Wireless Factory Automation: Radio Channel Evolution in Repeated Manufacturing Processes

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***Abstract*—Wireless technologies have to be enhanced to meet the latency and reliability requirements of mission-critical machine–type communication (MTC) in automation systems. Investigating the characteristics of radio channels in typical factory environments is fundamental when designing the wireless industrial Internet of the future. In this paper, we provide results of an indoor channel measurement campaign in a representative factory automation lab. The measurements were performed at a carrier frequency of 2.25 GHz. We focus on communication between industrial robots and their controller entities over short distances. Our use case is a pick-and-place process with repetitions. We allow other active machinery and moving personnel nearby the automation cell. Based on the power delay profile and the corresponding power spectral density, we analyze the time evolution of channel snapshots on fixed spatial positions in repeated processes. Furthermore, we study the correlation of successive channel profiles along the process trajectory. By obtaining high channel correlation over time, we show that scattering and reflection effects from active and moving obstacles surrounding the manufacturing area are limited. Our findings allow a channel-aware planning of wireless control loops by optimized link adaption in wireless systems.**

***Index Terms*—wireless factory automation; radio channel measurements; industrial robots; machine-type communication; radio channel evolution**

I. Introduction

Recently, wireless technologies have gained attention from the industrial automation community. It is expected that wireless solutions will enable highly efficient and highly flexible operation of production processes in factory automation if they can fulfill the challenging latency and reliability requirements in the context of mission-critical machine-to-machine (M2M) services [1], [2].

Enabling fail-safe transfer of actuator and sensor information is crucially important in automation systems. The operation cycles of manufacturing processes are required to be less than or around 10 ms. Therefore, the end-to-end latency for wireless signal transmission is often stated as below 1 ms, while maintaining a packet error rate of up to 10^{-9}. Usually, the packets contain only payload of a few bytes up to some kilobytes. Also, the communication distance in wireless automation systems is typically short, e.g. below 10 m according to automation equipment manufacturers.

In this paper, we will present results from a measurement campaign targeting short-range communication between industrial robots and their controller entities over the air. We used a broadband channel sounder at 2.25 GHz carrier frequency to study a repeatedly performed pick-and-place process within one automation cell, located in a typical factory facility. At the same time, other active machinery were operating in neighbouring cells.

Our main observations derived from the recorded radio channel are the following: We obtain a highly deterministic channel in a mobile manufacturing process which translates into a high correlation of the radio channel between measurement snapshots on fixed positions during the repeated process. We show that this correlation holds in the short-range profile of our measurement setup despite the fact that neighbouring production systems and even persons alter the scattering and reflection characteristics of the wireless channel over time. Basis of our findings is the analysis of the power delay profile (PDP) and the corresponding power spectral density (PSD).

The work presented herein extends our findings in [3], where we characterized the industrial radio channel at 5.85 GHz with a focus on channel delay statistics and their impact on latency-optimized symbol design of wireless communications for industrial applications.

The results from this paper motivate the channel-aware planning of reliable control loops for the wireless control of industrial robots. In this regard, one can utilize the a priori channel knowledge gained from the process repetitions in oder to achieve link adaption improvements and feedback optimization. Related work can be found in [4], where the authors analyzed communication-aware motion planning, channel estimation and prediction in robotic networks.

II. Measurement Scenario

A. Experimental Setup

Our channel measurement campaign is described in detail in [3]. It took place in a test automation cell of the Smart Automation Lab at the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University, Germany. The automation cell provides a top-mounted industrial robot system which is installed on a translational axis, see Fig. 1. It is surrounded by a live production environment with active machine tools and a limited number of personnel as described before. Consequently, it could be expected that the neighbouring environment is altering the scattering and reflection characteristics of wireless signals over time. In

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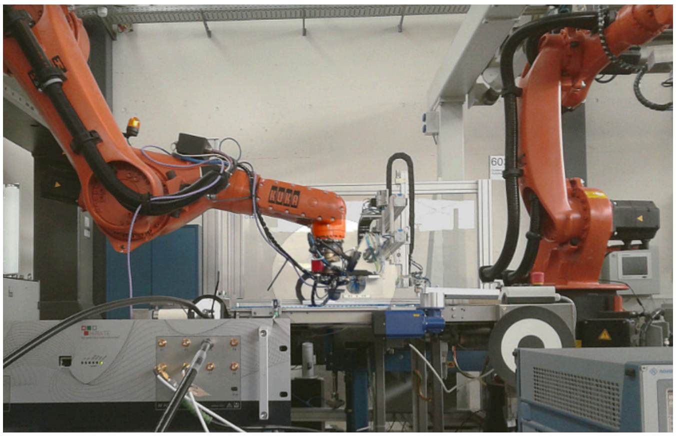

Fig. 1: Test automation system used for our experimental measurements in the Smart Automation Lab at the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University [3]. The measurement antennas are installed at the gripper of an industrial robot and nearby the channel sounder equipment outside of the manufacturing area. The dimensions of the manufacturing area are approx. 4×5 m.

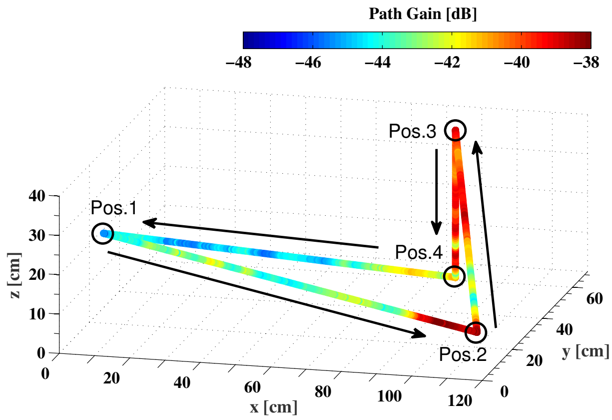

Fig. 2: Measurement trajectory of the repeated pick-and-place process. The table to pick and place items is on the x-y plane. Shown is the path loss at 2.25 GHz carrier frequency in a scenario, where the transmit antenna of the channel sounder was placed 1.20 m away from Pos. 2 on the x-axis. The marked positions 1 to 4 are turnaround points. The covered distance of one process is about 3 m in 8.6 s time.

Sec. IV, we analyze the temporal channel evolution for the short-range character of our measurements. In particular, we look at the correlation of channel snapshots over time and over the covered distance along the track.

We used the High Performance Digital Radio Testbed (HIRATE) [5] to perform real-time channel sounding. The equipment was configured to support measurements at 2.25 GHz for the analysis herein. Note that we conducted a similar measurement campaign supporting a center frequency of 5.85 GHz in [3], where further information on the configuration and antenna setups can be found. Basic configuration parameters are given in Table I. The effective signal bandwidth was 250 MHz, corresponding to a sampling resolution of 4 ns. We recorded the channel impulse response in snapshots with a temporal separation of 12.29 ms.

Scenario	mobile, short-range, industrial indoor
Center frequency	2.25 GHz
Bandwidth	250 MHz
Sampling resolution	4 ns
Path resolution	1.2 m
Speed on trajectory	0.4 m/s

TABLE I: Measurement Setup [3].

B. Manufacturing Process

Our considered use case is a repeated *pick-and-place process* of an industrial robot that picks up items which move on a conveyor belt. We investigate the wireless link between the transmit antenna of a robot control unit outside the manufacturing area and the receive antenna attached to the gripper at the tool center point of a flexible robot arm. One process run starts and ends at Pos. 1 in Fig. 2 which is called home state. From there, the gripper moves to Pos. 2 where it virtually picks an item from a table. The movement continues by placing the item at Pos. 3 before returning to the home state.

C. Radio Channel Analysis

We preprocess the recorded channel impulse response of the HIRATE system and obtain a power delay profile (PDP) and the power spectral density (PSD) for each snapshot of the measurement track, see Fig. 3 and Fig. 4. We use a scheme to improve the PDP representation through detection of a representative set of multipath components (MPCs) on a non-equidistant delay grid. Moreover, noise effects are suppressed by the applied scheme, see [6].

III. Evaluation Methodology

We introduce some metrics for the evaluation of the channel behaviour. Below, $(\cdot)^T$ and $(\cdot)^*$ describe the transpose and conjugated complex, respectively. The expectation of a random variable $X(t)$ at time instance t is defined as $\mathbb{E}[X(t)]$. If $X(t)$ is a wide sense stationary random process, then the mean and the variance are independent of the time instance [7]. Therefore, $\mu_X = \mathbb{E}[X(t)]$ and $\sigma_X^2 = \mathbb{E}\left[(X(t) - \mu_X)^2\right]$ are constant.

The autocorrelation of a wide sense stationary random process $X(t)$ depends only on the lag τ between two time instances. The normalized autocorrelation is defined as:

$$\rho_\tau = \frac{\mathbb{E}\left[(X(t) - \mu_X)\,(X^*(t-\tau) - \mu_X)\right]}{\sigma_X^2}. \tag{1}$$

The random process is observed over the time samples $t \in \{0 \dots T-1\}$. The column vector $\vec{x}(t)$ denotes a realization of the random variable $X(t)$ at instance t. In the unbiased case, each lagged correlation is normalized by the number of

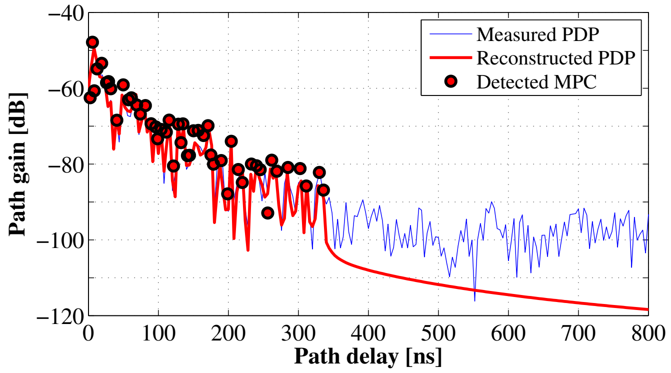

Fig. 3: Measured power delay profile (PDP) and reconstructed PDP after refinement by detection of the most dominant multipath components (MPCs) for a single measurement snapshot at 2.25 GHz.

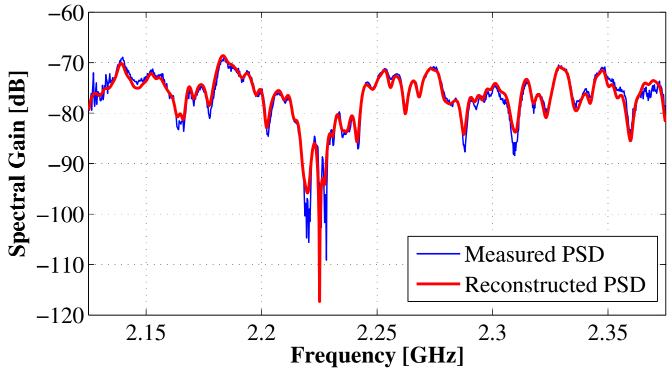

Fig. 4: The corresponding power spectral density (PSD) for the measurement snapshot of Fig. 3.

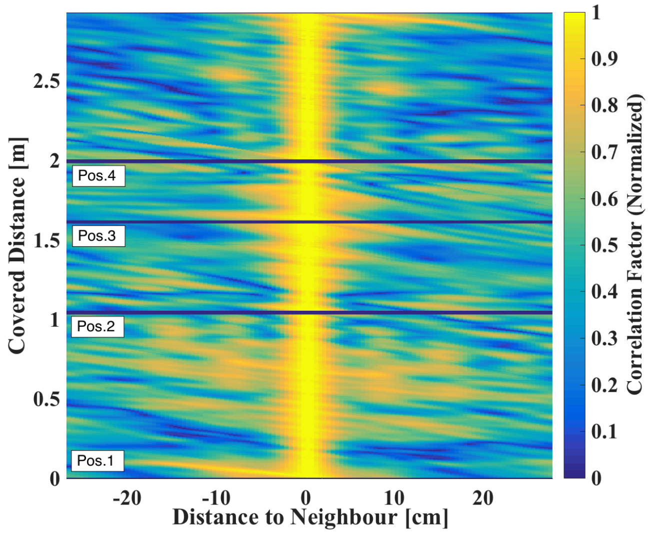

Fig. 5: Absolute spatial correlation to neighbouring positions based on the distance [cm].

observations, i.e. $(T - \tau)$. Therefore, the unbiased normalized autocorrelation within an observation period T is obtained by

$$\rho_\tau = \frac{1}{(T - \tau) \cdot \sigma_X^2} \sum_{t=\tau}^{T-1} \vec{x}^*(t) \cdot \vec{x}(t - \tau) \,. \tag{2}$$

If $X(t)$ is *not* a wide sense stationary random process, then the absolute normalized autocorrelation is additionally defined in dependence of the absolute time instance t:

$$\rho_{\tau,t} = \frac{1}{\vec{x}^*(t) \cdot \vec{x}(t)} \vec{x}^*(t) \cdot \vec{x}(t - \tau) \,. \tag{3}$$

This autocorrelation with lag τ at time instance t is normalized with respect to lag $\tau = 0$, see the denominator in (3). Consequently, the autocorrelation for lag $\tau = 0$ is $\rho_{0,t} = 1$.

The autocorrelation functions (2) and (3) can also be based on other metrics like the spatial distance.

IV. Evaluation Results

The measurement results are split into two parts, meaning that we explore the following two aspects: (i) the evaluation of the spatial evolution of the channel within a single automation process, and (ii) results on the time evolution of the channel over multiple process iterations.

The autocorrelation function is considered to characterize both the temporal and spatial correlation behaviour of the channel. In our results, the covered distance describes the traveled way over the movement trajectory from the home state (0 m) to the current position. Each covered section is calculated from the current position and the preceding position.

A. Spatial Evolution

Fig. 5 evaluates the spatial correlation of the radio channel along the process trajectory of Fig. 2. In particular, the absolute normalized correlation of each spatial position to their neighbour spots is shown. For better illustration, the position is plotted in terms of the covered distance. The absolute correlation is calculated from (3), where ρ depends on the spatial position and the distance to the neighbour. We observe, that a tiny region around the actual position is strongly correlated. However, the spatial correlation is steeply decreasing and a few centimeters are already sufficient to have uncorrelated channels.

An exemplary observation of the spectral channel power over the 250 MHz bandwidth is shown in Fig. 6, where the distance of 9 meters covers three process iterations. Within a single process of 3 meters track length, the pattern seems irregular, as presented in Fig. 5. However, a regular pattern is observed if we consider the repetition of the automation process, i.e. every 3 meters. This phenomena is evaluated below.

B. Time Evolution

From Fig. 6, the pattern of the spectral channel power seems to be reoccurring in each process iteration. This observation is supported through insights provided by Fig. 7. Here, we obtain the power spectral density over the complete 250 MHz frequency band at Pos. 1 of Fig. 2 over multiple iterations of the pick-and-place process and observe a very similar power spectral density for this time evolution. The single multipath components sustain while the time moves. Hence, we can show

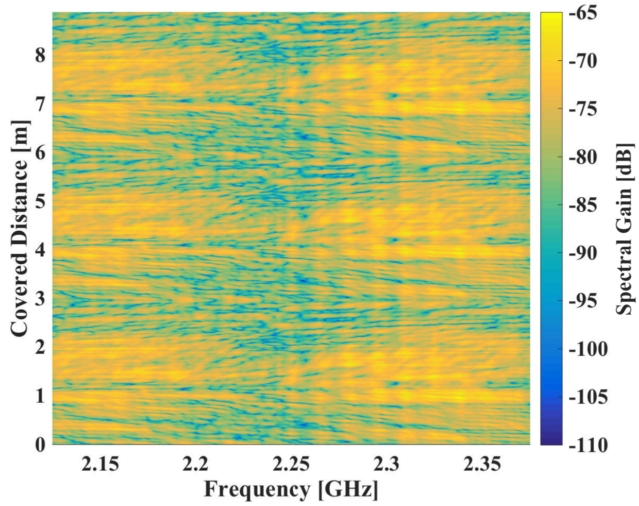

Fig. 6: Reoccurring power spectral density pattern over 3 automation processes, each covering a distance of approximately 3 m.

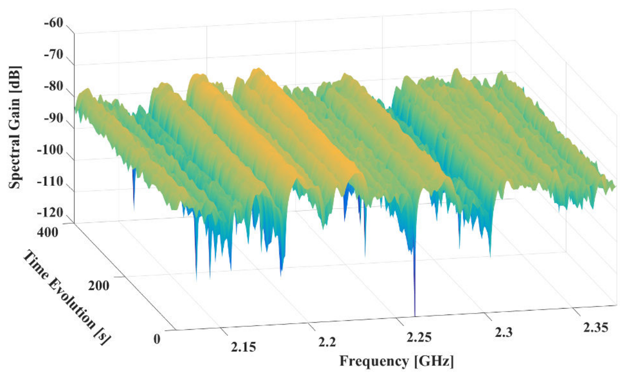

Fig. 7: Exemplary time evolution of the power spectral density over repeated automation processes at Pos. 1 of Fig. 2.

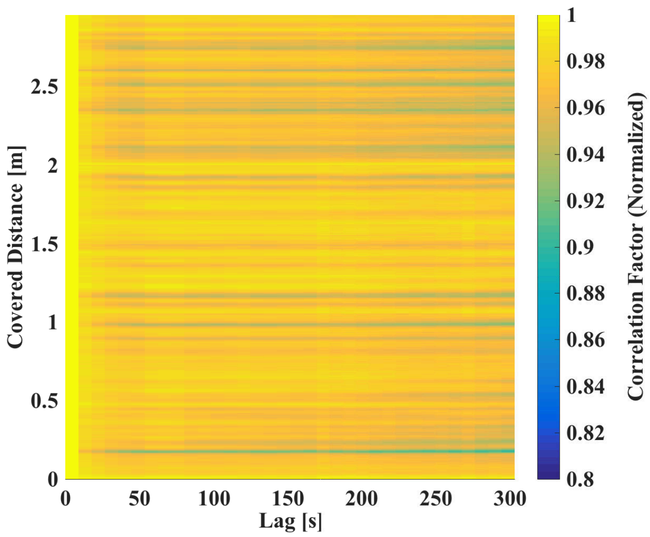

Fig. 8: Lagged autocorrelation of a fixed spatial position over multiple processes in seconds.

that altered scattering and reflection caused by changes in the surrounding environment do not critically influence the short-range indoor channel. Effects on the time evolution of wireless transmitted signals are expected to be limited for the factory automation use case under study.

More insights are provided in Fig. 8, where the time correlation (correlation for a certain time lag to other process iterations) is valued for each spatial position within one process. The correlation factor is derived by the normalized autocorrelation is calculated in (2) and depends only on the lag between two time samples. As stated from previous figures, no strong time evolution behaviour is seen in this exemplary measurement. Only slight variations occur. The normalized correlation factor is above 0.8 for almost all observed trajectory positions, Therefore, we can also conclude, that the process trajectory of the manufacturing robot is sufficiently precise to allow highly correlated channels over multiple process iterations.

V. Conclusion

This paper presents results on radio channel evolution and correlation for a measurement campaign in a representative factory automation system. For this, an industrial robot system was used, where the attached gripper moved along a predefined trajectory of a manufacturing processes. We measured the wireless link between the moving gripper and a robot control unit. A key observation of this paper is the strong temporal correlation of the wireless channel at fixed spatial position on the process trajectory. The highly deterministic behaviour of the channel enables channel–aware planning and improved link adaption schemes in order to achieve the stringent requirements of factory automation.

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References

[1] A. Frotzscher, U. Wetzker, M. Bauer, M. Rentschler, M. Beyer, S. Elspass, and H. Klessig, "Requirements and Current Solutions of Wireless Communication in Industrial Automation," in *Proc. of IEEE ICC'14, Workshop on 5G Technologies*, June 2014, pp. 67–72.

[2] A. Varghese and D. Tandur, "Wireless requirements and challenges in Industry 4.0," in *Proc. of IC3I*, Nov. 2014, pp. 634–638.

[3] B. Holfeld, D. Wieruch, L. Raschkowski, T. Wirth, C. Pallasch, W. Herfs, and C. Brecher, "Radio Channel Characterization at 5.85 GHz for Wireless M2M Communication of Industrial Robots," in *Proc. of IEEE WCNC*, April 2016.

[4] Y. Mostofi, M. Malmirchegini, and A. Ghaffarkhah, "Estimation of Communication Signal Strength in Robotic Networks," in *Proc. of IEEE ICRA*, May 2010, pp. 1946–1951.

[5] W. Keusgen, A. Kortke, M. Peter, and R. Weiler, "A Highly Flexible Digital Radio Testbed and 60 GHz Application Examples," in *European Microwave Conference (EuMC)*, Oct. 2013, pp. 740–743.

[6] M. Kurras, S. Jaeckel, L. Thiele, and V. Braun, "CSI Compression and Feedback for Network MIMO," in *Proc. of IEEE VTC'15 Spring*, Glasgow, May 2015, pp. 1–5.

[7] A. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge University Press, 2005.