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**Friedrich Burmeister**

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Ultra-Reliable Communications Systems**

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**Industrial Radio Channel Measurements for  
Ultra-Reliable Communications Systems**

Dipl.-Ing.

**Friedrich Burmeister**

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# Abstract

Historically, mobile communications systems have focused on providing connectivity to people. However, with the integration of wireless systems into highly automated industrial processes, the use cases and requirements for wireless data transmission have changed significantly. Radio systems must now operate with ultra-reliable performance and low latency to facilitate flexible and seamless industrial applications. This level of connectivity needs to be maintained across all locations within a given radio environment. At the same time, the characteristics of the predominant radio channel in any environment are highly dependent on both the location and radio frequency. The resulting variability of the wireless channel contradicts the stringent reliability requirements of industrial radio applications. Therefore, the specific conditions of the radio channel must be considered during both the planning and deployment stages of industrial radio systems.

In this dissertation, a novel radio channel measurement system was developed and utilized to gather data sets that effectively capture channel behavior in realistic, industrial ultra-reliable low-latency communications (URLLC) scenarios. The robustness, precision, and reproducibility of the measurement methodology distinctly set this work apart from existing studies. The data obtained from diverse radio environments underscores the significance and potential of integrating measurement data throughout various deployment stages of a reliable radio system. The evaluations conducted on this data aid in the dependable planning of transmission distances within radio networks.

Leveraging a mobile automated measurement setup, which achieves high spatial measurement resolution across extensive transmission distances, the channel data sets encompass both small-scale and large-scale behaviors of the wireless channel. By repetitively measuring the channel within a radio environment along consistent trajectories, the resulting data sets reveal the temporal consistency of the radio channel in time-varying environments. Building on this key insight, this dissertation offers innovative approaches to modeling the identified channel behaviors derived from the measurement data. Additionally, the thesis proposes several methods for exploiting spatial channel knowledge in the form of radio environment maps (REMs) within the context of URLLC. While REMs enhance the reliability of radio networks, they also pave the way for advancements in integrated sensing and communications (ISAC) through enhanced spatial channel awareness. The foundational findings and data sets presented in this work not only lead to further evaluations but also open up a multitude of promising research avenues.



# Kurzfassung

Historisch gesehen dienten Mobilfunksysteme der Vernetzung von Menschen. Mit der Integration drahtloser Funksysteme in hochautomatisierte, industrielle Prozesse haben sich die Anforderungen an die drahtlose Datenübertragung drastisch verändert. Um flexible und unterbrechungsfreie Funkanwendungen in der Industrie zu ermöglichen, müssen Funksysteme äußerst zuverlässig und mit geringer Latenz arbeiten. Diese Qualität der Konnektivität muss an allen Orten einer Funkumgebung erfüllt werden. Gleichzeitig hängen die Eigenschaften des vorherrschenden Funkkanals stark vom Ort und der Funkfrequenz ab. Die daraus resultierende Variabilität des Funkkanals steht im Widerspruch zu den strengen Zuverlässigkeitsanforderungen industrieller Funkanwendungen. Daher müssen die spezifischen Bedingungen des Funkkanals sowohl in der Planungs- als auch in der Bereitstellungsphase industrieller Funksysteme berücksichtigt werden.

In dieser Dissertation wurde ein neuartiges Funkkanal-Messsystem entwickelt und eingesetzt, um Datensätze zu sammeln, die das Kanalverhalten in industriellen URLLC-Szenarien effektiv erfassen. Die Robustheit, Präzision und Reproduzierbarkeit der Messmethodik heben diese Arbeit deutlich von bestehenden Studien ab. Die aus verschiedenen Funkumgebungen gewonnenen Daten unterstreichen die Bedeutung und das Potenzial der Integration von Messdaten in verschiedenen Einsatzphasen eines Funksystems. Die durchgeführten Auswertungen tragen zu einer zuverlässigen Planung von Übertragungsentfernungen in Funknetzen bei.

Durch den Einsatz eines mobilen automatisierten Messsystems, das eine hohe räumliche Messauflösung über große Übertragungsentfernungen hinweg erzielt, umfassen die Kanaldatensätze sowohl kleinräumige als auch großräumige Schwundverhalten des Funkkanals. Wiederholte Messungen des Kanals innerhalb einer Funkumgebung entlang konsistenter Trajektorien zeigen die zeitliche Konsistenz des Funkkanals in zeitlich variierenden Umgebungen. Auf Basis dieser wichtigen Erkenntnis, bietet diese Dissertation innovative Ansätze zur Modellierung der aus den Messdaten abgeleiteten identifizierten Kanalverhalten. Darüber hinaus schlägt die Arbeit mehrere Methoden zur Nutzung räumlicher Kanalkenntnisse in Form von Funkumgebungskarten im Kontext von URLLC vor. Während diese die Zuverlässigkeit von Funknetzen verbessern, ebnen sie durch eine verbesserte räumliche Kanalkennntnis auch den Weg für Fortschritte im Bereich des integrierten Sensings mittels Funkwellen. Die in dieser Arbeit vorgestellten grundlegenden Erkenntnisse und Datensätze ermöglichen eine Auswahl zukünftiger Untersuchungen und eröffnen eine Vielzahl vielversprechender Forschungsansätze.



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The term "measurement" is frequently associated with the structured preparation, execution, and analysis inherent to dedicated measurement campaigns, which can require significant time and resources. However, it is important to recognize that measurement can also be a passive process, occurring continuously during the operational phase of a system. This passive measurement facilitates the ongoing monitoring of parameters and allows for real-time adaptations. This distinction is equally applicable to wireless communication systems.

On one hand, thorough channel measurement campaigns provide critical insights that support the design and advancement of innovative wireless technologies [Dup+23]. Historically, the evolution of radio systems has driven researchers to explore various frequency ranges. Recently, the 3GPP working group has chosen to investigate a new frequency range of 7 GHz to 24 GHz for the forthcoming 6G. To understand the propagation effects of radio signals within these new frequencies, signal penetration measurements are commonly conducted [Sha+24a]. Additionally, dedicated channel measurements are carried out to understand the propagation effects in new radio environments [Dup+22]. Also in the context of planning future wireless systems, propagation measurements are valuable, aiding in the estimation of coverage areas [Sha+24b].

On the other hand, wireless radio systems, particularly cellular networks, continuously measure and monitor the wireless channel throughout their operation. Utilizing dedicated reference signals known as pilot signals, these systems maintain awareness of radio channel quality. Furthermore, channel estimation is integrated into every data transmission process, resulting in ongoing measurements and adjustments within the communications system, such as modifications to the modulation coding scheme (MCS) of the transmission. While this passively obtained data may not be centrally collected as it would be during a dedicated measurement campaign, it generates a substantial volume of valuable information. The primary challenge lies in managing the resulting data volume and effectively utilizing these data sets. Nevertheless, in today's data-driven landscape, marked by advancements in artificial intelligence (AI) and the rapid growth of machine learning (ML) technologies, there is a notable trend towards the collection of more data during operational phases. This enables ML algorithms to optimize the performance of communication systems.

As explored in this dissertation, both active and passive data collection methodologies are essential for radio systems that require high levels of reliability.

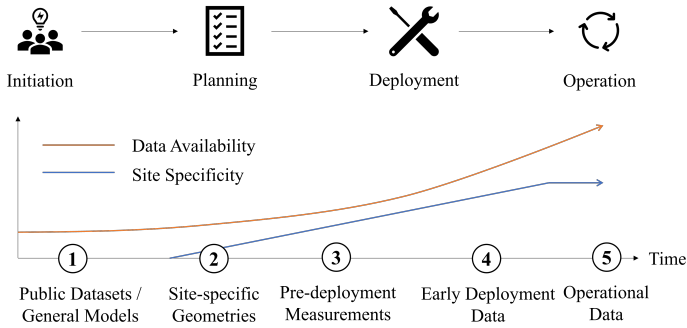


Fig. 1.1: General procedure of wireless system deployment and data acquisition.

## 1.1 Motivation and Problem Statement

Historically, mobile communication systems have focused on delivering voice and data services to end-users. With the conceptual design of 5G, however, there has been a shift towards non-person-related applications, which has led researchers and engineers to explore the potential of wirelessly connecting machines and devices [FA14; FB21]. Wireless communications are now recognized as a critical technology for advancing the next phase of industrial automation [APP19].

Connectivity for individuals is typically considered a non-critical wireless application. Although service interruptions or delays in data transmission may lead to customer dissatisfaction, they usually do not incur significant economic costs. In contrast, when industrial factory automation systems rely on wireless connectivity, a failure in the communication system can halt production, resulting in substantial financial losses. Therefore, this scenario is classified as critical, if not extremely critical. Consequently, radio systems designed for industrial environments must be engineered to eliminate any risk of wireless communication outages. Additionally, the real-time interaction of machines necessitates that data transmissions occur with minimal latency. As a result, industrial radio networks must comply with the requirements of URLLC [Fro+14]. These two types of networks, personal and industrial, demand distinctly different performance metrics.

To clarify the differing requirements for data collected during channel measurements based on network type, a comprehensive overview of the planning and deployment of radio systems is provided, as illustrated in Fig. 1.1. The process can be divided into the phases of initiation, planning, deployment, and operation of a radio network. The use cases and, hence, the wireless system requirements are defined at the initiation stage. In this overview, the planning considers details about the deployment area and the number of users or devices to be operated. In

the deployment phase, the actual system is set up and prepared for the following operation phase.

Simply speaking, maximizing coverage and connecting as many users as possible with high data rates is key in cellular systems. Thereby, the average quality of user connectivity is considered. This leads to *Best Effort* radio network design, meaning that it is acceptable if single users have temporary service outages. To assist the design of those networks, generally established signal propagation models, based on publicly available measurement campaigns, are used [AA16; Rap02]. During planning, geometrical information such as city or geological maps to simulate and maximize signal coverage areas might be used nowadays. In Fig. 1.1, the availability and site-specificity of measurement data are also qualitatively presented. The more relaxed the reliability requirements of a radio system are, the less perfectly tailored the system needs to be to the environment. Accordingly, the considered measurement data can be limited to public measurement campaigns and simulations, and hence, the site-specificity of the data does not need to be high. If done, measurements before and after deployment are not extensive. User data acquired during operation is often used for monitoring and maintenance rather than optimizing network operation with respect to a performance metric.

In comparison, one must remember the strict reliability requirements that industrial radio systems must fulfill. Hence, a wireless link has to work reliably at all locations in an industrial environment. Accordingly, much more site-specific data must be involved. Due to the diverse appearance of industrial plants, general propagation models are of limited use. Even simulations based on geometric models do not yet represent the exact properties of the radio channel in the target environment. Since the varying radio channel is the cause of unreliability in the transmission system, more detailed information about it must be considered. Therefore, pre-deployment measurements and early deployment tests play a much more important role in reliable wireless systems. Furthermore, the application-specific channel data can be used during the operational phase to optimize reliability.

In conclusion, it can be noted that the entire deployment process needs to be accompanied by more site-specific measurement data. The major problem is that the measurement data must be suitable for relevant investigations. For example, the randomness of the channel must be sufficiently observed and quantified in order to assess reliability. In addition, the communications outage behavior must be analyzed in the order of milliseconds for URLLC applications. Since the temporal sequences of outages matter in application-specific metrics, the channel data must reflect the correlations in this order of magnitude [HSF18; Muh+21]. The measurement data must also be similar to a relevant use case to investigate the use of data from the operational phase for reliability optimizations. However, the aim is to keep the measurement effort practicable. With respect to the acquisition and use of data for URLLC systems, the following section briefly discusses related works.

The deployment process of a radio network can be distinctly categorized into four phases: initiation, planning, deployment, and operation. During the initiation phase, the use cases are defined, along with the associated wireless system requirements. The planning phase subsequently addresses the specifics of the deployment area and the anticipated number of users or devices. The deployment phase entails the actual setup of the system, which is then prepared for the operational phase.

In the context of cellular systems, the primary objective is to maximize coverage while connecting a substantial number of users with high data rates. This focus inherently considers the average quality of user connectivity, which leads to a *Best Effort* design approach for radio networks. Under this paradigm, temporary service outages for individual users are deemed acceptable. To support the design of such networks, established signal propagation models, derived from publicly accessible measurement campaigns, are typically employed [AA16; Rap02]. During the planning phase, geometrical information such as city or geological maps is utilized to simulate and optimize signal coverage areas. Figure 1.1 qualitatively illustrates the availability and site-specificity of measurement data. The stringency of reliability requirements for a radio system directly influences its design; a more relaxed reliability criterion allows for a less tailored system. Consequently, the measurement data may be restricted to public campaigns and simulations, reducing the necessity for high site-specificity. If done, pre- and post-deployment measurements are minimal. User data collected during the operational phase is primarily leveraged for monitoring and maintenance, rather than optimizing network performance relative to specific metrics.

In contrast, industrial radio systems face stringent reliability prerequisites, necessitating that wireless links function consistently across all locations within an industrial environment. This demand mandates a greater integration of site-specific data, as general propagation models offer limited applicability due to the heterogeneous nature of industrial plants. Even simulations that utilize geometric models often fall short in accurately representing the properties of the radio channel in the target environment. Given that variations in the radio channel contribute to transmission unreliability, it is crucial to take detailed information about these variations into account. As such, pre-deployment measurements and preliminary deployment tests assume a critical role in ensuring the reliability of wireless systems. Moreover, application-specific channel data can be employed during the operational phase to enhance reliability further.

In conclusion, robust site-specific measurement data must underpin the entire deployment process. A principal challenge is ensuring that this measurement data is appropriate for relevant analyses. For instance, the randomness inherent in the channel must be thoroughly observed and quantified to assess reliability accurately. Additionally, the analysis of communications outage behavior must occur on the order of milliseconds for URLLC applications. Since the temporal patterns of outages are significant for application-specific metrics, the channel data must adequately

reflect the correlations at this temporal scale [HSF18; Muh+21]. Furthermore, the measurement data should closely resemble relevant use cases to support the investigation of utilizing operational phase data for reliability optimizations. The ultimate aim is to maintain a manageable effort in data collection. Regarding the acquisition and utilization of channel measurement data for URLLC systems, the following section provides a brief discussion of related works.

## 1.2 State of the Art

This work covers various interrelated topics, including radio channel measurements, channel characterizations, channel modeling, and, finally, the exploitation of measurement data for the operation of wireless systems. The acquired measurement data forms the backbone for all different topics and concepts. The comparison of related works must, hence, start with the existing measurement campaigns in industrial environments and the availability of the measurement data. Note that a detailed comparison with the state of the art is provided in all respective chapters, and we present a rough overview here.

In general, the interest in using radio systems in industrial environments led to many radio channel measurement campaigns in these environments. The campaigns often differ with respect to the environments and the measurement methods. Thereby, most existing measurements aim at general characteristics of channels such as the signal pathloss and the number and delay of present multipath reflections [Yin+24]. This information might be valuable for general propagation modeling. However, the corresponding measurement campaigns are often limited to a few, spatially separated measuring points. Furthermore, these measurements are typically carried out statically. Hence, most of the existing measurement methods cannot resolve the spatial evolution of the wireless channel in space but sample it at arbitrary locations. Consequently, the measurements do not represent the wireless channel as a radio device of a URLLC application would experience it. Thus, we conclude that only a few campaigns are suitable for reliability investigations of industrial wireless applications. In [Hol+16], the authors combine a channel measurement system with a real robotic arm use case and measure the channel with a sufficient temporal resolution compared to URLLC applications. Similar to other campaigns that ensure mobility and a sufficient spatial resolution [Deb+20; Zel+19], the resulting range of measurable transmission distances is very limited to vary within 2 m. Hence, related measurement campaigns do not combine high spatial measurement resolutions and meaningful extension of measured areas. Therefore, no joint evaluations of large-scale and small-scale variations of the channel can be carried out.

Stepping into industrial channel models, this fact is also reflected in the scope of existing channel models. If they consider both large-scale and small-scale conditions, small-scale variations are modeled for separated large-scale scenarios [NHA17;

Tra+19a]. Hence, their usability for supporting the investigation of wireless URLLC applications is limited. Another link between measurement data availability and channel modeling relates to the spatial consistency of the wireless channel over time. Measurement campaigns that evaluate the reproducibility of the channel over time are not precise and extensive enough to model temporary changes of the radio environment [Cam+23; WYX18]. Hence, the spatial radio channel conditions are not modeled as a permanent realization with temporary deviations.

With a lack of measurement observations, possible exploitations of spatial channel awareness are almost untouched concerning industrial URLLC applications. Combined with a missing link between existing measurement campaigns and relevant use cases during the measurements, using channel data during the operational phase, e.g., to improve reliability, is often not considered in existing work. The utilization of REMs for network optimization is a topic that is usually related to the trajectory planning of drones in outdoor scenarios to maximize line-of-sight (LOS) probabilities. If used in indoor scenarios, REM-based trajectory planning focuses on large-scale characteristics such as LOS maximization [Zho+22]. Similarly, REM-based sensing methods for ISAC are not well represented in existing work.

In conclusion, many channel measurement and modeling activities focus on general channel models that are as non-specific to radio environment appearances as possible. Considering the presented deployment phases in Fig. 1.1, these models and datasets are valuable to be used in the early planning phases of industrial radio networks, i.e., to understand propagation in general. However, industrial radio applications pose the highest requirements, and already industrial channel measurements must meet them. Otherwise, the achievable reliability and availability of industrial radio links cannot be verified. In summary, available industrial channel datasets do not satisfy these requirements.

## 1.3 Thesis Structure and Contributions

In the following, the remaining chapters of this thesis are introduced along with the main contributions from the respective chapters.

### Chapter 2: System Model

In the system model, we clearly define the essential fundamentals and assumptions that underpin this work. We introduce the relevant radio environment along with the specified use cases. A streamlined industrial scenario is presented, focusing on the mobility behavior of industrial objects. Furthermore, we provide a concise overview of the most significant wireless channel phenomena and outline the key assumptions regarding the communications system.

### **Chapter 3: Automated Radio Channel Measurement System**

In chapter 3, both the design considerations and the implementation of the measurement system are comprehensively explained. Thereby, the shortcomings of existing measurement datasets and the data requirements for URLLC investigations have led to the design. A comparison to the state of the art highlights the capabilities and uniqueness of our developed measurement system. Due to the similarity of the measurement procedure to an industrial radio application, the resulting measurement data can be used in the scope of all stages during a URLLC network deployment. Further on, the chapter introduces the four measurement campaigns carried out with the system and presents initial insights into the published datasets. Finally, the resulting limitations of the measurement system are discussed, and data processing methodologies are introduced to deal with the hardware imperfections of the system. Therefore, it is shown that flexible, non-synchronized measurements are equally suitable for carrying out precise measurement campaigns.

### **Chapter 4: Channel Measurement Data Evaluations**

This chapter analyzes the measurement data collected during the measurement campaigns presented before. The primary focus is on investigating the channel properties introduced in chapter 3. Concerning the considered small-scale and large-scale properties, this thesis comprehensively compares different radio environments. The combination of a high spatial sampling resolution and a high range of transmission distances is used for path-loss characterization. An outstanding feature is the extent of the datasets on which the evaluation is based. Considering URLLC systems, we can quantify the observed fading distributions. Thereby, during the investigations, the relation to the reliability of radio systems is kept omnipresent. In the context of large-scale properties, measurement evaluations are presented to dimension the transmission distances of a reliable radio link, considering critical fading margins. The capabilities of the data set to mimic multi-antenna systems are highlighted and used to pronounce the need for multiple-input multiple-output (MIMO) systems in the context of URLLC. By artificially reducing the size of the data set and degrading the location information of measurement samples, we can derive requirements for environment-specific measurement data collection during radio system deployment.

Finally, the precision of the measurement system is used to show the spatio-temporal consistency of the radio channel. This observation is not only elementary for understanding the radio channel as a random or deterministic process in certain use cases, but also opens the door for further investigations where the spatial knowledge about the radio channel can be exploited. In this context, it exemplifies nicely the need to understand the individual REM in any industrial or URLLC application and not to rely on stochastic models as defined by 3GPP.

## **Chapter 5: Measurement-based Channel Modeling for Reliability**

Chapter 5 presents the modeling-related work of the radio channel in this thesis. Inspired by the observations from chapter 4 that large- and small-scale channel characteristics are highly site-dependent and dominated by the dimensions, objects, and materials within an environment, this thesis concentrates on site-specific modeling approaches. A data-driven channel modeling approach is proposed that jointly reproduces both large-scale and small-scale properties of measured channels. Channel data can be randomly synthesized to support data-intensive link-level simulations for URLLC investigations.

In addition, based on a measurement campaign carried out in a radio environment that changes in a controlled manner over time, the spatial channel information is modeled as a static realization with temporary deviations. The underlying location information of the radio environment is used to derive a relation between the relative position of temporary objects and their influence on the static channel realizations. By quantitatively modeling the occurring channel deviations, we highlight the potential of using spatial channel knowledge in the form of REMs in time-varying industrial radio environments. Concerning the deployment phases, semi-deterministic, site-specific channel modeling during the operational phase of a wireless system is, thus, motivated.

With increasing site specificity, geometric channel modeling by ray-tracing is considered a third step. This thesis contributes to an initial comparison between measured and simulated REMs, using a suitable, measured data set.

## **Chapter 6: Using Radio Environment Maps for Reliable Communications**

Based on the assumption that spatial channel knowledge in the form of REMs is available through measurements and estimation, REMs can be used to optimize the operation of the radio network concerning communications reliability. In this context, chapter 6 presents different methods to use the REMs potentially. First, it is shown how REMs can be used to achieve channel awareness as a prior for intelligent radio resource allocation. At the same time, channel state information (CSI) feedback and hence communications overhead are reduced. Secondly, an adaptation of the transportation application relies on optimizing the trajectories of automated guided vehicles (AGVs) based on REM knowledge to improve the communications reliability. Thereby, the mentioned ways of using REM enhance the communications capabilities of the radio system.

On top of that, the chapter introduces two approaches of how REMs can extend the sensing capabilities of radio systems. On the one hand, the spatial similarity of the channel over time is used to perform sensor-free device localization, even in time-varying radio environments. Fingerprints from fading patterns in the spatial and frequency domains are exploited to localize moving radio devices with high precision. On the other hand, a concept is introduced on how to use the temporary

dissimilarities of the spatial channel information to localize passive objects in the radio environment.

