Empowering Cognitive City Wireless Communication Vision

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***Abstract*—Smart cities are becoming a beacon of progress towards economies of the future. This article analyzes commercial communication schemes and explores using enhanced communication aided by unmanned aerial vehicles (UAVs) in NEOM city, Saudi Arabia. As the city develops, connectivity needs must evolve. The study outlines future connectivity needs and potential communication solutions. A case study based on the Oxagon region demonstrates the feasibility of the proposed schemes and evaluates 5G and UAV techniques for smart services and applications. Oxagon is constructing a cutting-edge, environmentally friendly industrial ecosystem, accelerating Industry 4.0 adoption and embracing circular economy principles. Results show that both ground and aerial 5G mmWave stations can support devices at 354Mbps with densities of 330/km^2 and 440/km^2, respectively. Finally, we conclude with future research directions.**

I. Introduction

Rapid urbanization is driving nations to innovate in urban planning and technology to enhance citizens' quality of life. Smart city projects are key strategies, with governments leveraging advanced communication technologies. Singapore's "Smart Nation 2025 Plan" and the UAE's "Smart Dubai" initiative integrate modern information and communications technology (ICT) solutions to optimize resources and improve governance [1]. In this context, the Kingdom of Saudi Arabia has embarked on an ambitious journey to create NEOM, a mega-development project that envisions a futuristic smart city, establishing new benchmarks for global standards. NEOM, a ground-up urban development, begins with regions like Sindalah, Trojena, Oxagon, Gulf of Aqaba, and the Line, integrating advanced ICT solutions for transportation, healthcare, and entertainment [2]. As smart city initiatives expand, ICT's role in enhancing urban life is crucial. The NEOM administration's strategy encompasses far-reaching policies and action plans to implement ICT solutions over the coming decade. This ambitious blueprint includes developing innovative smart services for different sectors, while maintaining a steadfast commitment to environmental conservation [2].

While the International Telecommunication Union (ITU) standards are valuable for monitoring progress, they often lack focus on the specific wireless communication solutions and infrastructure crucial for smart cities. ITU performance standards, such as ITU-TY.4903, are invaluable in monitoring progress, but often do not delve into the wireless communication solutions and associated infrastructure that form the backbone of a city's ICT capabilities [3].

NEOM's unique challenge lies in its vast land mass, similar to Belgium in size, its diverse topology, and its commitment to limit construction to just 5% of the area. This presents a significant hurdle in achieving comprehensive connectivity, vital for environmental monitoring and public safety. Comprehensive connectivity in this vast, sparsely populated area is crucial for environmental monitoring and public safety, requiring a deep understanding of each region's communication needs. To overcome these challenges, a robust cellular network capable of reaching the most remote parts of NEOM is essential.

Smart cities like NEOM require cognitive wireless systems, integrating AI, ML, and intelligent systems for adaptive, self-organizing, and context-aware communications. These cognitive abilities are crucial for the effective deployment and management of wireless technologies in complex urban environments, where dynamic resource allocation, intelligent spectrum management, and adaptive network configurations are essential for meeting the evolving communication demands of smart city applications and services.

Extensive research highlights UAVs' potential in ICT for flexible, extensive coverage, even in less accessible areas [4], but practical implementation lags behind theory. Our study attempts to bridge this gap, paying particular attention to the tangible aspects that are instrumental in the real-world deployment of UAV-assisted wireless communications. We

The opinions presented in this paper are solely those of the authors. Communication scenarios presented are fictitious and presented for the sake of research debate based on the authors professional expertise.

consider the implications of UAV payload limitations, aerial performance parameters, and the intricacies of spectrum allocation within Saudi Arabia's regulatory framework, especially as they relate to multiple access technologies and resource allocation strategies for future ICT applications. Oxagon's innovative industrial ecosystem offers an ideal case study. We demonstrate how these elements contribute to a 5G network supporting UAV integration, providing insights into practical high-capacity wireless networks in smart cities.

II. Building A Blueprint for Smart and Connected NEOM

As NEOM evolves from a futuristic concept into a concrete reality through ongoing construction efforts, the achievement of its ambitious vision hinges significantly on the effective deployment of ICT capable of supporting the city's development goals. NEOM's regions have distinct characteristics and needs, influencing the kinds of ICT services and wireless communication necessities for each area; as provided in Table I.

Sindalah, an island resort on the Red Sea, features luxury hotels and entertainment venues [2]. Essential smart services include AI concierge, holographic interactions, and immersive AR/VR experiences, relying on robust wireless communication for high-data-rate applications and wide coverage. Additionally, maintaining the natural beauty of the island necessitates a wireless infrastructure that minimally impacts the visual landscape, even as the need for more base stations grows with higher network frequencies.

Trojena, conceptualized as a mountain retreat, showcases six unique development districts offering experiences that meld physical and virtual innovations in architecture and engineering [2]. Smart services here are designed to enrich visitor interactions and bolster the tourism and winter sports industries with functionalities like real-time weather information, ski lift notifications, GPS navigation, and rapid transit between districts. These applications depend on a resilient wireless infrastructure that can navigate the challenges of Trojena's rugged terrain and variable altitudes. A diverse array of wireless technologies is therefore necessary to ensure consistent coverage and reliability. The infrastructure must also be durable enough to withstand extreme weather and adapt to the varying demands of tourist seasons.

Oxagon is set to redefine advanced and sustainable industries, emerging as a beacon for innovation with its automated port and intelligent supply chain network [2]. The deployment of ICT services here aims to streamline manufacturing, enhance safety, and minimize waste. Robotics, for instance, can transform tedious or hazardous tasks, fostering an environment that encourages creativity and significantly contributes to Oxagon's economic and social landscape [7]. The wireless communication specifications for Oxagon must support the intensive data demands of its burgeoning port and industrial applications. The cognitive aspects of wireless communications can play a vital role in addressing the communication challenges in Oxagon. ML algorithms can be employed for intelligent resource allocation, optimizing the assignment of communication resources based on the dynamic demands of industrial IoT applications and port automation systems. Additionally, cognitive spectrum management techniques can ensure efficient utilization of available frequency bands, mitigating interference and maximizing network capacity in the presence of industrial machinery and potential signal obstructions. A robust and high-speed wireless network is crucial to manage the high data throughput and to navigate the particular challenges presented by a bustling harbor setting.

The Line, envisioned as a 170km linear urban development, seeks to connect diverse communities and urban hubs while preserving the ecosystem [2]. ICT services in the Line aim for more than just uninterrupted connectivity; they seek to enable smart urban planning and efficient resource management, culminating in a sustainable and habitable city. These services range from supporting remote communication and collaboration to implementing intelligent systems for managing energy, waste, water, and public safety. The Line will integrate state-of-the-art technologies like VR, the Metaverse, haptic feedback, and robotic avatars to provide residents with various modes of interaction virtual, physical, and mixed reality even from afar. Underpinning these services are cutting-edge wireless systems that support high-capacity applications like 5G and ensure low-latency connections for instantaneous data transmission, facilitating a seamless operational environment within the city and thereby enriching the lives of its inhabitants.

III. A Look at Wireless Communication Technologies

In this section, we examine the available wireless communication technologies that can be used in various regions during the construction phases. Additionally, we provide insights into emerging technologies that have been extensively studied at the research level but have not yet been put into practice. In this context, we focus on UAV technology and consider the practical constraints that must be carefully managed during real-world applications.

A. Established Wireless Communication Technologies

Modern wireless connectivity relies heavily on several commercial technologies to provide ubiquitous connectivity enabling numerous smart applications and services. Table II summarizes the key characteristics of conventional wireless schemes operating at various frequency bands, focusing primarily on commercially available ones. Given the importance of the proposed smart applications and services in NEOM, it is imperative to carefully evaluate the suitability of different wireless communication technologies and their application scenarios before deploying them. Thus, we will analyze these network technologies considering practical cases that may arise during the deployment process in the rest of this section.

ZigBee and LoRaWAN are both low-power wireless communication technologies that offer unique advantages depending on the specific use case. ZigBee is a wireless personal area network (WPAN) technology that operates on the 2.4

TABLE I
SUMMARY OF COMMUNICATION DEMANDS, CHALLENGES AND STRATEGIES FOR NEOM REGIONS

Region	**Examples of ICT Services**	**Communication Requirements**	**Challenges**	**Suggested Techniques**	**Cognitive Enhancements**
Sindalah (*Island Resort*)	AI concierge services, Underwater VR experiences, Marine connectivity	High data rate, Wide coverage, Underwater communications	Signal loss over water, Visual pollution from infrastructure	Heterogeneous networks, Aqua-Fi for underwater connectivity [5], Adaptive transmissions	AI-driven optimization for signal integrity and real-time adaptation to environmental and demand changes
Trojena (*Mountain Tourist and Sport Region*)	Real-time environment monitoring, High-altitude sports streaming, Emergency response systems	Robust infrastructure, Wide-area coverage, Weather-resistant equipment	Fluctuating demand, Weather, Challenging terrain	Deployable mesh networks, Satellite backhaul integration, Advanced weather prediction modeling	Cognitive network management to dynamically adjust resources based on varying user density and weather conditions
Oxagon (*Sustainable Industrial Region*)	Automated port management, Smart logistics, Industrial IoT	High-speed data transfer, Large bandwidth, Low-latency	Industrial interference, Heavy machinery impact, Efficient cargo handling	5G NR for ports, IoT integration, Integrated Blockchain via hybrid communication bands [6]	ML algorithms for traffic prediction to efficiently allocate resources
The Line (*Elongated Sustainable City*)	Smart city infrastructure, Integrated transportation systems, Metaverse applications	Ultra-high-capacity, Ultra-low-latency, Energy-efficient solutions	High user density, Sustainable development, Linear urbanization	Edge computing, Network slicing, Green network solutions	Cognitive routing algorithms to optimize traffic and energy usage, AI-enhanced security protocols

GHz frequency band, and is ideal for communication between devices in a small area, such as a home or building. In NEOM, it can be used for home automation, smart lighting, and other IoT applications. However, ZigBee's limited range and bandwidth make it less suitable for large-scale deployments and applications that require high data rates. LoRaWAN, on the other hand, is a low-power, wide-area network (LPWAN) technology that operates on sub-gigahertz frequency bands and offers long-range but low-data-rate communication to support a large number of devices. It can be applied in smart agriculture, asset tracking, and smart city infrastructure for cities such as NEOM. Generally speaking, in practical usage scenarios, ZigBee is ideal for communication of IoT devices distributed in a small area, while LoRaWAN is suitable for those smart services that require long-range communication but with low data rates.

Wi-Fi 6E offers several advantages such as faster data speeds, lower latency, more simultaneous connections, and improved power efficiency compared to previous Wi-Fi standards. For smart cities, Wi-Fi 6E would be ideal to support high-bandwidth and low-latency applications in smart homes and enterprises, such as 4k/8k streaming, AR/VR, and cloud gaming. The shorter coverage range means more Wi-Fi access points would be needed, but with the high density of smart devices and the popularity of bandwidth-hungry applications, Wi-Fi 6E can provide a seamless connected experience for residents and visitors with its faster speeds and additional bandwidth. However, given the scale and scope of smart and emerging cities, the cost and range limitations of Wi-Fi 6E should be carefully evaluated to ensure that the technology is deployed effectively and efficiently. Overall, Wi-Fi 6E is a promising technology for cities such as NEOM and has the potential to support a range of innovative applications and services.

4G and 5G are cellular networks that require communication tower support. While 4G technology is currently sufficient to meet the needs of many users, 5G technology offers significant improvements in terms of speed, latency, and device connectivity. In particular, the 5G sub-6GHz spectrum offers comparable kilometer-level coverage to 4G but with faster speeds and the ability to connect many more devices simultaneously. On the other hand, 5G mmWave spectrum offers extremely fast speeds but over shorter ranges and is susceptible to blockages from obstacles. For emerging smart cities, the use of 5G sub-6GHz would enable enhanced mobile broadband in urban and suburban areas, facilitating the connection of vehicles and smart devices throughout the city. The use of 5G mmWave would be particularly well-suited for high-density applications such as automated ports, manufacturing facilities, or entertainment venues, offering multi-gigabit speeds, ultra-low latency,

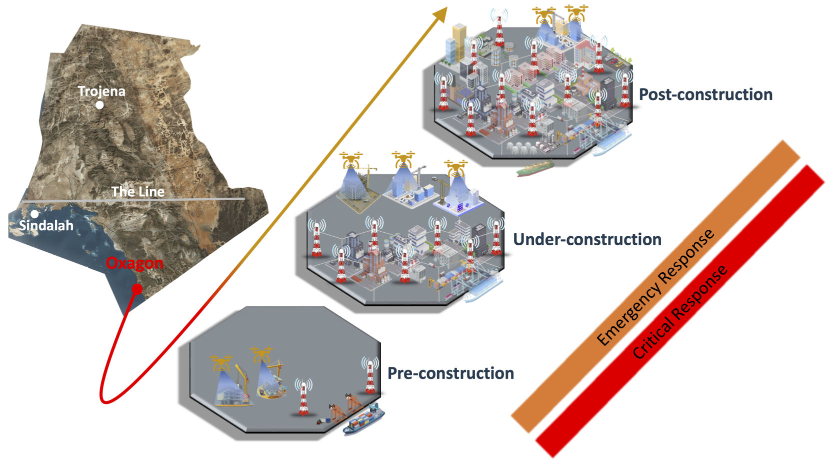

Fig. 1. NEOM city map and construction processes example at the Oxagon region.

TABLE II
KEY CHARACTERISTICS OF COGNITIVE WIRELESS COMMUNICATION TECHNOLOGIES

Scheme	Data Rate	Range	Work Mode	Cognitive Enhancements
ZigBee	$\leq$ 250kbps	10-100m	Mesh networking	Cognitive mesh network management for adaptive connectivity
LoRaWAN	$\leq$ 50kbps	$\leq$ 16km	Infrastructure	AI-based network management for optimal signal routing and energy usage
Wi-Fi 6E	$\leq$ 9.6Gbps	$\leq$ 45m (indoor), $\leq$ 150m (outdoor)	Infrastructure or ad hoc	AI-enhanced traffic management, cognitive interference management
4G	Uplink: $\leq$ 100Mbps, downlink: $\leq$ 200Mbps	1-10km	Infrastructure	Cognitive radio technologies for dynamic spectrum access
5G (sub-6GHz)	Uplink: $\leq$ 1Gbps, downlink: $\leq$ 2Gbps	1-3km	Infrastructure	Advanced AI for network slicing and predictive analytics
5G (mmWave)	Uplink: $\leq$ 4Gbps, downlink: $\leq$ 6Gbps	$\leq$ 300m (outdoor)	Infrastructure	High-frequency AI-driven beamforming for enhanced throughput and coverage

and massive device connectivity. However, given its limited coverage, the deployment of numerous cell sites would be necessary. By deploying these cellular networks, cities such as NEOM can leverage smart services and applications to create a more intelligent and connected city.

B. UAV-aided Enhanced Communication

In recent years, there has been significant advancement in unmanned aerial vehicle (UAV) technologies, resulting in a wide range of applications for UAV-based communication [11]. As a result, employing UAVs as an auxiliary means of communication for smart city services is a promising and cost-effective approach to overcome the challenges of ground communication methods. Table III lists some commercial heavy-lift UAVs and their specifications that could be considered for actual deployment in cities such as NEOM. Compared to fixed base stations, UAV-enabled communication offers several advantages. UAVs excel in expanding service coverage due to their ability to operate at various altitudes, offering a wider reach than ground towers as indicated in Table III. Rapid deployment capabilities allow UAVs to adapt to fluctuating service demands and ensure consistent connectivity for smart city applications. Technological miniaturization allows for the integration of lightweight base stations on UAVs, which in turn transforms them into mobile aerial hubs equipped with communication tools such as antennas and repeaters. Linked via high-speed Satellite communications and Heterogeneous Networks (HetNets), these UAVs can seamlessly connect to the internet, facilitating the use of 5G devices across the city. The scalability of UAV communication deployment aligns with the developmental phases of NEOM's infrastructure, providing tailored connectivity solutions as the city evolves.

However, the deployment of UAVs for communication purposes is not without its challenges. The integration of

TABLE III
SPECIFICATIONS OF COMMERCIAL HEAVY-LIFT UAVS FOR POTENTIAL DEPLOYMENT IN NEOM

UAV Model	Max Payload Capacity	Flight Time	Max Range	Altitude
EHang 216 [8]	250kg	21mins	17.5km	$<$500m
Dragonfly Heavy Lift Drone [9]	30kg	55mins	20km	N/A
JOUAV CW-80E [10]	20kg	480mins	100km	$<$5000m

cognitive capabilities into UAV-based communication systems can further enhance their effectiveness. AI and ML techniques can be leveraged for intelligent path planning and adaptive positioning of UAVs, ensuring optimal coverage and connectivity based on real-time network conditions and user demands. Moreover, energy-efficient deployment strategies can be developed using reinforcement learning algorithms, optimizing the flight trajectories and minimizing energy consumption while maintaining desired communication performance levels. Regulatory hurdles are a significant concern, as UAV operations must navigate complex airspace rules and public safety considerations. Battery limitations present a practical constraint, with the need for frequent recharging impacting continuous service availability. Privacy and security risks must be managed meticulously to protect citizen data and prevent unauthorized surveillance. Furthermore, adverse weather conditions can impair UAV performance, and potential interference with existing communication networks necessitates careful spectrum management. Addressing these issues is crucial to ensure that the advantages of UAVs can be harnessed effectively for NEOM's communication needs without compromising safety, privacy, or service quality.

IV. CASE STUDY OF OXAGON

As smart cities like NEOM evolve through construction phases, their communication infrastructure must adapt to support a growing range of services, from basic connectivity to specialized applications. Particularly, emergency and critical response systems face unique challenges in maintaining seamless integration with the complex communication network required by smart services and applications. Emergency response is responsible for immediate action in life-threatening events, and critical response manages the strategic oversight of incidents and the continuity of key operations. To meet the diverse and intricate communication demands across all stages, we propose a suite of 5G-based communication solutions that include ground base stations and UAV-aided communication. This robust strategy ensures consistent connectivity throughout Oxagon's project evolution, as illustrated in Fig. 1.

A. Evolving Connectivity Solutions with NEOM's Growth

Pre-construction Stage: During the pre-construction phase of smart city development, not only is communication infrastructure often sparse, but the capacity for swift emergency response is also limited. UAVs serve a dual function at this stage: providing essential communication coverage for initial smart applications and acting as first responders for any emergencies. By serving as aerial base stations, UAVs facilitate critical communication among emergency personnel, addressing the immediate needs of life preservation and safety.

Under-construction Stage: During the dynamic under-construction phase, the emerging 5G communication infrastructure begins to solidify, paving the way for the integration of new smart services. Rapid changes in communication needs are characteristic of this stage, as the infrastructure is scaled up to support an expanding array of smart applications. As the construction advances, the network not only accommodates a growing number of smart services such as smart buildings, inspection robots, and autonomous vehicles but also supports the city's capacity to respond to critical situations. The flexibility of the infrastructure ensures that it can readily embrace cutting-edge smart technologies within its domain. The established network facilitates strategic coordination during critical incidents, safeguarding the continuity of operations and the provision of essential services. Moreover, UAVs augment this adaptability, swiftly bridging coverage gaps that may occur in emergency scenarios and reinforcing the ground infrastructure in managing extended critical events that demand persistent communication links.

Post-construction Stage: With the completion of NEOM, the city features an advanced communication network, secured by ground-based 5G stations that ensure widespread and high-speed connectivity. In this sophisticated ecosystem, UAVs serve a dual purpose: they enhance routine surveillance by leveraging the expansive network coverage, and they act as deployable aerial base stations during critical incidents. This integration of a state-of-the-art 5G network with the strategic deployment of UAVs guarantees a rapid and efficient response to emergencies, from fires and medical crises to infrastructure disruptions. NEOM's network is designed to be both far-reaching and adaptable, ensuring that it can meet a broad spectrum of operational needs with agility and resilience.

Public Safety and Security: NEOM's grand vision places public safety and security at the forefront throughout each phase of its development. In the initial pre-construction phase, UAVs become the frontline of an extensive aerial surveillance system, providing critical oversight over the vast developing landscape. Simultaneously, automated ground sensors and geographical information systems form a vigilant foundation to guard against environmental and structural threats, complemented by robust alert systems. As the city transitions to the under-construction phase, the established safety network is significantly enhanced. A 5G-enabled suite of cameras and sensors can bolster real-time monitoring, creating a web of visual oversight across the cityscape. These technological advancements are reinforced by rigorous worker safety protocols and strategic oversight of a sophisticated central command center that coordinates a comprehensive network of emergency services. Finally, after the development of NEOM, UAVs will continue their critical role within this ecosystem, supported by integrated AI-driven threat detection systems and augmented reality tools that empower first responders with invaluable situational awareness.

B. Simulation Results

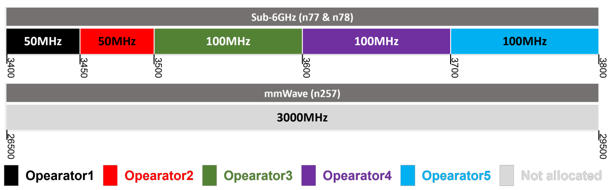

Fig. 2. Partial 5G frequency allocation in Saudi Arabia

Evaluating the performance of ground and UAV-based 5G, particularly delay impact, is crucial for supporting real-time applications like VR/AR. This evaluation focuses on 5G New Radio (NR), utilizing sub-6GHz and mmWave frequency bands, is shown in Fig. 2 as part of the 5G frequency allocation in Saudi Arabia [12]. Wide frequency bandwidth is crucial for high-bandwidth communication services, and in Saudi Arabia, a continuous frequency bandwidth between 3500MHz and 3800MHz of the C band is chosen for sub-6GHz communication to comply with local regulations. The n257 band of mmWave will soon be allocated to operators, so we use the entire band for performance evaluation. It should be noted that Oxagon spans 7 km and has a unique area approximated by 7 km^2, as illustrated in Fig. 1. VR is a typical smart application that is expected to be used extensively at NEOM. Based on the data rate requirements discussed in [13], we calculate a data rate threshold of 354Mbps for advanced VR with lossy compression of 300:1. However, data throughput alone is not sufficient for a smooth VR experience; low latency is also crucial. Interactive VR/AR applications require low latency communications to provide real-time responses and prevent user discomfort, such as motion sickness. Thus, the latency performance of the 5G network is also a key factor that needs to be evaluated. The key simulation parameters are summarized in Tab IV, and the simulation results are depicted in Fig. 3.

Ground 5G Base Station Communication Service: As communication infrastructure is constructed in Oxagon, a ground 5G cellular network comprised of base stations is gradually formed. Co-channel interference (CCI) presents a significant challenge for 5G networks, occurring when multiple services or cells transmit on the same frequency band simultaneously, leading to overlapping signals and mutual interference. This can limit network performance, particularly in densely populated areas where multiple base stations may be operating on the same frequency band. To mitigate the impact of CCI, our simulation assigns end devices located in the same cell with non-overlapping sub-bands based on their distance from the associated base station, enabling them to work simultaneously. However, CCI can still be introduced by neighboring cells. Beamforming is a key technique used in our simulation to suppress CCI, involving the use of multiple antennas at both the transmitter and receiver sides to transmit or receive signals in a specific direction [6]. In our simulation, beamforming is enabled through MIMO and beam steering antenna systems, which allow for highly directional transmission and receptions that can be dynamically adjusted based on the spatial location of users. In the following section, we provide a detailed illustration of the simulation results.

The propagation distance is longer for sub-6GHz carrier frequencies than for mmWave frequencies. Thus, we consider the CCI from tier 1 and tier 2 for each cell in sub-6GHz, while for mmWave, we only consider the CCI from tier 1. We assume a line-of-sight (LOS) channel model between ground base stations and end devices, while a non-LOS (NLOS) model is used for the corresponding CCI channel. Both LOS and NLOS models are defined in the 3GPP standard [14]. During the simulation, we evaluate uplink performance under different base station coverage settings ranging from 150m to 400m. We plot the simulation results in Fig. 3, using the metric of outage probability versus device density. The dashed curves with circles and stars represent sub-6GHz and mmWave, respectively. A common trend is that the outage probability increases as device density grows. For the same coverage radius of R = 300m, the ground mmWave base station performs better than the sub-6GHz base station due to its ability to provide 10 times greater bandwidth to end devices. According to the simulation results, the ground mmWave base station outperforms the ground sub-6GHz base station in terms of both coverage and device service capabilities.

UAV-aided 5G Communication Service: To evaluate the effectiveness of 5G communication aided by UAVs, we assume a hovering altitude of 100m for UAVs equipped with sub-6GHz and mmWave base stations. We further assume that the end devices' antennas are directed toward the aerial base station and that the links between the end devices and the aerial base station are LoS channels, facilitated by the high hovering altitude of the UAV [15]. Therefore, it is unnecessary to take into account co-channel interference (CCI) in this scenario. As the channel between devices and UAVs differs from traditional terrestrial mobile access channels, we employ a channel model obtained through actual measurements [16]. Based on these assumptions, we present simulation results of the outage probability versus device density in Fig. 3 with solid curves, where we evaluated coverage ranging from 200m to 400m. As expected, the outage probability of the aerial communication service increases with increasing end device density in a specific area. The general performance of the UAV with mmWave base station stands out in all simulated coverage areas compared to the one with sub-6GHz base station, not only in terms of coverage, but also in outage probability. This is due to the larger bandwidth of mmWave, which allows more end devices to work simultaneously. Furthermore, the results

TABLE IV
SOME KEY SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Oxagon area	7000m*7000m	Rate threshold	354Mbps
Carrier frequency	3.5-3.8GHz@sub-6GHz 26.5-29.5GHz@mmWave	Transmit power	33dBm
UAV hovering altitude	100m	Tx antenna number	4

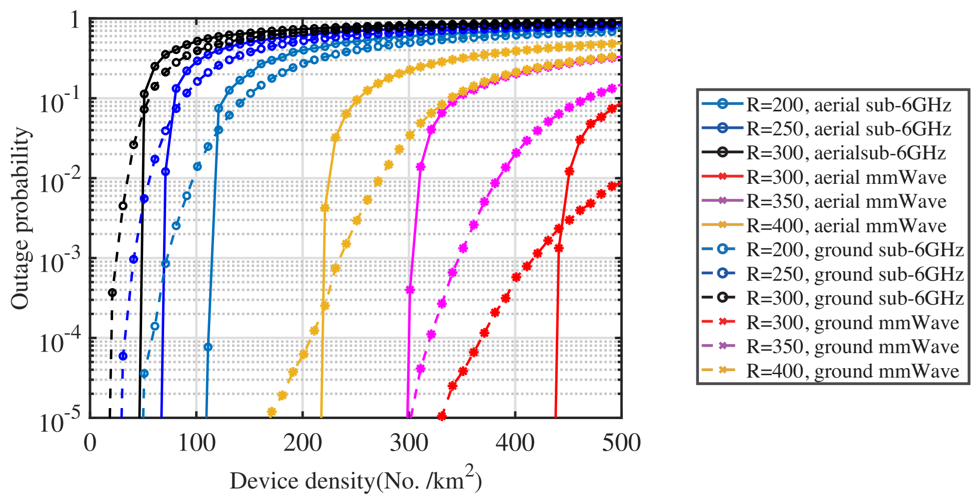

Fig. 3. Ground and aerial 5G communications uplink performance evaluation

show that UAVs equipped with mmWave base stations have the ability to provide adequate communication services in areas where ground communication infrastructure is insufficient.

The case study demonstrates the feasibility of supporting smart services using ground and UAV-aided aerial mmWave base stations. Beamforming techniques can reduce interference from neighboring cells, improving system performance. The study also shows the effectiveness of UAV-aided communication in supporting high-speed services in inaccessible areas. Cognitive wireless techniques can further enhance the performance of Oxagon's 5G ground and UAV-based communication systems. Intelligent beamforming algorithms can dynamically adjust the antenna patterns based on user locations and channel conditions, reducing interference and improving signal quality. Additionally, machine learning can enable context-aware resource allocation, optimizing resource use while meeting the diverse quality-of-service demands of industrial and smart city applications.

V. Future Research Directions

In order to enhance the functionality of smart services and applications in NEOM, we have identified three potential areas where significant improvements can be made in feasible ways.

Construct a comprehensive 3D aerial communication system: To achieve seamless coverage for the different regions of NEOM, we need to develop a comprehensive 3D aerial communication system leveraging multiple platforms to provide complete coverage. At the lower altitudes, tethered UAV can operate as mobile aerial base stations to provide enhanced communication services to ground users and devices of specific area due to their continuous power supply. In the stratosphere, high-altitude platforms (HAPs) such as balloons and airships can act as aerial base stations to provide wider area coverage [17]. At higher orbits, low Earth orbit (LEO) and medium Earth orbit (MEO) satellites can provide coverage for entire regions and serve as a backbone connectivity between the lower aerial platforms. By integrating tethered UAVs, HAPs, LEO and MEO satellites into a unified network with inter-platform links, this 3D aerial system can deliver high-speed, low-latency and uninterrupted connectivity from space all the way down to NEOM.

Leverage The Line for distributed UAV 5G communication: With The unique nature of the Line region, its infrastructure presents a unique opportunity for boosting the 5G network. By deploying fiber along The Line, it could serve as a backbone for the network. Additionally, wireless relays positioned at the top of The Line could be directly linked to UAV base stations, enabling distributed 5G communication without the need for satellites or HAPs in some regions around The Line. This approach would also contribute to enhancing network coverage and capacity, further improving the quality of smart services and applications in NEOM.

Exploring higher frequency bands for growing bandwidth demands: In this article, we focus on bands around 28GHz with 3000MHz bandwidth. However, with the proliferation of smart services and applications, the demand for spectrum in even higher frequency bands is likely to emerge. It is worthwhile exploring higher frequency bands above 28GHz, including millimeter wave bands from 30 to 300 GHz, and sub-millimeter THz between 300GHz and 3THz [18], [19]. However, there are also significant technical challenges that must be overcome during the commercialization at these extreme frequencies. These frequency bands' narrow beams and antenna beamwidths necessitate precise beam steering and alignment between transmitting and receiving antennas. Additionally, higher path loss and signal attenuation make it harder to achieve good coverage range and reliability. Therefore, before new capabilities can be exploited to meet future demand, significant advances need to be made.

Evolution from cellular networks to cell-free massive MIMO networks: Traditional mobile networks rely on cellular topologies. In the given case study, the Oxagon is divided into small cells, with each cell serviced by a single base station. However, such centralized cellular networks may prove inadequate in the future, as they struggle to accommodate billions of machine-type connections simultaneously. This is due to high interference and limited bandwidth experienced by terminals at the cell boundaries. To address these issues, decentralized cell-free networks have emerged as a promising evolutionary direction. Concurrently, massive MIMO technology should be considered for serving a large number of devices and streamlining signal processing in a distributed manner. As a result, a new research direction called cell-free massive MIMO networks is gaining attention as a way to overcome the limitations of traditional cellular networks.

Cognitive Wireless Communication and AI-enhanced Communication Technologies The integration of cognitive capabilities and AI-enhanced communication technologies presents a promising research direction for empowering integrated terrestrial and non-terrestrial networks (TN-NTNs) in 6G. Deep learning techniques can be explored for intelligent wireless resource management, enabling dynamic and adaptive allocation of communication resources based on complex network conditions and diverse application requirements. Transfer learning approaches can be investigated for developing adaptive communication protocols that can seamlessly adjust to the highly dynamic and heterogeneous environment of integrated TN-NTNs. Furthermore, reinforcement learning algorithms can be leveraged for intelligent network slicing and orchestration, optimizing the allocation of network resources across multiple virtual slices while ensuring quality-of-service guarantees, efficient resource utilization, and adaptability to the unique characteristics of integrated networks, such as large-scale topology and high mobility [20].

VI. Conclusion

In this article, the integration of 5G and UAV technologies for enhancing NEOM's connectivity and intelligence has been examined. The analysis has included an assessment of the strengths and weaknesses of existing communication systems, including the support provided by UAVs. The practical implementation of these technologies in NEOM's Oxagon project has been presented as an example. The findings indicate that ground-based mmWave stations can cover a radius of 300m, supporting 330 devices/km² at a speed of 354Mbps. On the other hand, UAVs have the potential to serve up to 440 devices/km². These results suggest the need for further investigation into the use of 5G mmWave and UAV communications for NEOM's future smart applications.

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