1 Introduction

The modern civilization as we know it today has come a long way. The conveniences that we experience in our modern day-to-day life, ranging from clean running water and electricity available anytime to highly sophisticated devices combining cutting-edge technology such as smartphones and vehicles with autonomous driving capabilities, are a result of the accumulation of longstanding knowledge and numerous innovations. Thus, the comprehensive implementation of novel technologies has gradually transformed our world and facilitated or taken over many of our daily tasks. One of the most notable events that has undeniably paved the way for today's modern world and greatly accelerated technological progress started in Great Britain in the 18th century: the *Industrial Revolution*.

From today's view, the Industrial Revolution can be separated into four major stages. The First Industrial Revolution, which can be traced back to the 18th century, involved the mechanization of factory processes, extensive iron production, and the utilization of steam and hydropower [1]. The Second Industrial Revolution started in the late 19th century and defined milestones such as the discovery of electricity and the invention of the combustion engine, which further enabled mass production and laid the cornerstone for further technological progress [2, 3]. Next, the invention of the first working transistor in 1947 initiated the shift from mechanical systems and analog electronics to digital technology, eventually giving rise to the digital world we know today. This marked the beginning of the Third Industrial Revolution, further leading to the introduction of sophisticated computer systems, comprehensive automation of processes, digital communication, and the internet [4]. Finally, the year 2011 coined the term *Industry 4.0*, now widely regarded as an early phase of the upcoming Fourth Industrial Revolution, introducing smart technology and interconnecting machines and processes throughout the whole value chain [5].

The future vision: Sophisticated networks consisting of numerous connected physical devices and sensors, i.e., Internet of Things (IoT) utilizing large-scale Machine-to-Machine Communication (M2M) combined with computational processes and Artificial Intelligence (AI), form Cyber-Physical Systems (CPS) that play a central role in the smart automation of factories and logistics. This aims to minimize the need for human intervention and decision-making and is expected to lead to an unprecedented increase in efficiency and economic growth in the near future [6]. The number of connected IoT devices is predicted to triple between 2021 and 2030, leading to a potential annual market revenue of over $ 620 billion worldwide [7]. However, the interconnectivity and coherent utilization of numerous novel technologies in the field give rise to many challenges, requiring a vast collaborative network with a broad range of technical knowledge. This necessitates substantial research effort and close collaboration between academia, industry, and government, leading to strong governmental funding [5, 8].

It becomes evident that wireless communication technologies play a prominent role in an environment demanding ubiquitous network access, even more so when considering the four derived key elements for Industry 4.0: Interconnection, information transparency, technical assistance, and decentralized decisions [9]. All mentioned aspects either directly or indirectly premise interconnectivity and availability of information. Thus, the ultimate challenge is to bridge the gap between the physical and the digital world to establish a link between the flow of physical materials and objects and the flow of information. The key technology to make this possible is Radio-Frequency Identification (RFID).

1.1 Importance of RFID in the Modern Factory and Supply Chain

The necessity to track and uniquely identify physical assets in retail and throughout the supply chain has long been apparent. In 1974 the first item – a pack of chewing gum – uniquely marked with a Universal Product Code (UPC) barcode was scanned at a retail checkout in Ohio, USA [10]. Since then, together with the related European Article Number (EAN), it has experienced a comprehensive implementation and is still in wide use today. In 2003, the Auto-ID Labs and EPCGlobal research network was founded with the primary goal of replacing the UPC with the newly developed Electronic Product Code (EPC) and establishing worldwide standardization and area-wide use in conjunction with *RFID* technology [11]. As RFID has the potential to tremendously increase the reliability and efficiency of numerous processes throughout the whole supply chain, it has become a field of great interest and colossal research effort in the past decade and, thus, has been hyped with a predicted market growth of up to $ 20 billion worldwide until the year 2013 [12].

RFID systems generally use electromagnetic waves for communication and, therefore, offer numerous benefits compared to other Automatic Identification (Auto-ID) technologies such as barcodes. For instance, the possibility to bulk-read hundreds of tags at once with no line-of-sight, nor a power supply required, quickly has made RFID the preferred choice for many applications in retail, logistics, and manufacturing. The additional possibility of a bidirectional information flow is of great value for many applications in production. Important data required during manufacturing can be saved on the tag and updated throughout the process. As a result, error-proneness can be significantly reduced, and specific customer needs can be automatically accounted for [13]. Further, the possibility to exchange and store data will facilitate the introduction of another recent major trend, the development of digital twins of whole systems and physical environments [14, 15].

In regard to Industry 4.0 Ultra-High Frequency (UHF)-RFID is particularly interesting due to the high read rates and higher read range. Realizing that this specific technology will be one of the key components to establishing the industrial IoT, the RAIN Alliance was formed in 2014 to promote the cost-effectiveness, simplicity, availability, and widespread use of passive UHF-RFID. As a result, the term *RAIN* RFID was defined to avoid confusion with other RFID technologies, such as Low-Frequency (LF) and High-Frequency (HF) RFID or active systems, making RAIN RFID the fastest-growing segment of the market [16, 17]. Further initiatives led to the approval of the European Commission to introduce the new upper EU-band in 2019. This band operates within the Federal Communications Commission (FCC) frequency band, allows a doubled amount of radiated power and an increased channel bandwidth [18]. Experts see this as a big step forward towards worldwide standardization. The new tailwind for RFID can also be confirmed in recent market reports, predicting a more than doubled global market size of $ 35.6 billion by 2030 [19]. Further, the American retail giant Walmart issued a mandate – starting September 2022 – for its suppliers to include RAIN RFID with their goods on item-level for a broad range of product categories, planning to expand to more categories in the future. The mandate was justified by listing quantifiable improvements while using RFID across their supply chain, including an inventory accuracy of over 97 %, a stock-keeping unit-level accuracy of up to 99 % (compared to around only 60 % without the use of RFID), an 80 % improvement in shipping and picking accuracy and a 90 % improvement in item receiving time [20]. Considering the high degree of measurable improvement and return on investment with the fact that one of the major retailers is committing to RAIN RFID, it is expected that a considerable amount of parties along the supply chain will follow this trend, pushing the importance of this technology.

It is safe to say that RAIN RFID will continue to gain momentum as the need for interconnectivity increases and the IoT is increasingly populated. Non-digital physical assets like tools or components required for manufacturing processes, as well as all kinds of goods, will be able to enter the digital world and be linked to the collaborative and smart environment, providing real-time data on inventory levels and ongoing processes. This will enable a high degree of automation and short response times in case of arising issues. Although the benefits in logistics and production environments utilizing conventional RFID systems have been remarkable, additional interconnectivity and collaboration, as foreseen in Industry 4.0 concepts, will lead to unprecedented improvements, offering more than just improved accuracy in inventory tracking. From formerly posing the backbone of the supply chain, RFID technology has now become the key element to extending the borders into a new world with endless possibilities.

1.2 State of the Art and Current Challenges

As shown in the previous section, RFID offers numerous benefits. Especially RAIN RFID is growing in popularity, keeping the demanding requirements of Industry 4.0 in mind. Therefore, the focus in the following lies on passive UHF-RFID technology that comes with specific susceptibilities. Most frequently, issues arise in the form of dead-zones (i.e., locations where the tag cannot be read, although still within the operational range of the reader) and undesired overreach-zones (i.e., locations enabling a tag-read, although already outside the intended operational range of the reader). Also, due to the resonant antenna element, the tag performance is highly susceptible to objects and materials in its vicinity. Both issues can lead to a substantial deviation of actual system performance from the expected behavior and necessitate costly and time-intensive modifications of the operational environment after system deployment. Blinded by this technology's many advantages, all potential benefits are often taken for granted and associated challenges neglected, especially regarding system implementation into the final operational environment under non-ideal conditions.

As RFID is already researched and widely used for over a decade, the underlying technology is well-understood. However, electromagnetic interference effects are complex and hard to predict, even for domain experts. While early RFID systems utilizing the LF- and HF-bands have mostly been used for basic asset tagging and tracking, recent and now dominating technology like RAIN RFID is utilized for more sophisticated tasks, requiring more attention regarding system implementation. Enabled by the high operational range of RAIN RFID, well able to exceed 10 m [21], this technology is suitable for high-in-demand Direction of Arrival (DoA) estimation applications and localizing systems [22, 23, 24, 25]. The high data transfer rates also make this technology attractive for harsh and metallic environments in automated manufacturing sites exchanging production data [26, 27, 28]. The typical operational indoor environments, combined with the high read range, give rise to a high level of reflections and strong multipath propagation, leading to complex interference effects. This poses a non-trivial challenge regarding signal coverage prediction [22, 29, 30, 31]. Therefore, a successful and cost-optimal implementation into a new environment requires an ex-ante evaluation of electromagnetic wave propagation and the reciprocal effects.

Although various methods for signal coverage prediction exist and many tools for electromagnetic analysis are commercially available, predictive analysis for RFID is rarely performed before system deployment [32]. This is particularly true for larger-scale scenarios. In addition, the current factory and warehouse planning processes are performed independently of the RFID system planning. This often leads to suboptimal system integration and system malfunction in the final operational environment, followed by costly system modifications ex-post. Because RFID systems are incorporated into existing processes on-site and are not planned simultaneously in mutual coordination with its operational environment, complex reciprocal effects with the environment cannot be considered in planning phases, nor during system set-up [33, 34, 35, 36, 37]. This leads to a highly inefficient and unstructured trial-and-error scheme integration.

The research community has proposed various solutions for the predictive analysis of RFID system performance. Existing methods can be broadly classified into site-general models (i.e., purely analytical and empirical) and site-specific, i.e., deterministic approaches [38]. Site-general models can be expected to yield fast but less accurate results, as characteristics of the specific environment and resulting small-scale fading effects such as multipath propagation cannot be accounted for accurately or at all. This category of methods has been widely discussed in literature, ranging from simple models based on the free-space Friis-transmission equation and refined link budget analysis [39, 40, 41, 42, 43] to empirical and more sophisticated hybrid models [38, 44, 45, 46]. Most of the presented models are highly limited in predictive accuracy for real use-cases and only applicable under specific conditions.

Deterministic approaches, on the other hand, can potentially yield highly accurate results, however, at the expense of computational effort. In this category, the numerical computations can be either based on asymptotic (also called ray-tracing) or full-wave methods. Asymptotic approaches have been widely investigated in literature [47, 48, 49, 50, 51]. A lot of the research using ray-approximation techniques considers very simplistic scenarios. Effects such as diffraction and multipath propagation are either neglected or taken into account under very idealistic environmental conditions, often in conjunction with a statistical component. One particularly interesting project in that regard, developing a ray-tracer to analyze large-scale scenarios based on realistic logistical use-cases, is presented in [52]. However, considering the relatively long wavelength $\lambda = 34.5\,\mathrm{cm}$ for UHF-RFID, the high-frequency approximation for this method introduces significant inaccuracies, especially for more complex scenarios containing objects comparable in size to the investigated wavelength [52]. As a result, full-wave techniques that solve Maxwell's equations with no fundamental approximation are of high interest. The analysis of UHF-RFID scenarios utilizing full-wave simulation has only been reported for individual small-scale applications [51, 53]. It is to be expected that full-wave methods will gain popularity as the feasibility of large-scale analysis increases due to the improved availability of computational resources in the form of High Performance Computing (HPC). Also, emerging trends associated with Industry 4.0 will promote the deployment of accurate geometrical models suitable for deterministic simulation. However, many questions remain unanswered regarding the feasibility and prerequisites to utilize full-wave methods for large-scale scenarios and the attainable accuracy considering the added informative value.

Another issue that needs to be considered when dealing with UHF-RFID is the susceptibility to detuning effects. Objects and materials in close vicinity to the tag have an impact on antenna characteristics and, therefore, can drastically degrade overall tag performance [54, 55]. Current literature considers read range as one of the major quantities to evaluate tag performance [21, 45, 56]. As the read range is often just computed under ideal free-space conditions, this quantity is not applicable for predicting performance in realistic environments. Previous work investigates the tag performance degradation induced by nearby materials merely experimentally by performing time-consuming infield trials [57, 58], or analytically for simple use-cases, introducing the term gain penalty [43, 54]. Further research combines analytical approaches with electromagnetic field-solvers to investigate a wider range of surface materials, eliminating the requirement to determine the gain penalty manually [59, 60]. As tags are adhered to a broad range of materials for various applications, the organization GS1 defined a grading methodology and test procedures for tagged-items to specify tag performance under realistic in-field conditions [61]. Besides obvious downsides like the manual effort necessary to perform the specified procedures, expensive measurement equipment and an anechoic chamber are required. An efficient rating method based on unambiguous quantities to assess the reliability of a specific tagged-item, considering the decrease of harvestable power and the alteration of the radiation pattern, is clearly lacking.