WHITEPAPER

AUTOMATION.COM
A subsidiary of the International
Society of Automation

Wireless Deployment Challenges in Construction: A 5G Strategy

A research report by Richard Candell, Mohamed Kashef (Hany),
Jing Geng, and Karl Montgomery of the Communications
Technology Laboratory, National Institute of Standards and
Technology (NIST), Gaithersburg, MD, USA.

Wireless Deployment Challenges in Construction: A 5G Strategy

Richard Candell, Mohamed Kashef (Hany),
Jing Geng, and Karl Montgomery

Abstract

In the construction context, integrating 5G networks presents numerous challenges. This article explores deploying wireless communication networks within construction projects, introducing a comparison approach to assess deployment difficulty at each project phase. Additionally, we outline a strategic blueprint for a specialized testbed to evaluate 5G network performance in real-world construction conditions. This controlled environment mimics actual construction scenarios. We aim to offer valuable insights into the unique challenges of implementing 5G in construction, emphasizing untapped research opportunities. The discussed structured approach evaluates network performance, addressing wireless communication complexities in the industry.

INDUSTRIAL WIRELESS AND THE CONSTRUCTION INDUSTRY

Construction sites are areas of land where construction work takes place. Construction sites may include activities such as demolition, filling, and grading of land and the erection of structures such as buildings, bridges, and other improvements for future human activities. Construction sites, especially industrial or commercial construction, can be highly dynamic environments characterized by heavy machinery, tools, and people in constant motion. Activities within the construction environment must be coordinated and monitored to efficiently achieve daily goals, monitor the health of equipment, monitor the ambient environment, and assure the safety of the people working within the construction environment. Future construction sites will include automated vehicles, remote control of heavy machines, numerous sensors, surveillance cameras,

---

Published May 2024 by Automation.com, a subsidiary of International Society of Automation (ISA). Authors Richard Candell, Mohamed Kashef (Hany), Jing Geng, and Karl Montgomery are with the *Communications Technology Laboratory*, National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA.

safety alarms, and emergency stops. Reliable and rapid communication is a key requirement to achieve coordination and safety objectives, and due to the highly mobile and dynamic nature of the construction site, wireless emerges as the primary form of communication for these scenarios. In some construction scenarios, a hybrid deployment of wired and wireless technology is indicated, yet wireless communications will lead due to its untethered nature and resulting perceived ease of deployment. While it is possible to communicate to a remotely controlled bulldozer without wireless, such a scenario is impractical as having cables run throughout the work zone presents reliability and safety concerns. Therefore, wireless communications present itself as the lead communications mode in the construction industry, and, given the locale and highly heterogeneous mix of applications in construction, the 5G network becomes a lead contender in supporting such a mix of applications.

ARE ALL CONSTRUCTION SITES THE SAME?

Construction sites all have similarities that are unique to the construction industry. For example, most construction projects begin outdoors with the movement of terrain. Some remain entirely outdoors, and others change into mostly an indoor profile or a hybrid of the two because of the construction. Construction projects that begin with bare terrain require heavy machinery and ground personnel, and most modern construction projects employ some degree of automation, remote machine operation, video surveillance, and voice conferencing and always include human safety.

Communication is a key element of coordination, tracking, and safety in all cases. It is important to note the difference between a completed construction project and an ongoing one. An active construction project requires that the communications network supporting construction activities adapt to the project itself, whereas a completed construction project will have a communications network that supports the intended operation of the enterprise within. This work focuses on the wireless networks supporting an active construction project from inception to completion.

Construction projects may be classified into three main categories: Commercial, Industrial, and Public. Table I lists several examples of our three classifications of use cases. It is worth noting that airports are divided into the commercial space and the runway. Arguments could be made to keep the two together as one project example; however, to remain true to the division of commercial space and public works, we maintain the two as separate entities. Indeed, a runway, similar to a road or railway, is distinctly different from large spaces such as an airport.

TABLE I: Examples of Construction Projects

Industrial	Commercial	Public
Assembly Plants	Shopping Centers	Roads
Oil Refineries	Residential Buildings	Bridges
Water/Wastewater	Tall Office Buildings	Railways
Tank Farms	Flat Office Buildings	Ports & Harbors
Power Generation	Warehouses	Runways
Wood and Chip Yards	Hospitals	Schools
Space Ports	Stadiums	Tunnels
Underground	Airports	Garages
Food Processing		

Industrial: Industrial construction projects, in contrast, include the building of manufacturing and assembly facilities, oil refineries, chemical plants, tank farms, agriculture, and water/wastewater treatment facilities. Industrial facilities are usually composed of open, graded terrain with industrial larger open or closed structures made of steel supports with a sheet metal roof and walls resting upon a concrete slab. Industrial projects are usually characterized by large rectangular spaces where radio signals may propagate openly. For example, a large pulp and paper chip mill will require extensive civil engineering work to grade and level the industrial site to provide ground for the storage of raw and processed materials and the installation of large machinery. The machinery within the chip mill will tend to be large and the spaces more open. Inside communications would be required at times, yet the scale and openness of the construction site will mostly remain.

Commercial: Commercial construction projects include the building of warehouses, residential spaces, office spaces, airports, and other projects used for private or public use. Due to the architectural design of these spaces, radio signals will often have difficulty propagating through these spaces as construction progresses. The materials in commercial construction usually have a mixture of concrete, steel, plastics, and wood products and tend to contain more absorptive materials at times. Commercial construction sites will become more cluttered and closed off as the construction progresses as spaces are created, and absorptive materials are laid.

Public: Finally, public construction includes roads, bridges, railways, and public works. Public construction projects will vary in their characteristics and may resemble either a commercial project or an industrial project, depending on the nature of the construction. Roads and railways will often be long open spaces and remain that way throughout construction. In contrast, a school will begin with open space and steadily progress to have many enclosed spaces within reinforced concrete construction. A public water works facility will have indoor and outdoor components and a mixture of concrete and metal, which is not necessarily reminiscent of any other industrial type of construction.

CONSTRUCTION ZONE CHANNEL IMPACT FACTORS

While considering the many different types of construction environments, during our investigation, we discovered that the key elements affecting the viability of a construction network simplified to three principal considerations relating to the physical environment. These considerations include the geometry of the work zone, the number of materials for the walls being constructed, and the types of materials used to construct floors and ceilings. Much research has been and is currently being undertaken to characterize the propagation characteristics of construction spaces primarily focusing on the finished industrial spaces such as in [1]. While it is important to understand all of the impacting factors of a work zone, we must be careful to capture the factors such that they minimally overlap in their impacts on wireless system performance. This approach is synonymous with maintaining the linear independence of variables in a system of linear equations, and we attempt to maintain this independence throughout this work. We should also note that the focus so far has been on the physical environment, yet construction has other factors that can otherwise degrade the performance of the construction network such as radio frequency interference from welding, unshielded power electronics, and co-existing network traffic. In the following sections, each attribute has been assigned a value such that the assigned value may be directly mapped to a wireless channel degradation impact of *Low*, *Moderate*, or *High*.

A. Work Zone Geometry

The geometry of a work zone indicates the relative size and shape of the physical volume inside which the construction activities will take place. A larger work zone requires a more powerful wireless network, and the shapes and general clutter within the vicinity of the work zone will determine the ease of getting a wireless signal into the work zone from the outside.

The work zone geometric factors include the area and exterior radio frequency (RF) penetrability of the zone.

Area of the Work Zone: All work zones are three-dimensional geometrical volumes constrained by the area of the construction site and the height of the objects within the work zone including the object being constructed and the machinery utilized. The work zone *area* is defined as the horizontal geometrical area of the work zone along the surface of the construction terrain (i.e., usually Earth's surface). Not all work zones are the same. Work zones vary by the construction class, be it a roadway or a tall building. A tall building usually begins with one or more city blocks, and a city block is approximately 2.5 acres or 10,000 m^2. An average airport runway typically runs 45 m by 3 km. In contrast, an oil refinery is an enormous construction of several hundred football fields such that the typical land area of a refinery becomes 2.5 km^2. While all of these types of construction zones are large and complex, the size difference of an oil refinery is vastly different from that of an office building. Thus, the range, power, and subsequent licensing requirements differ vastly. Each work zone area (i.e., its size) is attributed as *Small* (under 10,000 m^2), *Medium*, and *Large* (greater than 2.5 km^2).

Height of the Work Zone: The height of the work zone can range from several meters for a typical roadway or warehouse to several hundred meters for a tall building. While the height of the work zone is important, to maintain independence, we have captured the impact of height in other variables to follow.

Exterior Penetrability: The ease of getting an RF signal into a structure under construction is noted as its exterior penetrability. Exterior penetrability indicates the ability of an RF signal to enter into the interior of the work zone. For example, at the beginning of a green field construction project, this factor will indicate unencumbered propagation as nothing has been erected; however, as the work progresses, structures are built, and the penetrability impact of the factor increases. In a high-rise building, as the steel structure is built and a center concrete structure is constructed, passing a signal to the interior becomes more difficult. Once the exterior walls are affixed to the structure, passing a signal through those walls becomes more impactful. Exterior penetrability has been parameterized as *Open*, *Somewhat Blocked*, and *Blocked*.

B. Interior Walls

Interior walls play an important part in how well wireless signals propagate from one room to the next. This area of research has been well-studied for home and office buildings. Finished industrial spaces have also been studied relatively well regarding the reflectivity of materials and the level of resonance within a particular industrial space. In construction, the types and materials of the wall structures are similar and are presented in [2]. Principal factors for a wall include transparency, reflectivity, and numbers. Maintaining variable independence, we omit other well-known factors, for example, absorption, as it is dependent on transparency and reflectivity such that total power is the sum of reflected, absorbed, and permeated powers. We consider these factors from the more practical engineering perspective of bulk power transfer rather than field strength and other measures.

Wall Transparency: The ability of a wall to allow RF power to pass from one side to the other is its transparency. Transparency is considered as *High* (<5 dB of power loss), *Medium*, and *Low* (>22 dB of power loss).

Wall Reflectivity: The tendency to reflect RF power back into the environment rather than to permit power to pass through it or absorb it is its reflectivity. A highly reflective environment will resonate, whereas a low reflective environment will tend to attenuate. It is typically measured in decibels of attenuation of incident power and is dependent on the material and angle of incidence, yet we consider reflectivity as an average value. Reflectivity can be helpful or hinder the performance of a wireless network. For later impact analysis, we assume that the reflections will lead to resonance causing destructive multi-path, yet this is not always the case. The values of reflectivity are given as *Low* ($< 20\%$), *Medium*, and *High* ($> 50\%$).

Number of Walls: The number of walls has the apparent impact of additional attenuation on a signal. Many highly transparent walls will accumulate to a high loss of power as the number of walls grows. A highly attenuating material such as reinforced concrete will significantly attenuate a wireless signal with a single 10 cm wall and with two walls, almost completely. We consider the cases of *No Walls*, *One Wall*, and *Two or More* as a progression of severity.

C. Floors and Ceilings

While interior walls divide horizontal spaces, floors and ceilings divide vertical spaces. The type of floors and ceilings in construction zones depends mainly on the class of construction undertaken. Many construction projects are single-story edifices, but many are multi-storied. Roofs and ceilings will impact to some degree the penetrability of outside signals to enter the work zone. Internally, ceilings will either reflect or absorb a wireless signal. Story dividers, *i.e.*, floors, may be built of wood, concrete, plate steel, and perforated steel. These vertical dividers inhibit signal propagation vertically as construction progresses. Some steel flooring, for example, in industrial spaces come in rectangular panels, that are perforated, grated, serrated, and galvanized. The propagation characteristics of this material both reflect and pass wireless signals and are highly dependent on wavelength. When considering floors and ceilings, we employ the same factors that we utilize for walls: Transparency, Reflectivity, and Numbers.

D. Impact Analysis of the Factors

Among the several construction project scenarios listed in I, the impact attributes for each scenario were assigned a value for three stages of construction: Early-Stage, Mid-Stage, and Late-Stage. We begin our analysis by making the assumption that the project begins with a "green field" or follows demolition thus exposing a green field. Demolition can be considered as beginning with an existing brownfield synonymous with a late-stage construction field. Early-stage construction indicates a green field or otherwise open environment that is clear of clutter, obstructions, or other channel-impacting variables. Middle-stage construction is characterized by the main structure for the project having been erected or in the process of being erected but still unfinished. Finally, Late-Stage construction is characterized by the most final product having been erected with most exterior elements, such as walls and windows being installed. Technically, communications deployment may begin at any stage of construction. In Table II, we illustrate the impact attribute assignments for each of the scenarios selected at each stage indicated.

It is interesting to note that, at the early stages, assuming green field construction, all of the scenarios begin with a relatively low wireless impact except moderate to large site geometries such as long or large work zones such as roads and rails, assembly, and oil refineries. Larger construction sites indicate larger transmission distances; hence, licensed band wireless technologies are indicated to accommodate the increased transmission power requirement to accommodate those distances. Of course, unlicensed band technologies work over larger distances but at reduced throughput. Such technologies would support the Industrial Internet of Things (IIoT) within the construction work zone, but it would not support the higher data rates needed for video, augmented reality, and remote-controlled operation of heavy machinery.

As construction progresses and structures are erected, the complexity of the work zone increases, as do the impact factors on the wireless channel, as shown in the radar plot of Fig. 1. From this figure, we can observe that the impact factor attributes of each construction project

TABLE II: Asserted Impacts to the Wireless Communications Channel in Construction.

		Public			**Commerical**												**Industrial**					
		Roads and Rails			Garages			Warehouse			Stadiums			Tall Office Buildings			Assembly			Oil Refinery		
	Attribute	E	M	L	E	M	L	E	M	L	E	M	L	E	M	L	E	M	L	E	M	L
Site Geometry	*Area*	◑	◑	◑	○	○	○	○	○	○	◑	◑	◑	○	○	○	◑	◑	◑	●	●	●
	Penetrability	○	○	○	○	◑	◑	○	◑	◑	○	●	●	○	○	◑	○	○	◑	○	◑	●
Walls	*Transparency*	○	○	○	○	◑	◑	○	◑	◑	○	◑	◑	○	◑	●	○	◑	●	○	◑	●
	Reflectivity	○	○	○	○	○	○	○	◑	◑	○	◑	◑	○	◑	◑	○	◑	●	○	◑	●
	Numbers	○	○	○	○	◑	◑	○	○	○	○	◑	◑	○	●	●	○	◑	◑	○	◑	◑
Floors & Ceilings	*Transparency*	○	○	○	○	◑	◑	○	○	○	○	◑	◑	○	●	●	○	●	●	○	◑	◑
	Reflectivity	○	○	○	○	○	○	○	◑	◑	○	◑	◑	○	◑	◑	○	●	●	○	◑	◑
	Numbers	○	○	○	○	◑	◑	○	○	○	○	◑	◑	○	●	●	○	○	○	○	●	●

Stages: Early (E), Middle (M), Late (L); Factors: ○ Low, ◑ Moderate, ● High

differ substantially with the wireless channel becoming increasingly difficult as each trace pushes toward the outer edge of the diagram. For example, a stadium having begun as a green field progressively becomes more challenging for a wireless system as steel structures and concrete are installed with the most challenging factor being exterior penetrability, which becomes a factor for external networks. This challenge poses an obvious research opportunity for construction. Similarly, the high-rise building becomes an increasingly challenging wireless environment as walls, floors, ceilings, and other structures are built, creating an increasingly harsh wireless environment.

If we then study the progressively more complex wireless channel environment, we can observe that the channel becomes evermore challenging by defining a channel impact score defined as the sum of all attributes for a particular construction work zone at a particular project stage, normalized by the maximum possible score. Using this approach, we have created a wireless channel impact score based on the attributes of the work zone that indicate the severity of the wireless propagation channel. Correlating this score to a spatial-temporal channel impulse

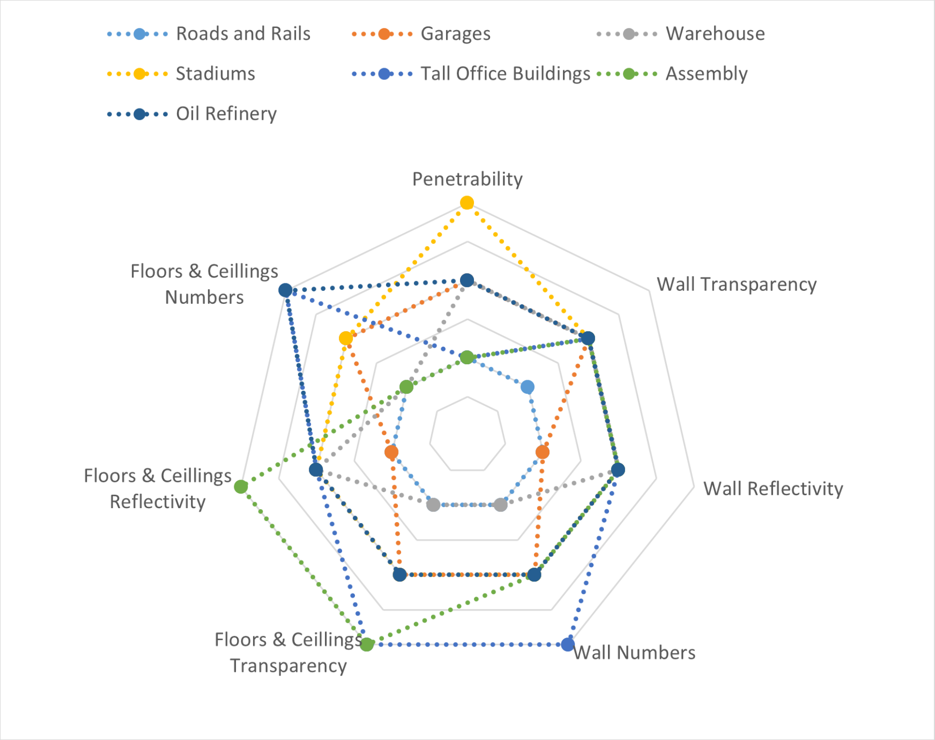

Fig. 1: Comparisons of Wireless Channel Impact Factors for Different Construction Projects.

response similar to those found in [3] is an important area of research. Fig. 2 illustrates the normalized impact score for each of the seven example construction areas that we have so far discussed. This scoring mechanism represents a basis by which wireless network performance for selected construction scenarios may begin to be evaluated taking into consideration the reliability and latency requirements of the use cases supporting the said scenario and the 5G service classes used to support those scenarios.

5G IN CONSTRUCTION

5G Service Categories

Why consider 5G? Its versatile wireless technology accommodates diverse communication needs and deployment structures, making it suitable for various construction applications. While other wireless solutions are viable, we opt for 5G stand-alone (SA) private networks for several reasons. Firstly, 5G's built-in determinism, leveraging time and frequency diversity, supports channel resource allocation. Spatial diversity is enhanced with multiple-input multiple-output (MIMO) antennas, including massive MIMO systems for optimal device support and beam

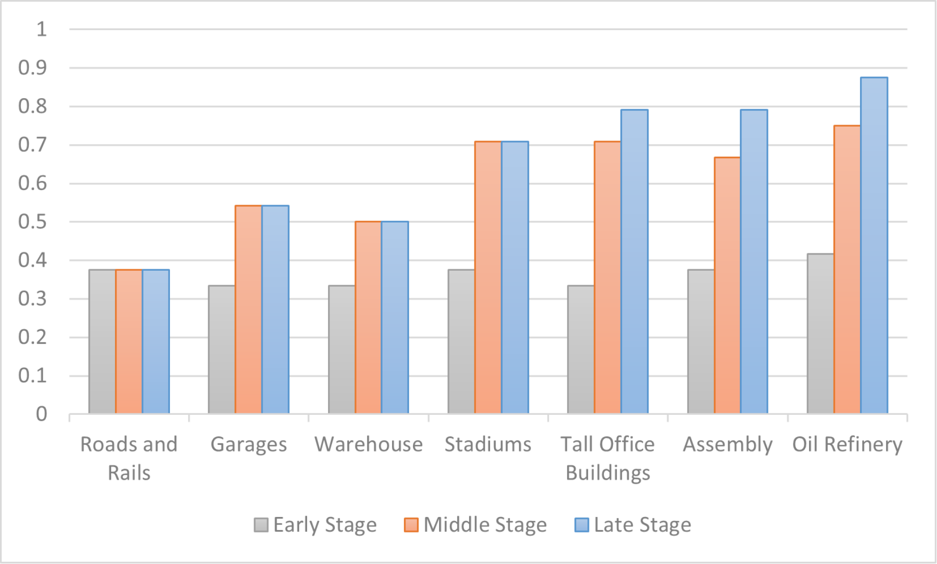

Fig. 2: Normalized Total Channel Impact due to Construction Site Factors.

directionality, ensuring a higher quality of service. Secondly, 5G offers Quality of Service (QoS) support and flexibility in enforcing reliability policies through different service classes and network slicing. Additionally, it supports licensed and unlicensed deployment options, expanding available RF bands, and is progressing towards supporting various industrial protocols for improved interoperability in automation systems.

There are three main 5G service categories: enhanced mobile broadband (eMBB), massive machine type communication (mMTC), and ultra-reliable low-latency communication (URLLC). A new service class, Reduced Capability (RedCap), is emerging, offering reduced capabilities to that of URLLC class with less stringent latency and reliability requirements, making it more cost-effective and energy-efficient. URLLC, with 1 ms latency and reliability exceeding 99.999%, is particularly relevant for construction applications. However, considering cost and battery life, RedCap may become a preferred choice for some applications. URLLC achieves low latency by allowing transmissions to interrupt lower-priority ones through the mini-slot concept and periodic grant-free transmission. URLLC can support connectivity for automated guided vehicles, mobile robots, teleoperated heavy machinery, and safety equipment in various construction scenarios.

The eMBB category, with peak data rates up to 10 Gbit/s, benefits high-data-rate applications like augmented reality and remote operation video feedback. The mMTC category, with a node density of up to 100 nodes/m^2, is suitable for massive wireless sensor networks, site asset management, and various monitoring applications. A 5G network is not confined to a specific service category, as these categories represent network performance limits from different perspectives. Generally, a 5G implementation can meet specific communication demands through QoS guarantees enforced by the user plane function (UPF) in the 5G core network.

5G Enabling Capabilities

Various 5G releases offer capabilities to meet diverse service category demands, including those vital for construction communication networks. Key features such as network slicing, QoS support, software-defined networking (SDN), and network function virtualization (NFV) enable dynamic resource allocation and separation of user and control plane functions. Network slices, tailored to specific QoS requirements, span core network to radio access network (RAN) domains, while multi-access edge computing (MEC) places computing resources closer to the RAN and within construction sites for low-latency applications.

Specific capabilities introduced for industrial wireless support in 5G include 5G-time-sensitive networking (TSN) integration and Open Platform Communications (OPC) Unified Architecture (UA) support. In release 18, 5G-TSN integration achieved centralized TSN implementation, ensuring time synchronization and timely data delivery through traffic shaping and scheduling. The generic precision time protocol (gPTP) facilitates time synchronization between nodes. Additionally, OPC UA (IEC 62541-1) standardizes data communications in industrial automation, enabling vendor-neutral interoperability. Integrating 5G with OPC UA allows construction applications to operate over 5G, facilitating coexistence and communication with legacy systems. Interaction with OPC UA devices can occur through TSN middleware or directly via the network exposure function (NEF) introduced in release-16.

5G Deployment Options

There are two main deployment approaches from the point of view of integration to a public 5G network. The isolated SA deployment is not integrated into the public network, and all the 5G network components are separated from the public network. The other deployment approach is the public network integrated (PNI) 5G networks where industrial 5G non-public network (NPN) share some resources with a public 5G network. Shared resources are as follows: 1) a shared public access network where a publicly available RAN is connected to an industrial 5G non-public network (NPN) core residing in a private cloud; 2) a shared public access network

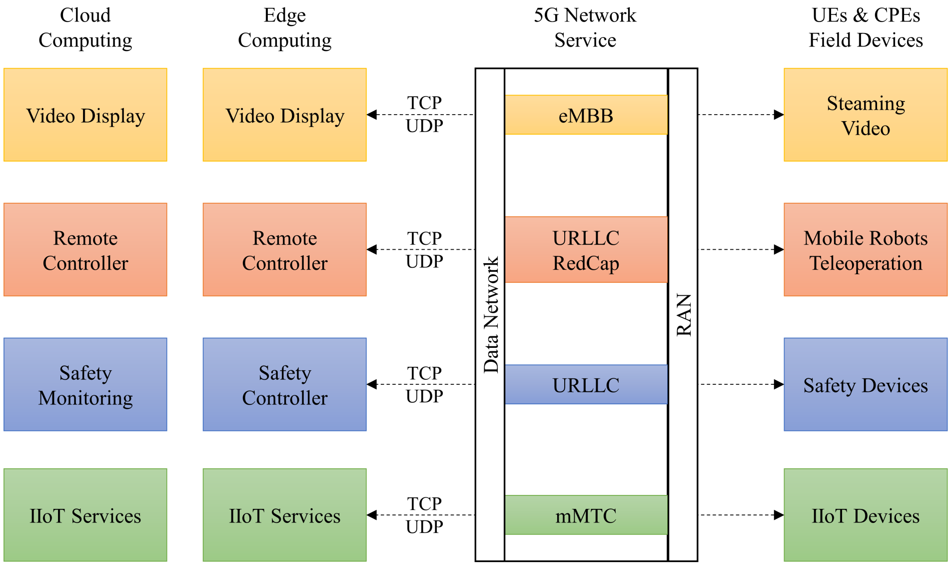

Fig. 3: 5G Service Classes for Construction Scenarios.

where time-critical control plane functions and UPF functions reside on the local premises (edge) to assure low latency communications; or 3) a 5G network entirely hosted by the mobile network operator (MNO).

Although isolated deployments require high capital expenditure for the procurement and setup of equipment, they allow complete control over the configuration and deployment of the industrial 5G network. Additionally, it offers the highest level of data ownership, reliability, privacy, and security. This is mainly required for mission-critical applications such as motion control, augmented reality, and low-latency closed-loop control. However, the main influencing factor for low-latency applications is the location of the UPF that performs packet forwarding and QoS enforcement in addition to the RAN location. Isolated and PNI deployments, placing RAN and UPF within industrial premises, are ideal for low-latency applications. Shared-resource deployment options align better with use cases needing wide service area coverage and public network interconnection, like remote control, monitoring, and asset management.

5G Uses Cases in Construction

Utilizing the various service categories, enabling capabilities, and deployment options, many use cases become available to support the construction industry. As shown at the top of Figure 3, streaming video is the first on the list that would utilize the eMBB service category. Streaming video enables situational awareness of construction activities as well as security monitoring of the work zone. Additionally, streaming video has become an essential part of the teleoperation of machinery and drone-based inspection. Streaming video is, therefore, an essential component of most, if not all, construction projects, and thus the eMBB service category must be supported. Streaming high-definition (HD) video at a rate of 60 frames per second equates to a minimum of 5 Mbps with a peak bit rate of 10 Mbps. The high video quality may seem excessive, but it's likely necessary for teleoperating heavy machinery around people in the work zone and drone-based inspections. Furthermore, several of these activities operating concurrently would have a multiplying effect on the 5G system.

Teleoperation and mobile robotic platforms, apart from video-based observation, require a service category that guarantees latency and reliability targets. As an example, teleoperation requires that control messages reach the vehicle being controlled by recurring deadlines on the scale of milliseconds. Every type of remotely operated machine is different, therefore, the service category may be either URLLC or RedCap. A teleoperated front loader requires the ability to move forward, and backward, turn left and right, raise and lower its bucket, and control the orientation of its front, rear, and side cameras. A heavy-grade mobile manipulator would need similar control mechanisms and more degrees of freedom to control its end-effector. Additionally, haptic and audible feedback which are also latency and reliability sensitive are required as these signals provide important sensory feedback to the remote driver.

Safety mechanisms such as fall detection, emergency stops, alarms, or the ability to stop or slow a nearby vehicle while a human is crossing in its path in a loud and confusing environment require strict latency and reliability requirements. Hence, the URLLC service category is indicated. It is expected that actual safety execution be controlled at the edge, at the construction site itself, to minimize latency concerns. General safety conditions could be monitored remotely through the cloud.

Machine and environmental condition monitoring through Industrial Internet of Things (IIoT) devices indicates the use of the mMTC service category. The mMTC service category was specified in the 5G standard to support IIoT use cases such as environment sensing and machine health monitoring. Generally, within a construction site, mMTC would be used to monitor environmental conditions within and around the structure being built and the machines that are being used and left on-site. Depending on the scenario, the mMTC use cases could scale from a few to hundreds of sensors.

Given these use cases and the requirements for each, one must also consider that the use cases would exist concurrently such that video, teleoperation, safety, and monitoring would be operating simultaneously. The deployment architecture, type of service provider, and RF band or bands should be selected carefully to support the requirements of the construction project. The requirements of each scenario would then determine if a 5G private network could be deployed locally, a large service provider would need to be employed, or a combination of both. We recommend that the selection of deployment architectures be an area of study for construction activities.

5G TESTBED FOR CONSTRUCTION

To enhance our understanding and practical application of expertise in 5G construction environments, we conducted a literature review for applicable testbeds and channel measurements. Despite finding various experiments on 5G propagation in indoor and outdoor settings, we did not identify a suitable 5G testbed specifically designed for construction environments. Channel measurement studies include a study on path loss in a reinforced concrete stairwell at different floor levels [4], a survey on building penetration losses at various frequencies [5], and an assessment of iron oxide levels in mortar for absorption [6]. Other studies addressed 5G in rural, suburban, and urban environments [7], highlighted limitations in current wireless communication capabilities in construction [8], and discussed the need for 5G applications in construction [9]. Given the lack of comprehensive coverage for construction scenarios, we recommend developing a dedicated 5G testbed for researching construction-specific concerns.

Unlike conducting wireless network tests directly in an actual construction environment, our testbed offers enhanced flexibility for system validation and testing. It allows emulation of real-world environments without affecting operational settings, easily adapts to diverse use cases, and provides more accurate results than simulations. The testbed includes 5G system hardware, various 5G-compatible user equipment (UEs) from different vendors, PCs, industrial collaborative robotic manipulators, and networking devices. Our current focus is establishing a

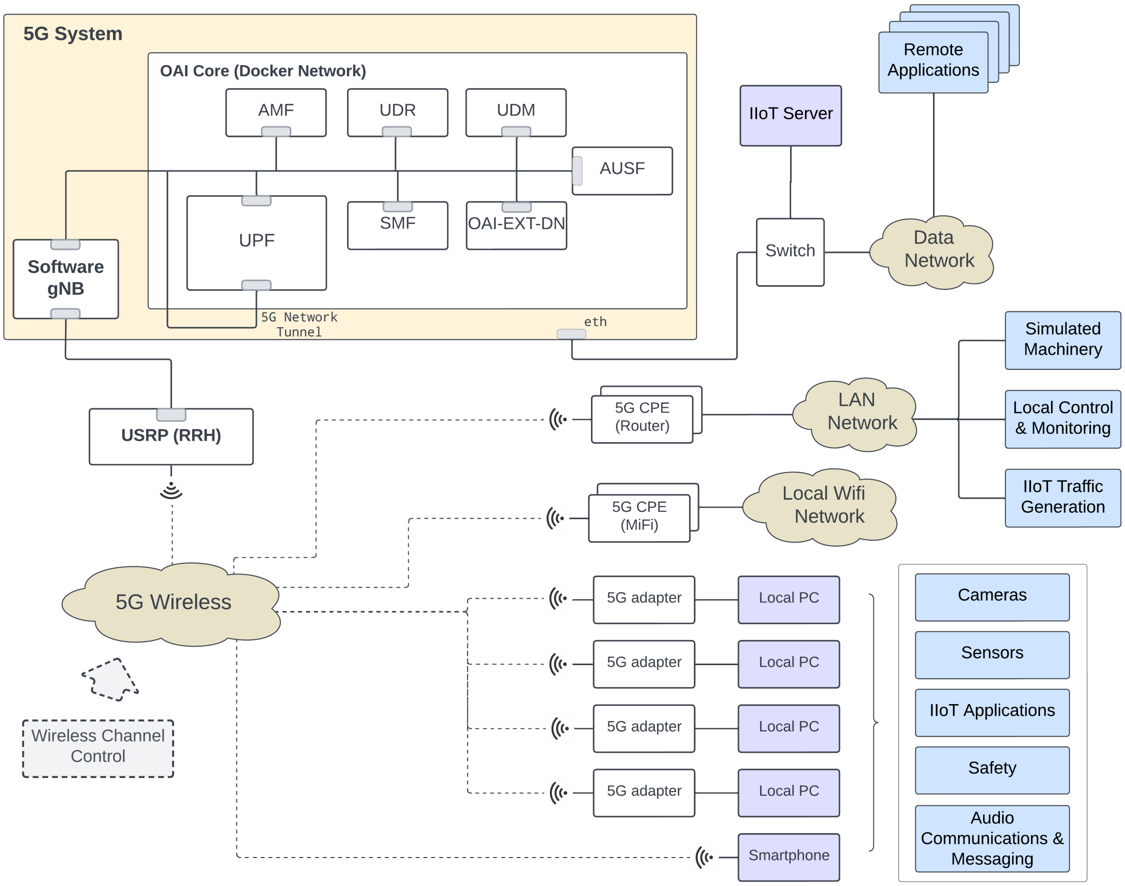

Fig. 4: 5G Testbed Architecture for Experimentation in Construction Scenarios.

remote operation control scenario with different Industrial Internet of Things (IIoT) traffic and interference, a common use case in construction.

Fig. 4 illustrates the primary building blocks and elements of the testbed. The 5G system is constructed using a low-latency PC with 5G core network functions and a software-based virtualized gNB, leveraging the softwarization of 5G network functions. A Universal Software Radio Peripheral (USRP) serves as the remote radio head for the Radio Access Network (RAN) implementation. This software-defined system allows experimentation on network function optimizations and developments, providing flexibility for various levels of hardware acceleration upgrades. The 5G core utilizes container-based OpenAirInterface (OAI) network functions, encouraging contributions and potential collaboration within the OAI community.

In addition to the primary 5G system depicted in Fig. 4, our testbed includes various 5G UEs and computing devices tailored for IIoT applications, network traffic generation, and wireless channel control. 5G routers act as Customer Premises Equipment (CPE), facilitating connectivity between the 5G network and the local area network for remote operation of machinery, local control systems, and monitoring. 5G USB adapters are used to equip PCs and devices with 5G capability, allowing experimentation and validation of the 5G system with various IIoT applications and traffic, such as data from cameras and IIoT sensors. To emulate real-world scenarios, the testbed incorporates different wireless network devices to manage the impact of fading and RF interference, creating a wireless channel environment reflective of practical deployments.

RESEARCH OPPORTUNITIES

Looking ahead, the advancement of wireless communications in the construction industry presents a myriad of exciting research opportunities that can shape the future of infrastructure development. These opportunities include the following:

1) A more detailed understanding of wireless communications requirements in diverse construction scenarios is paramount. This involves delving deeper into the specific needs of different project classes and work zones to tailor communications solutions accordingly.
2) Scoring approaches for various construction scenarios are essential for refining the accuracy of wireless connectivity assessments.
3) Standardization of testing methodologies and RF aggressor specifications for construction, as exemplified by standardization efforts of IEEE P3388 [10], is critical for assessing the performance of wireless solutions in real-world construction scenarios.
4) Improved 5G transmission scheduling algorithms for optimizing resource utilization and minimizing communications latencies. This includes the development of intelligent algorithms that can adapt to the dynamic activities of construction sites.
5) Developing 5G QoS support for different classes of construction scenarios through defining 5G QoS mechanisms that dynamically manage the QoS requirements and perform QoS-based traffic differentiation. This includes opportunities for integrating different 5G capabilities, such as TSN, into the corresponding 5G QoS classes.
6) Incorporating functional safety standards within construction use cases is another area for exploration. Investigating the implementation of black and white channels to ensure reliable and disruption-free communication aligns with the industry's stringent safety requirements [11].

7) Developing effective mitigation techniques for the changing wireless communications environment of construction sites is an essential research area.

These research opportunities offer a road map for research engineers and industry practitioners to collaborate and contribute to the evolution of wireless communication technologies tailored to the unique demands of the construction industry. By addressing these challenges head-on, we can collectively advance the adoption of wireless solutions in construction.

CONCLUSION

This article addresses complex wireless communication challenges in the construction industry. We introduce a systematic scoring system to assess wireless connectivity difficulty throughout construction phases, incorporating a comprehensive set of attributes. Exploring 5G service classes for construction enriches our understanding of tailoring next-generation wireless communications networks to industry needs. We present a novel testbed design for deploying and exploring strategies in a simulated construction environment. This research contributes to theoretical 5G integration and offers practical insights for practitioners. Our multifaceted approach aims to advance wireless communication technologies for construction, fostering efficiency and innovation in future projects.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions from Karl Jefferson, Jr., of the LiUNA Laborers' Health and Safety Funds of North America (LHSFNA) and Paul Vineyard of Ohio Laborer's Training Center (OLTC) for their insights.

REFERENCES

[1] K. Zhang, L. Liu, C. Tao, K. Zhang, Z. Yuan, and J. Zhang, "Wireless Channel Measurement and Modeling in Industrial Environments," *Advances in Science, Technology and Engineering Systems Journal*, vol. 3, no. 4, pp. 254–259, 2018.

[2] W. Stone, "Electromagnetic Signal Attenuation in Construction Materials (NIST-IR 6055)," *National Institute of Standards and Technology (NIST)*, October 1997. [Online]. Available: https://doi.org/10.6028/NIST.IR.6055

[3] M. Hany, P. Vouras, R. Jones, R. Candell, and K. Remley, "A machine-learning approach for the exemplar extraction of mmwave industrial wireless channels," no. 1, June 2022. [Online]. Available: https://doi.org/10.1109/OJIM.2022.3181309

[4] M. A. Samad, D.-Y. Choi, and K. Choi, "Path loss measurement and modeling of 5G network in emergency indoor stairwell at 3.7 and 28 GHz," *PLOS ONE*, vol. 18, no. 3, p. e0282781, mar 2023. [Online]. Available: https://dx.plos.org/10.1371/journal.pone.0282781

[5] K. Haneda, J. Zhang, L. Tan, G. Liu, Y. Zheng, H. Asplund, J. Li, Y. Wang, D. Steer, C. Li, T. Balercia, S. Lee, Y. Kim, A. Ghosh, T. Thomas, T. Nakamura, Y. Kakishima, T. Imai, H. Papadopoulos, T. S. Rappaport, G. R. MacCartney, M. K. Samimi, S. Sun, O. Koymen, S. Hur, J. Park, C. Zhang, E. Mellios, A. F. Molisch, S. S. Ghassamzadeh, and A. Ghosh, "5G 3GPP-Like Channel Models for Outdoor Urban Microcellular and Macrocellular Environments," in *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*. IEEE, may 2016, pp. 1–7. [Online]. Available: https://ieeexplore.ieee.org/document/7503971/

[6] J. P. S. Ng, Y. L. Sum, B. H. Soong, M. Maier, and P. J. M. Monteiro, "Electromagnetic wave propagation through composite building materials in urban environments at mid-band 5G frequencies," *IET Microwaves, Antennas & Propagation*, vol. 16, no. 10, pp. 627–638, aug 2022. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1049/mia2.12274

[7] A. Schumacher, R. Merz, and A. Burg, "3.5 GHz Coverage Assessment with a 5G Testbed," may 2021. [Online]. Available: http://arxiv.org/abs/2105.06812 http://dx.doi.org/10.1109/VTCSpring.2019.8746551

[8] J. Mendoza, I. De-la Bandera, C. S. Álvarez-Merino, E. J. Khatib, J. Alonso, S. Casalderrey-Díaz, and R. Barco, "5G for Construction: Use Cases and Solutions," *Electronics*, vol. 10, no. 14, p. 1713, jul 2021. [Online]. Available: https://www.mdpi.com/2079-9292/10/14/1713

[9] "5G and Verticals." [Online]. Available: https://5g-ppp.eu/verticals/

[10] *IEEE Working Group on Standard for Radio Frequency Channel Specifications for Performance Assessment of Industrial Wireless Systems*. [Online]. Available: https://standards.ieee.org/ieee/3388/10702/

[11] "Industrial communication networks - profiles - part 3: Functional safety fieldbuses - general rules and profile definitions," *International Electrotechnical Commission (IEC)*, February 2021. [Online]. Available: https://webstore.iec.ch/publication/62095