Wireless Industrial Communication and Control System: AI Assisted Blind Spot Detection-and-Avoidance for AGVs

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Keywords: Edge Cloud, Industrial Control, Wireless Closed Loop Control, AI based Channel Prediction, Communication Control Co-design, Multi-link Communication, Flexible Coding, Low Latency, High Reliability

Abstract: An Edge cloud based industrial control systems set high requirements on the latency and reliability of wireless communication link. In order to improve the performance of the communication system, an approach of industrial control and communication co-design is proposed. The system consists out of three components; Artificial Intelligence(AI) control, Industrial control and Communication control. An AI predictive algorithm forecasts the expected signal strength and detects the potential coverage blind spots on a factory floor. Based on this, industrial control system adjusts the paths for AGVs in order to spatially as well as timely avoid the communication drops. The communication control manages the communication resources taking into consideration the present control requirements and AI predicted channel information. Besides, the communication system is enhanced by multi-RAT capability in order to further increase the communication reliability. The investigations show that AI based industrial control and communication co-design approach provides an increase of the reliability of communication link. Even more, the proposed system features the ability of reliability guarantee, based on the applications' requirements.

1 INTRODUCTION

One of the major achievements of the industrial revolution Industry 4.0 is the introduction of the wireless communication to manufacturing areas (Aktas et al., 2017). Since the manufacturing devices or even the parts of the devices gained the ability to communicate with each other, new possibilities for flexible and scalable industrial applications of the future have emerged. Among the targeted application fields are factory automation, process automation, closed loop control. Also, human related applications such as human-machine interaction or different kinds of workers assistance gain advantages of wireless communication. This large variety of applications also put heterogeneous requirements on the wireless communication system. Thus, the Radio Access Technology (RAT) utilised should provide high amount of flexibility in order to serve different kind of applications.

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Further promising technology emerged in recent years is edge cloud computation. It provides some benefits also to industrial control applications. The actuators are usually less powerful devices which are tailored to low energy consumption. Offloading the processing and the controller to the cloud may reduce the power consumption at the device. Moreover, an edge cloud as a centralized entity provides a possibility of an easy interconnection of applications running on different devices and promotes collaborative working.

In this paper, Automated Guided Vehicle (AGV) control use case is considered as an illustrative example. Especially mobile devices are more prone to interference, Doppler shifts and channel deep fading, which leads to drop of communication link quality. Thus, the reliable communication, which is critical for control applications, cannot be guaranteed. Unfortunately, this effects are of stochastic nature and cannot be easy modeled. Nevertheless, an AI algorithm shown in this paper is able to predict the drops of the link quality, which we call blind spots, so that counter measures can be applied on time.

Melnyk, S., Tayade, S., Zarour, M. and Schotten, H.
Wireless Industrial Communication and Control System: AI Assisted Blind Spot Detection-and-Avoidance for AGVs.
DOI: 10.5220/0011583100003329
In *Proceedings of the 3rd International Conference on Innovative Intelligent Industrial Production and Logistics (IN4PL 2022)*, pages 307-313
ISBN: 978-989-758-612-5; ISSN: 2184-9285

In order to effectively withstand link quality drops, a communication control co-design approach is proposed. On the one hand, the communication system itself is enhanced to mitigate deep fading effects. It is realized by utilising a combination of several RATs such as WLAN, 5G or other. Since any RAT is utilising an other frequency band, the probability of deep fading on every channel is significantly lowered. Thus, distributing communication via several links provide an improvement on the overall link reliability. On the other hand, AGVs are mobile platforms, which are centrally controlled from the edge cloud. By means of AI predictions, a blind spot may be physically avoided by planning a path around it. Due to outsourcing the industrial control to the edge cloud, the overall complexity of the system is then also reduced.

Even though AGV control is the leading use case of this paper, the investigations fit also other control applications. This is why we propose a flexible functional architecture of the system, which is also applicable to various industrial scenarios. Section 2 an overview on the proposed architecture as well as a brief description of its components. In following sections, the detailed insight in the three main components *AI based channel prediction*, *Industrial Control* and *Communication Control* is given. Finally, section 6 summarizes the results of the paper.

2 FUNCTIONAL ARCHITECTURE

The upcoming industrial revolution Industry 4.0 have exemplified the necessity of wireless communications in an industrial control. The transitioning of industry from wired to wireless have imposed stringent requirements on latency, reliability of wireless communications. In order to achieve the performance similar to wired technology, the wireless system needs to be adapted to fulfill the KPI requirements of an Industrial control. Therefore, we present an Edge-cloud based functional architecture of wireless industrial control, as shown in Figure 1. An industrial control consists of a controller that is located in an edge cloud. Based on the sensors data as well as actuators feedback received, the controller generates control commands and sends them to the actuators. The functions and in-depth description is presented in this section.

2.1 Edge Cloud

An Edge cloud enables faster data computation and processing to reduce latency for processing large amount of data. Moving industrial control system to the edge cloud enables centralized processing, collaboration and coordination of actuators and sensors in a factory devices to realize a task. Moreover, the edge cloud based industrial control allows faster information exchange between the industrial control and the communication control.

2.2 Industrial Control

The main functionality of an industrial controller is to generate the control commands and inputs for the actuators in the factory. The control commands are applied to actuators to perform a specific task. The control commands can be generated periodically or even-triggered depending on the characteristic of the control system. In a closed loop feedback control system, i.e. AGV control, the control commands are generated and updated periodically. In the process automation and monitoring, the control command generation can be event-triggered and needs to be performed only when the measurement data from sensors are not within desired threshold. Depending on the state of actuators and measurement data, the error evaluation block determines the error by comparing the current state with the desired state (output). The evaluated error is then used by controller to generate the control commands to mitigate the error. The error is evaluated from the feedback received from the sensors and actuators over an uplink wireless channel.

2.3 Communication Control

Communication control is a spectrum-aware management component that controls the transmission of control updates over a wireless channel. The communication control ensures the availability of high quality link to industrial control applications while simultaneously optimizing the utilisation of communication resources. The communication resources are optimized by control aware resource allocation techniques, such as presented (Tayade et al., 2020). The Channel State Information (CSI) feedback received, the link quality and the current control state are used to optimally allocate resources over available RATs. The RAT selection functionality selects the best performing link from 5G, LTE WiFi or other, according to the requirements of control application and current communication channel state. Moreover, the communication control provides optimal Modulation and

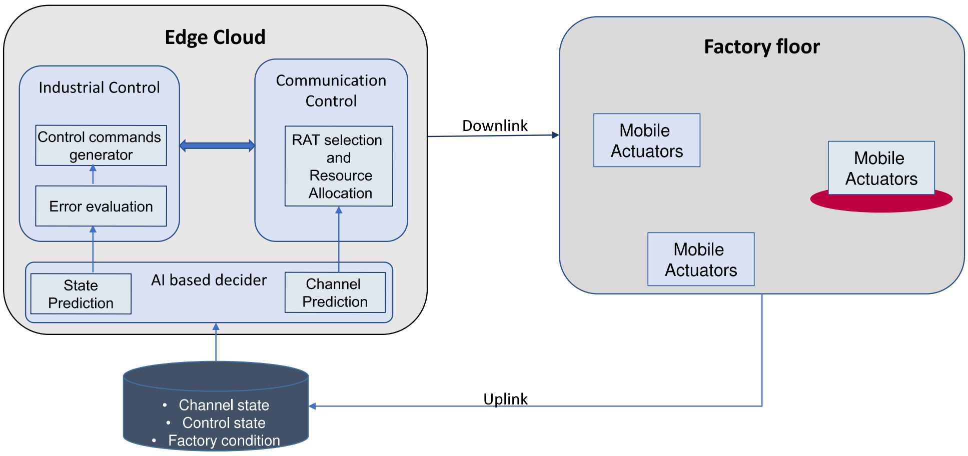


Figure 1: Functional Architecture of Edge Cloud based industrial control.

Coding Scheme (MCS) selection based on the control state of industrial application.

Furthermore, in presence of deep channel fading, the communication control can delay the transmission of control updates in order to save resources and prevent losses of control information. For example, the communication control can perform the task of resource management in an multi-AGV scenario assuring that every AGV get enough resources to remain stable. This means, the settings of any communication link should meet the latency as well as reliability requirements of industrial control applications.

2.4 AI based Decision Making

In industrial control applications like process automation or multi-AGV control and coordination, a larger amount of data from the sensor devices needs to be processed. An AI based techniques can be adapted to analyse the data and predict the future outcomes of the control state as well as channel condition. As the communication occurs over a wireless channel, outages and packet losses could lead to the instability of industrial control. As a consequence, the control information is not available at the actuators within the latency constraints. AI based techniques can predict the error and channel state and provide these information to the industrial and communication control. The AI based decider collects channel information, control state and the factory environment for evaluating and predicting the future states.

3 BLIND SPOTS DETECTION

During the design phase of an industrial communication system, the industry floor map is created to provide the area with sufficient receiving power, taking into account the industry layout and the antenna pattern. For analysis purposes, the industry map is partitioned into square areas of $1 \times 1\,\mathrm{m}^2$. These positions should have sufficient connectivity, reliability and lower packet loss for the real time networked control system. However, the guarantee of reliable wireless connection is not provided due to time-varying effects such as shadowing or multi-path fading which occur in a highly dynamic environment with a lot of metal surfaces.

The automatic robust blind spot detector solves a binary classification problem of identifying the blind spots using Support Vector Classifier (SVC) and updates the industry received power map. The classification model must first be trained to optimally determine the model parameters. In the validation phase, it needs to check whether the model has over-fitting or under-fitting problems so that the classification model can be generalized.

In the testing phase, the classifier should be able to classify the industry map into two classes. Each position in the industry map has one of the two class assignments, positions with or without sufficient reception power. The model must have high performance to make a positive decision about the blind spot positions, so the blind spots detection class must have a high positive predictive value and low miss rate.

SVC has to provide the solution to the positions separation in the industry power map in online phase. The blind spots position is taken as positive decision with industry map sampling distance 1 m. If the position is provided with the required power within coverage map, but the received signal power at these positions is less than the receiver sensitivity, the class assignment is positive. If the positions is located outside the coverage map and has a large distance to the transmitter or has received signal power more than the receiver sensitivity, then the decision is for negative class. In this way, SVC inspects the industry map at each position with sampling distance of 1 m.

Channel Data Generation. In training, validation as well as model testing phase, the SVC needs channel measurement information in the industry environment. This is generated using the channel measurements in the QUAsi Deterministic RadIo channel GenerAtor (QuaDRiGa) model in industry scenario. Multiple communication models are simulated for line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. The power map is generated under consideration of all possible signal propagation path loss, shadowing, multi path fading effect. Several different power maps can be obtained for the same industry layout with different communication system parameters. After that, each sampled position has to be labeled from prospective of the distance path loss power map. Thereafter, the model is trained and L-fold is validated.

Support Vector Classifier: the SVC can be considered as a function between input information and output position classes. The input information is the industrial wireless channel information, which is considered as a feature matrix $[X] = x_j(i);\ i = (1:m);\ j = (1:n)$, whereas m is the number of features and n is the number of positions to be considered. As the output, the system must be able to assign the position from industrial map in binary class assignments $y = \{+1, -1\}$. The separation of the two classes requires a nonlinear hyperplane. Moreover, a correspondent linear separated hyperplane is preferred based on the mapping $\Phi(x_i)$ in the infinite dimension using the radial basis kernel. With the kernel function, the nonlinear separation level can be achieved without increasing the dimension value m of the vector space, i. e., either a mapping $\Phi(x_1, x_2)$ to the height dimension space is used until linear separation is possible, or a kernel function $K(x_i, x_j) = \Phi(x_i)^T \cdot \Phi(x_j)$ is used, which has the condition that the kernel function must be an inner product in at least one feature space. This will avoid the internal product in the optimization problem in the height-dimensional space. The penalty parameter C represents the inverse effect of the regularization parameter. The penalty parameter C and the kernel parameter σ can be optimally configured using L-fold cross validation.

4 AGV TRAJECTORY PLANER WITH BLIND SPOTS AVOIDANCE SYSTEM

In this section, the AGV edge cloud control system is considered. As shown in Figure 2, the AGVs are moving on the factory floor. Due to low computation power of the AGVs, they do not feature capabilities for path planning or trajectory following. Any AGV expects the control input signals to be provided by external control system, which is located on the edge cloud. The AGVs follow the control signals and give a feedback on their control states. The power consuming computations of control signals are performed on the edge cloud. Thus, edge cloud control system has full control over the behaviour of the AGVs.

Edge cloud has to use wireless channel to communicate with AGVs, since these are highly mobile platforms. In this case, wired communication channel is not feasible. However, the wireless link is the critical part of the system, since both up- as well as downlink may suffer deep fading effects, which affects the whole control loop. This behaviour might be mitigated by means of AI based blind spots detection algorithm described in section 3.

The coverage blind spots elimination (CBSE) system is the trajectory planning algorithm, which takes periodic blind spots forecast updates into account in order to avoid the communication link outage. In following, detailed description of the CBSE system components is presented.

Reference Trajectory Planning. Initially, a start as well as a destination position, which must be reached within a given time T, is reported to the controller. The AGV has to follow a shortest blind spot free path to the destination. Trajectory planning starts with a creation of a binary occupation map of the factory floor. As can be seeing in Figure 3, white areas can be accessed by an AGV, whereas black areas represent obstacles. Those are physical obstacles such as walls, pillars, machines etc. Besides, blind spot areas are also declared as obstacles to be avoided. Thereby, blind spot detection algorithm provides an up-to-date blind spot forecast. Afterwards, probabilistic roadmap (PRM) algorithm (Kavraki et al., 1996) is utilised in order to find the optimal trajectory from start to the destination. This path is represented with the red color in Figure 3.

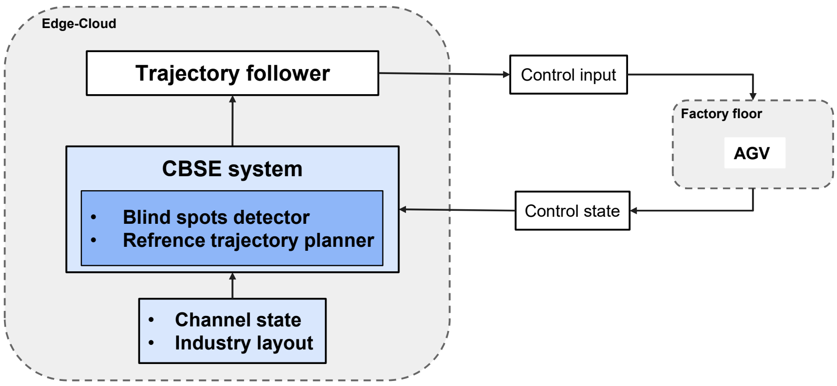


Figure 2: Coverage blind spot elimination system.

Trajectory Replanning. needs to be performed periodically, since blind spots may occur spontaneously and can be predicted on short time scale only. Thus, on any update by blind spots detection algorithm, the AGV's trajectory needs to be reconsidered. If the trajectory does not collide with the new occured blind spots, no action is required.

However, Figure 3 shows the situation, in which an AGV would suffer a connection drop, if it would follow the red path. Thus, the PRM algorithm is applied again in order to plan an alternative trajectory, which is shown with blue color. In this manner, an AGV would avoid potential blind spots and keeps the reliable communication channel to the edge cloud.

Trajectory Follower. is required to generate the control inputs for the AGVs. The available trajectory information in the trajectory (re-)planner output presents only the *xy*-coordinates of the nodes,

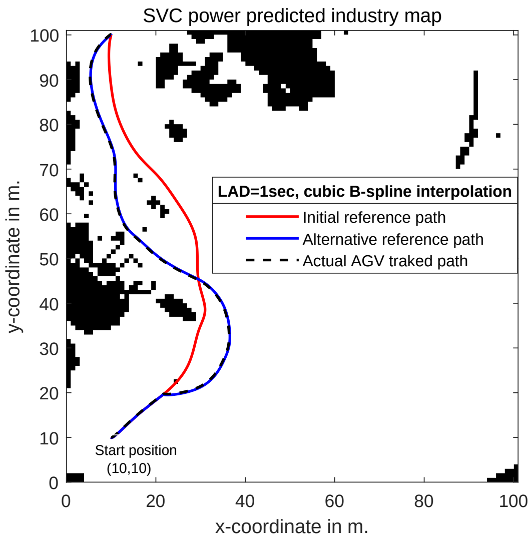


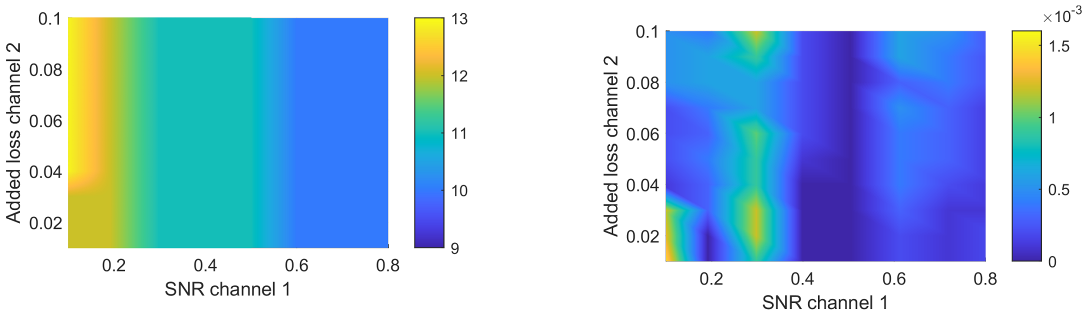
Figure 3: Path replanning example – reference, alternative and actual AGV path from start to destination.

whereas the path segments are non-uniform. However, the uniform path sampling with controller frequency leads to an unfavorable jumping velocity profile. With cubic Basis spline (B-spline) interpolation, the availability of the first as well as the second path derivative is assured. In Figure 3, the final trajectory of the AGV is depicted with dashed line.

5 ADAPTIVE CODING FOR MULTI-RAT RESOURCE ALLOCATION

In order to further improve the reliability of a communication link, the packets to be sent may be distributed via several communication channels, or RATs. In this manner, local signal power drops like blind spots may be mitigated, since this effects depend on transmitter frequency, which differs for different RATs. However, packet duplication techniques such as Parallel Redundancy Protocol (PRP) (Ehrig et al., 2017) or MultiPath TCP (Paasch and Bonaventure, 2014) lead to inefficient resource utilisation, since they do not feature error correction capability for corrupted packets.

In contrast, fountain codes are able to produce as many sub-codewords out of one packet, as it is required. That means, this codes are raterless, because the coding rate can be flexibly adjusted due to requirements. On the decoder side, a certain number of sub-codewords should be received in order to decode the packet (K-out-of-N-principle). However, fountain codes require an erasure-channel, i. e., they can withstand a drop of sub-codewords, but they are not able to correct the erroneous sub-codewords. In order to mitigate this issue, fountain codes should be used in conjunction with error-correcting codes, as proposed in (Berger et al., 2008).



(a) Estimated number N of RaptorQ sub-codewords per channel

(b) PER simulation with *NS3*

Figure 4: RaptorQ enhanced multi-RAT system for PER guarantee (PER threshold: 10^{-3}).

Combined with multi-RAT transmission, fountain codes provide a flexible tool to distribute a packet over multiple links. Especially utilising channel prediction algorithms, the number of sub-codewords to be sent may be tailored to real channel conditions but channel estimations. This provides further improvement of reliability, whereas resource utilisation remains optimal.

In our investigations, we considered a system based on two OFDM communication links. As a fountain code to work with, RaptorQ code was chosen. A packet should be encoded with RaptorQ, and the generated sub-codewords should be sent through both links. The goal is to generate the number of sub-codewors sufficient to meet a reliability theshold based on the Signal-to-Noise-Ratio (SNR) prediction for each channel.

For the estimation of the number N of packets to be sent per channel, analytical error estimation for OFDM signals was performed. In order to reduce simulation time, Packer Error Rate (PER) threshold of 10^{-3} was selected. However, the result can be translated to such demanding thresholds as 10^{-9} and less. Figure 4a shows the estimated number N for both channel models based on SNR per channel. Hereby, x-axis shows the SNR (in dB) of the channel 1, whereas y-axis show the additional signal attenuation A (in dB) on the channel 2. Thus, $SNR_2 = SNR_1 - A$.

The results were verified by a simulaiton setup with network simulator *NS3*. Figure 4b shows the achieved PER over the considered SNR range. It can be seeing, that for the most combinations of SNR_1 and SNR_2, the estimations yield a reliable PER which meets the required threshold of 10^{-3}. Nevertheless, Figure 4b still features some areas, where the PER drops below the threshold. The reason is, that more sophisticated channel model should be used for the estimation in order to better fit the fading behaviour of the channels. Nevertheless, the combination of multi-link transmission and rateless coding may be used in order to provide guaranteed PER, whereas the resource usage can be flexibly tailored to channel conditions.

6 CONCLUSIONS

In this paper, an Edge-cloud based industrial control functional architecture is proposed for enabling control communication co-design. Furthermore, we discuss applicability of AI based decision making to adapt the control and communication system design. We present channel condition based AGV navigation control to avoid the coverage blindspots and adapt the tracks in real-time. Moreover we adapt the communication system by performing the channel coding across RAT based on link quality. Furthermore, AI based channel state predictions can be utilised by communication control. Utilising multi-RAT system in conjunction with rateless coding, it is possible to tailor the coding rate as well as the distribution of the sub-codewords to different links to the expected channel quality, or SNR. By doing so, the required reliability of a communication link could be guaranteed.

In future, the coding rate adaptation algorithm needs to be improved in order to provide better reliability of the communication links. Further, it is also possible to enhance this algorithm with machine learning techniques in order to provide more precise results based on the AGV position. Besides, further investigations on the overall reliability of the communication as well as the impact of the forecast time are required.

ACKNOWLEDGEMENTS

This work has been supported by the Federal Ministry for Economic Affairs and Climate Action of the

Federal Republic of Germany (Foerderkennzeichen, 01MT19006A, AIRPoRT). The authors alone are responsible for the content of the paper.

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