEs decode and forward the message to the user in survival mode.

Dramatic performance gain of multi-node transmission is revealed in simulations, where an indoor factory environment is modeled according to [8]. The factory layout of the sim-ulation is depicted in the left side of Fig. 4, demonstrating four BSs symmetrically located in a factory, while the system-level parameters are noted on the right side of Fig. 4. The tapped delay line (TDL) channel and the indoor factory (InF) path loss parameters are from [8]. The scheduler prioritizes survival mode users by first allocating resources to those users and scheduling the remaining resources for the remaining, normal mode, users. The center of Fig. 4 depicts the measured PER and CPER (i.e., the rate of two or more consecutive errors), against the total number of users, in three settings: pure single node transmission, pure multi-node transmission and a combined method where multi-node transmission is only applied in survival mode. It is shown that both PER and CPER are significantly improved with pure multi-node transmission, at cost of consuming 300% more transmission power than single node transmission. The combined method has slightly worse CPER, consuming only 0.3% more power than pure single node transmissions.

Table II: Summary of survival mode strategies for industrial wireless control with survival time.

Strategy	Motivations & expected impact	Building blocks of the strategy	Challenges & open problems
Channel prediction	Predicting channel fading in advance allows for taking preventive measures to avoid packet loss.	Accurate channel prediction requires information about the macro environment, such as blocking objects	Achieve sufficient prediction accuracy for ultra-reliable systems, especially if relying on neural network-aided predictions
Link adaptation target PER	Using a different target PER for normal and survival modes allows for optimizing the two modes separately. Thus, normal mode can be designed for efficiency, and survival mode for reliability.	Determine the proper PER targets for the LA algorithm based on the error probabilities of data and control channels	Incorrect survival mode PER target could starve the system of the resources, accurate error statistics might be difficult to obtain in a real system
SINR back-off	Use a pessimistic SINR assumption to ensures that the data is transmitted with enough redundancy	Amount of back-off depends on channel coherence time and can be determined from historical CSI data, users with low relative SINR demand higher back-off factor	Excessive use of high SNR back-offs can be wasteful in terms of the radio resources, demanding a proper trade-off between reliability and efficiency
User prioritization	Give higher scheduling priority to users in survival mode, to ensure their next transmissions can be done timely and successfully	Requires the possibility to cancel already scheduled resource allocations to accommodate survival mode users	De-prioritization of normal mode users might cause resource outage and increase the number of users in survival mode, calling for careful balancing
Multi-node & multi-path transmission	Use of multi-node and multi-path transmissions in survival mode avoids the problems of spatio-temporally correlated fading	SFN- and CDD-type omni-directional transmission from multiple BSs with different delays to guarantee constructive superposition; device-to-device cooperative relaying	Requires synchronization and cooperation between BSs and large backhaul capacity; Similarly, device-to-device relaying requires low-latency UE relaying and careful coordination among nodes
Duplicated carrier	Multiple frequency domain resources, or carriers, can be scheduled to survival mode users. This increases reliability via the diversity of the different channel conditions on the multiple carriers.	Wideband receivers are required if the carriers are far apart in the frequency domain	Carrier duplication is unlikely to help if the initial outage is due to blockage

A multi-node transmission scheme requires symbol level synchronization and cooperation between BSs. The synchronization requirement between BSs can be relaxed to several samples but should be smaller than the cyclic prefix duration to avoid inter-symbol interference. In the downlink, packets must be sent over to all BSs in time when multi-node transmission is needed. With cloud-radio access network (RAN) implementations commensurate with NR, switching between single-point to multi-point transmission in multi-transmission reception point (TRP) technologies can happen in near-to-zero time. In the uplink, multi-node reception at BSs, can be combined in the network. In both cases, high capacity and low latency backhaul is essential.

VI. Conclusions and Open Problems

Industrial wireless control requires service availability that lasts for several years of continuous operation, imposing stringent requirements on the probability of burst errors of wireless communications. We addressed how the design paradigm is evolved as a result of transitioning from PER-based link reliability to service availability based on a survival time requirement. We presented survival time strategies for a communications network, which are summarized in Table II: for each strategy the related motivations, anticipated impacts and relevant challenges are listed. Such strategies are vital to satisfy time-critical requirements with efficient use of network resources of time, frequency and cooperation in the future industrial wireless control in 5G and 6G systems. Although some of the proposed solutions are feasible within the means of the existing technologies, we expect to see additional effort in research and development towards enabling such solutions in the era beyond 5G.

The strict service availability requirements calls for preventive measures to avoid packet loss, more so for users in survival mode. This requires a real-time awareness of the dynamics of the macro environment, to be able to predict sudden and severe changes in the link quality caused by movement of small and large objects. Given the complexity of such prediction problem, we expect to see advanced neural network-based techniques that accurately estimate channel quality.

Further, the introduction of survival time as a new service requirement, challenges the conventional approach to link adaptation, which targets a fixed packet error rate for a traffic type. It is proposed to use different target PER for normal and survival modes, allowing substantial savings in radio resource utilization. Given the necessity of successful packet transmission when in survival mode, pessimistic estimation of the link quality and applying large SINR backoff is advisable. Moreover, prioritizing users in survival mode over normal mode users becomes essential at the scheduler, especially in loaded periods. This calls for new system-level optimization endeavors for a proper trade-off between reliability and resource utilization efficiency, and to guarantee heterogeneous service requirements in multi-user networks.

Additionally, the design and deployment of multi-node transmission and reception techniques is expected to take a big step forward from its current inelastic and inflexible nature to enable timely and on-demand cooperation among network and user nodes, and establish temporary multi-path links with high reliability to users in survival mode. For such network-device cooperation we expect to see development of coordination protocol design as well as distributed multi-antenna transmission and beamforming. Finally, using carrier multiplication is suggested as a mean to improve link reliability via the diversity of the different channel conditions on the multiple carriers.

The presented strategies are proposed to be available to the communications network to be activated and configured on-demand, e.g., when the service types have survival time and service availability requirements. Nevertheless, due to the end-to-end nature of those requirements, it is vital for the network to diagnose the root cause of packet failures and directly focus the survival mode emergency resources on them. This creates further opportunities for end-to-end network design improvements to be explored in future research.

VII. Acknowledgment

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