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AI-Enhanced Digital Twin Simulations for Optimized Wireless Communication in High-Density Construction Sites

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Agenda

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- Introduction
- Problem Statement
- Proposal
- Progress
- Conclusion

Introduction: Challenges Faced by Construction Sites in Urban Areas

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- In recent years, urban redevelopment and high-rise construction have rapidly intensified, leading to unprecedented site density.
- At the same time, reliable on-site **communication infrastructure has become crucial** for improving operational efficiency, safety, and remote site management.
- In reality, steel structures and temporary environments often cause communication bottlenecks, resulting in delays in progress sharing and increased reliance on physical inspection, significantly reducing productivity.
- To address these challenges, we propose a communication optimization approach leveraging AI and digital twins and **create dataset.**

Introduction: The Importance of Communication in Construction Sites

- **Scale and complexity of construction sites**
  - Large-scale construction sites involve a high number of workers and span wide physical areas.
- **Crowded workforce and dispersed activity zones**
  - Miscommunication can immediately lead to operational errors or safety incidents.
- **Necessity of communication infrastructure**
  - Reliable communication is essential for ensuring safety and improving operational efficiency.

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Coordination among workers

Real-time information sharing enables smooth division of labor and prevents coordination errors, even across distant locations.

Electronic sharing of progress

Digital blueprints allow both on-site workers and managers to share up-to-date structural and progress information during construction.

Remote site management (e.g., via video calls or live streaming)

Integrated access to video, location, and progress data allows for fast and accurate decision-making without being physically present on site.

Challenges Without On-Site Communication (1): Inefficiency Due to Physical Movement

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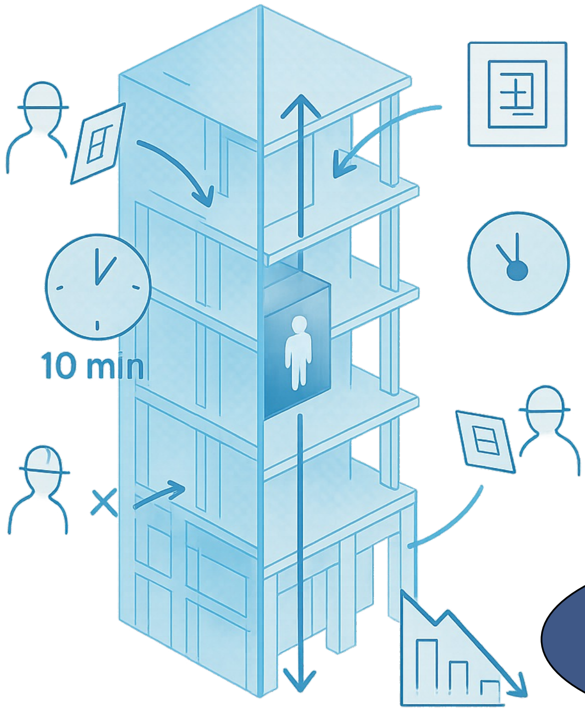
- Without communication tools, **all confirmations require physical movement**
  - Workers must travel between floors (e.g., by elevator) to give or receive instructions
  - A single exchange can take over 10 minutes, and the cumulative loss significantly reduces work efficiency

Confirmation means movement

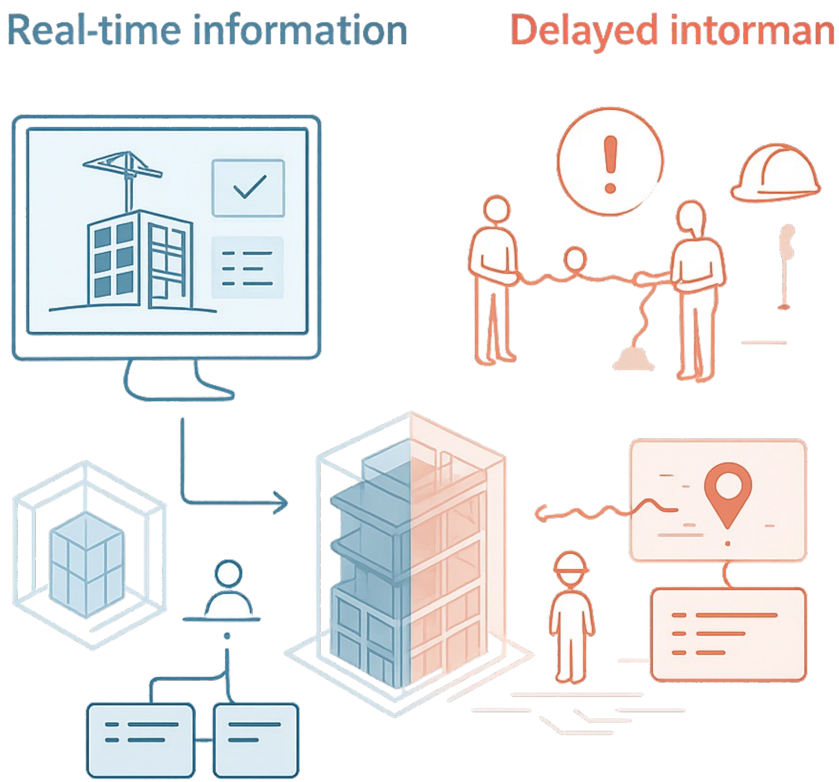


Increased labor costs

Reduced productivity

Challenges Without On-Site Communication (2): Delayed Information Sharing

- Poor communication leads to delays in information delivery

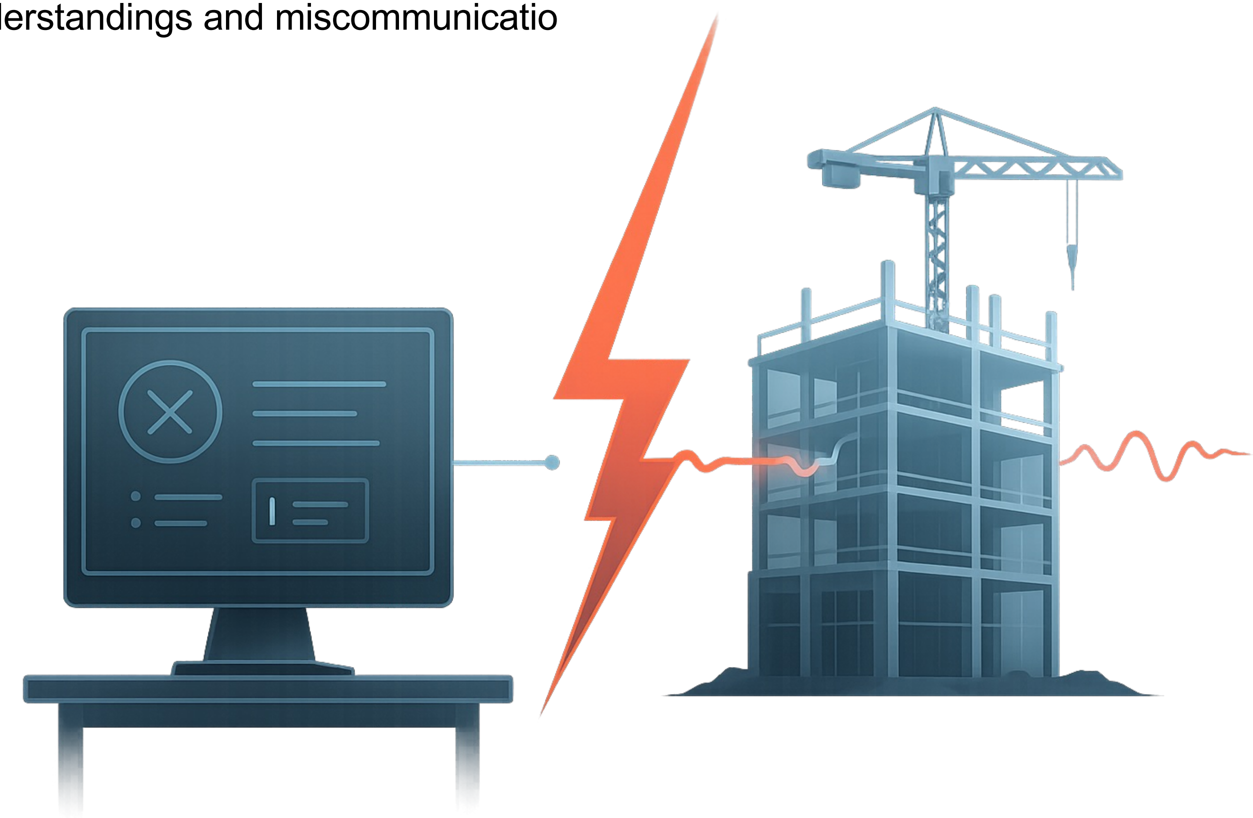


Workers do not receive the latest updates at hand

Real-time progress tracking becomes impossible

Challenges Without On-Site Communication (3): No Remote Visibility

- Site status cannot be monitored from the office or other locations
- Increased risk of misunderstandings and miscommunicatio



Problem Statement

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- In large and complex construction sites, real-time communication infrastructure is essential for operational efficiency, safety, and quality control.
  However, communication environments on-site are often unstable or insufficient.
  As a result, the following issues frequently occur:
  - Workers must physically move across the site for confirmation or reporting
  - The latest blueprints and progress information are not shared in real time, leading to errors
  - Remote supervisors cannot grasp the on-site situation, causing misinstructions and delays

- These inefficiencies and risks are part of daily operations.
  In short, the lack of communication infrastructure is the root cause of many challenges in site management.

Proposed Approach: Overview

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Problem

- The lack of communication infrastructure significantly impacts efficiency, safety, and quality in construction sites.
- Temporary Wi-Fi setups and visual inspection are insufficient countermeasures.

Proposal

- We propose a method to simulate the optimal placement of communication infrastructure by virtually reconstructing the site using a digital twin.

Method

- Evaluate the placement and coverage of communication devices in the reconstructed virtual space
- Account for attenuation and reflection caused by obstacles and materials (e.g., steel frames, walls, floors)
- Visualize coverage areas and explore communication layouts with minimal blind spots using the digital twin

An affordable method for creating digital twin datasets is essential to realize this approach.

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We introduce the process from dataset creation to full digital twin construction.

Digital Twin Construction Workflow

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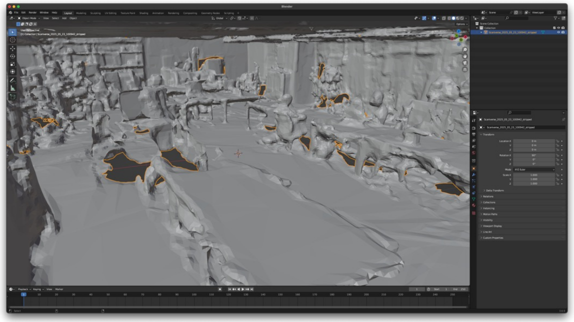

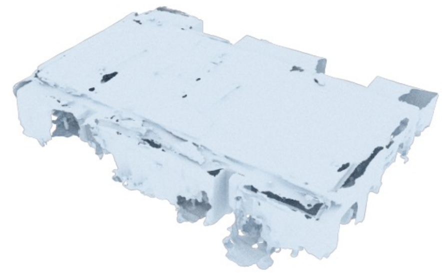

LiDAR scanning of the construction site
Acquire point cloud and mesh data of the environment

Conversion using Blender
Convert the scanned data into Mitsuba XML format and organize material and structural properties

Simulation with Sionna
Import the virtual scene into Sionna and simulate communication performance based on radio propagation characteristics

LiDAR

Blender 3D icon by Icons8

NVIDIA

Preliminary Experiment: Digital Twin-Based Simulation

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- Imported a real construction environment into a digital twin
- Performed radio wave propagation simulation within the virtual space
- Compared the simulation results with actual propagation measurements using **local 5G signals**

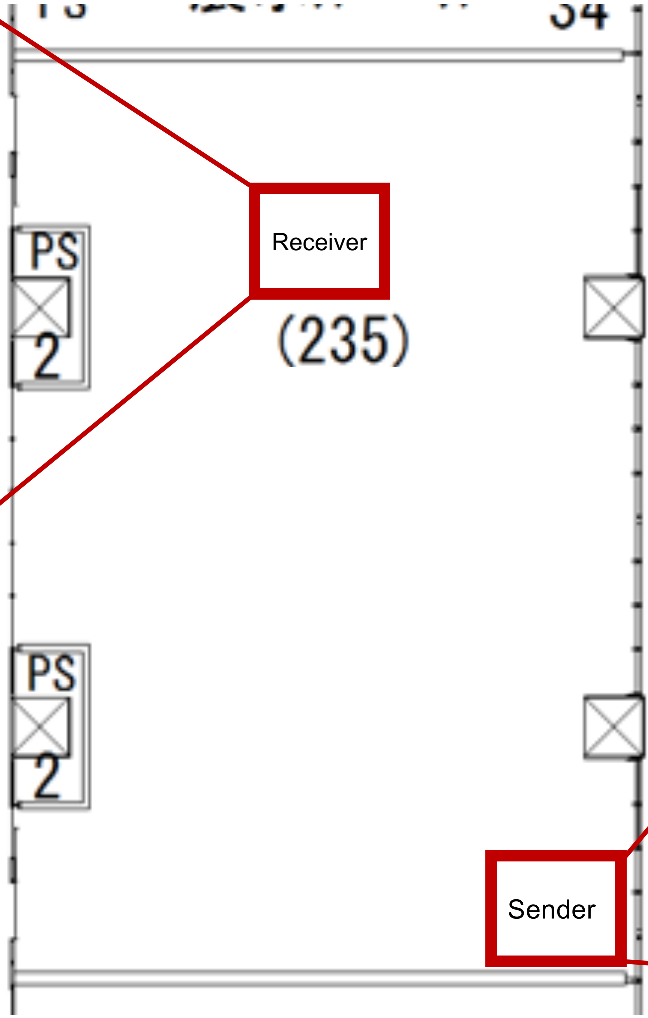
- **Evaluation Metric:**

Metric	Description
RSRP (Reference Signal Received Power)	Used to assess the absolute scaling consistency between Sionna output and real-world measurements.
RSRQ (Reference Signal Received Quality)	Helps evaluate the validity of Sionna’s noise and interference modeling.
SINR (Signal to Interference plus Noise Ratio)	Verifies whether Sionna correctly models the structure of signal vs. interference.

Measurement Environment

Receiver
K5G-C-100A

https://www.kyocera.co.jp/prdct/telecom/office/iot/products/k5g-c-100a.html



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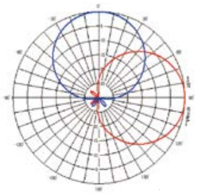

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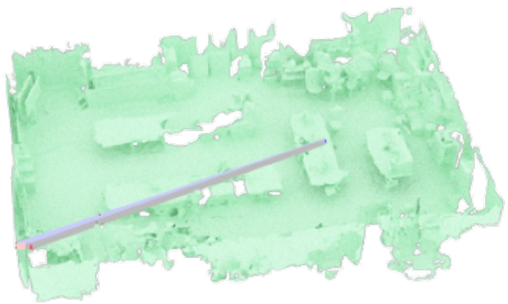
Simulation on Sionna

- Mesh data obtained via LiDAR scanning was converted using Blender into a format compatible with the Sionna simulator
- Transmitter and receiver positions were placed in the digital twin to match their actual locations in the real environment

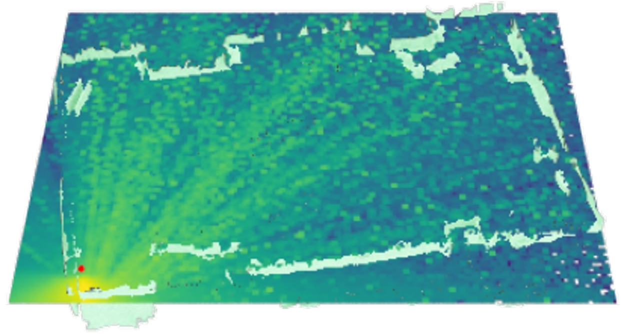
Visualization of Propagation Paths in the Digital Twin

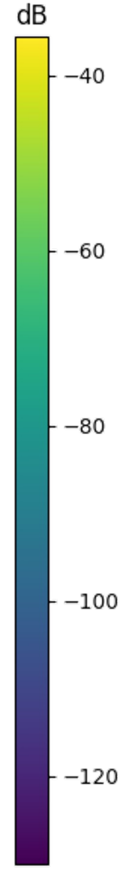


Using the constructed 3D scene, Sionna was used to visualize the radio propagation paths (LoS/NLoS) between transmitter and receiver.

These paths are overlaid onto the digital twin, allowing intuitive understanding of signal obstruction and reflection caused by structural elements.

Spatial Gain Distribution by Sionna





For each point in the scene, the directional antenna gain from the receiver's perspective was mapped on a dB scale.

This visualization enables assessment of how the spatial structure affects signal reception performance.

Comparison Results

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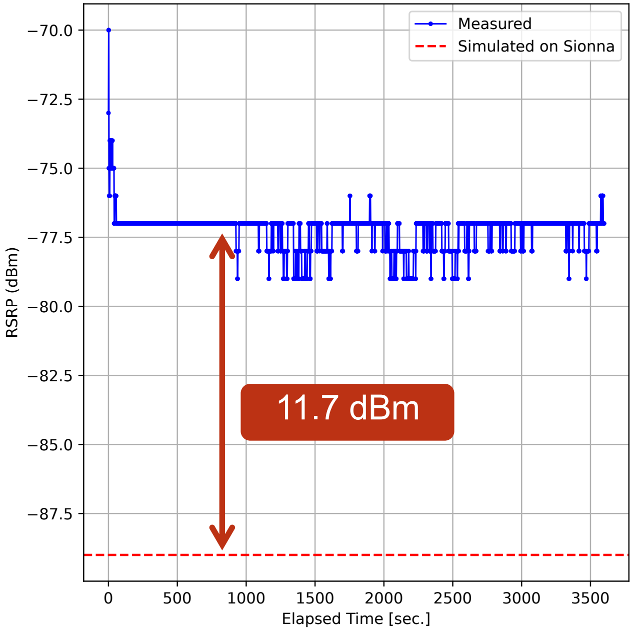
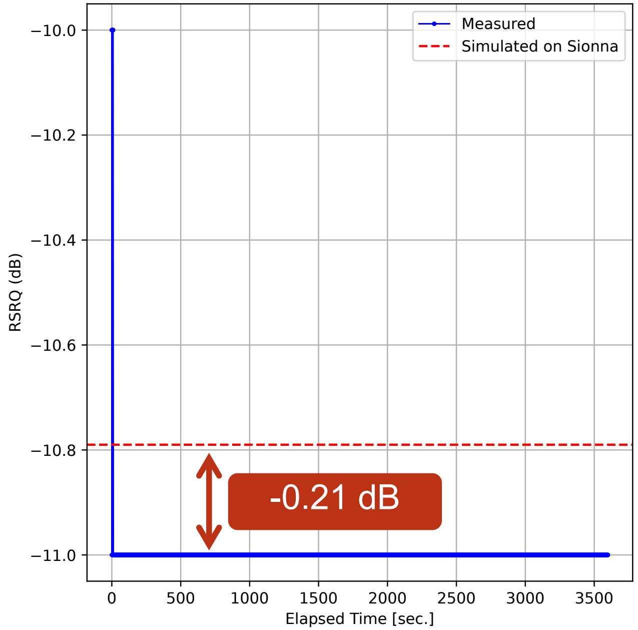
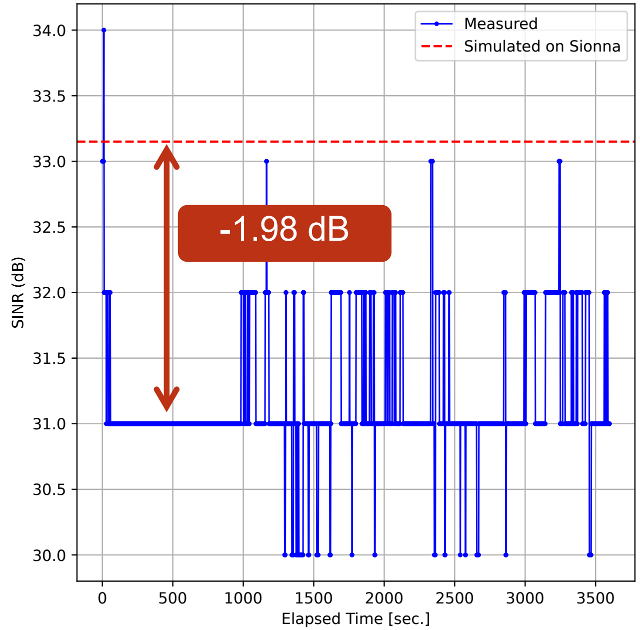
RSRP



RSRQ



SINR



- RSRP showed a difference of about 11.7 dBm, but this is only a small power gap (nanowatt level) and acceptable for practical use.
- Differences in RSRQ and SINR were within 0.2 dB and 2 dB, showing good match in noise and interference modeling.
- These results suggest that Sionna accurately reflects real-world conditions and can be trusted for future evaluations and applications.

Conclusion

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- **Importance of Communication in Construction Sites**
  - Urban redevelopment and high-rise projects are increasing site density.
  - Stable communication is essential for efficiency, safety, and remote management.
  - Steel structures and temporary setups often cause bottlenecks in progress sharing and task coordination.

- **Proposed Approach and Contribution**
  - Simulated optimal communication placement using a digital twin.
  - Visualized coverage considering material and obstacle effects to eliminate blind spots.
  - Presented a low-cost digital twin workflow: LiDAR → Blender → Sionna.

- **Evaluation and Insights**
  - RSRP showed a ~11.7 dBm gap, but the power difference was minimal (nanowatt level) and acceptable.
  - RSRQ (0.2 dB) and SINR (2 dB) showed strong consistency with real-world results.
  - Sionna's structural and interference models can reliably reflect physical environments, supporting future applications and accuracy improvements.

Acknowledgment

- We would like to thank **ITU** for the cloud credits generously provided to support our team during this project!