60 GHz Wireless Connectivity for an Automated Warehouse

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Contributor: Rahul Gulia, Abhishek Vashist, Amlan Ganguly, Clark Hochgraf, Michael E. Kuhl

The fourth industrial revolution, often referred to as industry 4.0, envisions a technological transformation in industries, primarily centered around automated manufacturing. This transformation encompasses automated material handling, facilitated by smart interconnections among components, and the integration of artificial intelligence (AI) into production facilities.

Keywords: automated warehouse ; industry 4.0 ; 60 GHz propagation models ; SINR heatmaps

1. Introduction

The fourth industrial revolution, often referred to as industry 4.0, envisions a technological transformation in industries, primarily centered around automated manufacturing. This transformation encompasses automated material handling, facilitated by smart interconnections among components, and the integration of artificial intelligence (AI) into production facilities. Erboz [1] highlights the potential for enhancing efficiency in smart industries through self-monitoring systems. The convergence of machinery and the internet of things (IoT) empowers smart industries to autonomously analyze and diagnose issues within their operations. In the context of a smart warehouse, this entails the integration of multiple IoT sensors with automated forklifts, drones, and other mobile devices. To realize this fundamental shift in smart industrial environments, innovative wireless connectivity is imperative. Such connectivity should offer high bandwidth, flexibility, intelligence, speed, security, and low latency. Effective connectivity is pivotal across the entire supply chain, from production stations to customer orders, encompassing warehousing and delivery. It plays a pivotal role in ensuring the seamless delivery of consumer goods. Consequently, to enhance the operational efficiency of a warehouse, robust wireless connectivity is a prerequisite for the successful transition from a human-operated warehouse to an automated one.

Sophisticated path planning models have been developed to enhance the performance of autonomous material handling agents (AMHAs) within intricate warehouse environments, with the aim of improving delivery systems, as referenced in [2][3]. AMHAs represent autonomous forklifts or vehicles employed in smart warehouses, specifically designed for efficient material transport within various warehouse sections. When these transport vehicles, known as AMHAs, are operational in a smart warehouse, they are tasked with autonomous navigation. This entails the meticulous detection, prediction, tracking, and planning of paths, particularly in the presence of other autonomous vehicles operating in close proximity, as discussed in [4][5]. Such coordination requires extensive information exchange among AMHAs, necessitating the presence of robust wireless connectivity, as emphasized in [6].

The Federal Communications Commission (FCC) has designated an unlicensed spectrum ranging from 57 to 64 GHz for wireless communications. Within this 60 GHz millimeter-wave (mmWave) band, there exists significant potential for delivering exceptionally high speeds and robust channel capacity, catering to line-of-sight (LOS) as well as nLOS applications. The remarkable performance attributes of the 60 GHz band make it well suited to meet the connectivity demands of smart warehouses, thereby enhancing the performance of AMHAs and facilitating secure multi-tasking operations. Deployed alongside advanced antenna systems, this band leverages its distinctive propagation characteristics, including high oxygen absorption, excellent immunity to interference, heightened security, and frequency reuse, as elucidated in [7]. However, it is worth noting that mmWave frequency bands are susceptible to increased penetration and diffraction losses compared to lower frequency bands. Consequently, directional transmission becomes a critical feature within the 3rd Generation Partnership Project (3GPP) 5G new radio (NR) standard. In response, 3GPP has redesigned the antenna systems for mmWave frequency bands, with a focus on beam management, as detailed in [8][9], as well as beam measurement to support directional communication, as discussed in [10]. The intrinsic characteristics of the 60 GHz band, coupled with these advancements, make it capable of delivering a high quality of service (QoS) in smart industrial environments that rely on numerous machine-to-machine (M2M) communications and IoT sensors.

2. 60 GHz Wireless Connectivity for an Automated Warehouse

Channel modeling serves as a foundational element in the design of efficient wireless communication systems, and there has been notable research activity in this realm at the 60 GHz frequency band. One noteworthy endeavor involved obtaining real-world data through the use of a 60 GHz channel sounder to explore the application of the multiple-input multiple-output (MIMO) technique within indoor environments, as documented in [11]. The enhancement in multi-hop indoor wireless connectivity was achieved through the implementation of a diversity reception scheme, as discussed in [12]. Another innovative approach leveraged the physical characteristics of the uniform planar array (U-PA) and 2-dimensional discrete Fourier transform (2D-DFT) to introduce a novel channel estimation scheme tailored for 60 GHz massive MIMO systems, as outlined in [13]. Effectively transmitting multi-gigabit-per-second (Gb/s) customer data within a 60 GHz indoor communication system involved the application of various modulation schemes, as detailed in [14]. Furthermore, network performance within the 60 GHz frequency band was investigated in a smart warehouse context, without human intervention. This encompassed a comprehensive study of multipath components originating from metallic structures and various storage materials surrounding the access points (APs) and AMHAs, as elucidated in [15]. They conducted an extensive investigation into multipath components to discern the influence of metal frames within this dynamic network context, drawing comparisons between the 60 GHz and 5 GHz bands. However, this work does not demonstrate connectivity with fine-grained heatmaps.

In [16], channel characteristics were studied in a real warehouse environment at 2.4 GHz and 868 MHz to guarantee flexible and reliable connectivity in dynamic large-scale industrial applications, especially for connected warehouses. In [17], a 5G system architecture in smart factories was presented, focusing on ultra-reliable use cases at 28 GHz and 60 GHz. The study included channel modeling, ray tracing simulations, and a frequency comparison to highlight the potential of 60 GHz channels for reliable communication in industrial settings.

In [18], the manuscript delves into the propagation characteristics at 60 GHz within indoor environments, employing the shooting and bouncing ray tracing/image (SBR/IM) method. In [19], the analysis encompasses both LOS and nLOS scenarios, addressing omnidirectional path loss models and received power. Furthermore, a propagation measurement campaign at 60 GHz was conducted within an indoor office setting, leveraging a vector network analyzer (VNA) to exploit multipaths generated by various indoor elements, such as people, furnishings, and obstructions. In [20], the study encompasses 60 GHz channel sounding and throughput measurements, focusing on nLOS path characteristics in an indoor residential environment. In [21], the investigation extends to studying outdoor-to-indoor (O2I) penetration losses for frequencies ranging from 28 GHz to 73 GHz across various scenarios, utilizing the NYUSIM model. It scrutinizes the impact of diverse building materials (including glass, wood, IRR glass, and concrete) and antenna properties in O2I scenarios. In [22], for indoor-to-indoor and O2I scenarios, an office building was utilized to analyze penetration losses across different incident angles, underscoring the substantial penetration loss experienced by a 60 GHz channel in indoor environments. Additionally, in [23], the terragraph sounder (TG) channel sounder tool, developed by META, serves as a practical instrument for measuring physical channel properties. The investigations conducted encompass both LOS and nLOS scenarios, evaluating path loss and signal-to-interference-plus-noise ratio (SINR). To enhance the understanding of indoor propagation, a ray tracing simulator was discussed, leading to the creation of a data-driven indoor propagation model for multiple frequencies, as described in [24]. This model was subsequently employed with a convolutional encoder–decoder to predict path loss in uncharted areas of indoor environments.

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