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Article

Energy-Efficient 5G mmWave Network Planning for Sustainable Digital Transformation in Saudi Arabia

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Abstract: Saudi Arabia needs to develop an advanced wireless communication infrastructure to provide high-speed connectivity, ultra-low latency, and high network performance within the country's smart cities, industrial zones, giga projects, and public services in the context of digital transformation through its Vision 2030 strategy. In terms of new 5G technologies, mmWave communication is capable of providing high-bandwidth data rates, thus making this technology applicable for dense urban areas, smart infrastructures, airports, stadiums, industrial estates, and future digital networks. However, the implementation of mmWave poses numerous planning difficulties due to high propagation loss, low coverage radius, poor penetration ability, need for dense cell deployment, and energy consumption.The current paper will analyze the energy-saving planning practices associated with 5G mmWave in the context of sustainable digital transformation in Saudi Arabia. Specifically, emphasis will be placed on small-cell optimization, massive MIMO technologies, advanced beamforming, intelligent sleep mode, renewables-driven telecommunications site infrastructure, edge computing, traffic-dependent network management, and energy consumption optimization using artificial intelligence. Furthermore, the paper will highlight potential benefits related to the development of energy-efficient mmWave, such as cost reductions, enhanced reliability, smart city initiatives, as well as alignment with Saudi Arabia's environmental and digital economy agenda. In conclusion, the findings of the current research provide valuable information about creating a sustainable planning practice framework for Saudi Arabia's 5G mmWave infrastructure.
Keywords: 5G mmWave, energy-efficient networks, Saudi Arabia, Vision 2030, sustainable digital transformation, small cells, network planning, smart cities, massive MIMO, green telecommunications

1. Introduction

Saudi Arabia is quickly growing its digital infrastructure to help with Vision 2030, smart cities, big projects, changes in industry, tourism, logistics, new healthcare ideas, and better public services. In this change, 5G networks are more than just ways to communicate; they are important foundations for the digital economy. In the world of 5G technology, millimeter wave, or mmWave for short, is very important. This is because it can offer very fast data speeds, a wide range of bandwidth, and communication with very little delay. These features make mmWave a good choice for busy city areas, smart neighborhoods, airports, sports stadiums, industrial sites, and large projects like NEOM, The Line, Qiddiya, Red Sea Global, and King Salman Park.

But, setting up mmWave is technically harder than setting up regular mobile networks. mmWave frequencies work at very high frequency levels, usually starting from 24 GHz and going higher. These bands can hold a lot of data, but they also have problems like losing signals easily, not covering long distances, having a hard time getting through walls, and being affected by obstacles such as buildings, trees, cars, and even people moving around. As a result, mmWave networks need more small cells, with sites placed closer together, improved beamforming, better backhaul connections, and careful planning of the network.

Energy efficiency is one of the most important issues in mmWave network planning. Since mmWave networks require dense infrastructure, energy consumption can increase if deployment is not carefully designed. More small cells, active antennas, cooling systems, edge equipment, and transport links can raise operational costs and environmental impact. This is especially important for Saudi Arabia because the country is building large-scale smart infrastructure while also working toward sustainability, energy efficiency, and environmental responsibility. Therefore, the challenge is not only to deploy high-speed 5G mmWave networks, but to deploy them in a way that supports sustainable digital transformation.

Efficient mmWave design would involve designing networks that ensure high coverage and capacity but require less energy than needed. Some of the ways in which such an approach can be accomplished include optimized small cell location, sleeping, power control, traffic activation, incorporation of renewable energy sources, energy efficient equipment, and AI network optimization among others. For instance, mmWave small cells in a smart city would not have to be operating on full energy at all times. In off-peak hours, the small cells can go into sleep mode while some near by continue providing minimal connectivity, and when it is peak hours, the network activates itself.

In Saudi Arabia, planning for energy-efficient 5G mmWave is very important because upcoming digital services will rely on wireless networks that can handle a lot of data. Smart cities will need constant connections for cameras, sensors, public safety systems, smart lights, smart traffic management, self-driving transport, and online public services. Industrial areas will require dependable, fast communication for robots, remote monitoring, predictive maintenance, and automated logistics. Places for tourism and entertainment will require fast internet connections to handle big groups of people, provide engaging media experiences, support online ticket sales, and offer real-time services for visitors. These examples need good network performance, but they also need to be backed by careful planning for lasting infrastructure.

The next critical aspect is fiber backhaul and edge computing. While mmWave access networks offer extremely fast speeds in terms of wireless technology, they demand reliable transport to transmit the generated data. The role of fiber backhaul becomes important for connecting small-cell networks to the core. On the other hand, edge computing allows decreasing latency through on-site data processing. Nonetheless, fiber and edge computing also have their energy demands. This implies that when it comes to energy-efficient planning, the entire chain should be taken into account.

This paper looks at how to plan energy-efficient 5G mmWave networks to support sustainable digital change in Saudi Arabia. It talks about the technical function of mmWave, the energy issues caused by having a lot of them in one place, and the planning methods needed to find the right balance between performance, cost, and sustainability. The paper also points out that mmWave can help achieve the goals of Vision 2030 by making smart cities possible, encouraging new ideas in industry, providing digital services, and preparing for future 6G technology. The main goal of this study is to suggest a useful plan for setting up mmWave networks that enhances fast internet connections while also lowering energy use and minimizing harm to the environment.

2. Literature Review

The growth of 5G mmWave networks is a key focus in research because today's digital economies need quicker, more dependable, and more sustainable wireless communication systems. Unlike regular low-band and mid-band mobile networks, mmWave works at much higher frequencies, typically over 24 GHz, and offers a very wide bandwidth. This enables very fast data speeds, minimal delays, and strong ability to handle many users in crowded places. The research also indicates that mmWave networks need to be planned carefully. This is because high-frequency signals do not travel far, lose strength more quickly, have a harder time going through walls, and are more affected by obstacles.

Earlier studies show that mmWave technology works best in places where many users or devices require very fast internet connections in a small area. These places include airports, sports stadiums, business areas, college campuses, smart city sections, factories, ports, hospitals, and places for entertainment. In Saudi Arabia, this is important because Vision 2030 involves big smart infrastructure projects, tourist attractions, large-scale projects, logistics centers, and programs to modernize industries. So, mmWave shouldn't just be seen as an upgrade for telecom; it should be seen as a tool for digital infrastructure that can help change the nation.

A big subject in the research is how mmWave setup connects with making networks denser. Since mmWave signals don't reach as far as signals with lower frequencies, providers must set up more small cells to ensure they have good coverage and enough capacity. Small cells can boost local network performance by positioning radio access points nearer to users. This cuts down on signal loss that happens over long distances and makes the data transfer speed better. But having many small cells installed means we need more energy, it costs more to set up, requires more connections to the main network, needs various permissions for the sites, and makes maintenance more complicated. This highlights the importance of planning for energy efficiency, particularly in countries like Saudi Arabia, where big smart cities and industrial zones might need thousands of connected network points.

The energy used in 5G networks comes from various parts, such as radio units, baseband processing, antennas, backhaul equipment, edge servers, power systems, and cooling systems. mmWave networks might lead to higher overall energy consumption because they need more radio stations compared to traditional macro-cell networks. The research shows that energy efficiency shouldn't be thought about only after something is put into use; it needs to be part of the planning right from the start. This involves choosing the best places for sites, steering clear of any unwanted overlap, using smart cell activation, adjusting the transmit power for better performance, and using hardware that saves energy.

Big MIMO and beamforming are also talked about a lot in studies of mmWave technology. Massive MIMO uses several antennas to enhance the quality of signals and support more users at the same time. Beamforming focuses radio energy towards the user rather than spreading it out in every direction. This is really important for mmWave because targeted beams can lessen signal loss and make coverage more dependable. Looking at it from an energy point of view, beamforming can help cut down on the unnecessary use of transmission power. In the busy cities and smart places of Saudi Arabia, these technologies can enhance how well networks work and save energy.Another key aspect is how smart sleep mode works. In regular networks, a lot of websites keep running even when there aren't many users visiting them. This creates unnecessary energy consumption. In mmWave networks, the amount of traffic needed can change a lot based on the time and where you are. For instance, places like stadiums, airports, business areas, and entertainment spots might have a lot of people wanting to use them during certain times, but at other times, not as many people might be interested. Smart sleep mode lets certain small cells lower their activity or turn off for a short time when there is less traffic, while still keeping service available through nearby cells. This can greatly lower energy use while still keeping a good experience for users.

Also, the importance of using AI for improving network performance is emphasized in the current review of the literature. The main goal of this project is to build a telecommunication network. However, AI can help save energy by predicting how much traffic there will be, spotting areas with too much congestion, adjusting power levels, turning small cells on or off, and directing beams in the best way. Since smart cities and digital areas in Saudi Arabia will create a lot of network data, using AI for operations would help in managing mmWave networks more effectively.

Renewable energy integration is another important theme. Saudi Arabia has a lot of potential for solar energy, and using renewable energy for telecom sites can help meet sustainability goals. Small solar-powered cells, mixed power systems, and energy storage options can be helpful in remote locations, industrial areas, highways, and specific urban settings. Even though mmWave is mostly used in crowded places, renewable energy can still help telecom systems by lessening the need for the power grid and cutting down on emissions from operations.

Furthermore, edge computing is associated with the preparation for developing efficient energy consumption in the mmWave technology. In fact, edge computing entails the proximity of computation processes to the end users, thus eliminating latencies and assisting smart manufacturing, autonomous driving vehicles, analysis for public safety, and digital twins. Nevertheless, edge devices use power. Therefore, there is a need to deploy computing resources in locations where it makes sense to increase performance. Thus, a good planning of edge computing would assist in saving unnecessary data transmission processes.

5.3 Table 1: Key Literature Themes in Energy-Efficient 5G mmWave Planning

Literature Theme	Main Finding	Relevance to Saudi Arabia
mmWave capacity	Provides very high speed and bandwidth	Supports smart cities, airports, giga-projects, and dense venues
Network densification	Requires more small cells due to short range	Needs careful planning to control cost and energy use
Beamforming	Improves signal direction and reduces wasted energy	Useful for urban and industrial mmWave deployment
Intelligent sleep modes	Reduces power during low-demand periods	Suitable for stadiums, business districts, and entertainment zones
Renewable energy	Can reduce grid dependency and emissions	Aligns with sustainability and clean energy goals
Edge computing	Reduces latency but requires efficient placement	Supports industrial IoT, smart mobility, and digital twins

Suggested Visual Figure

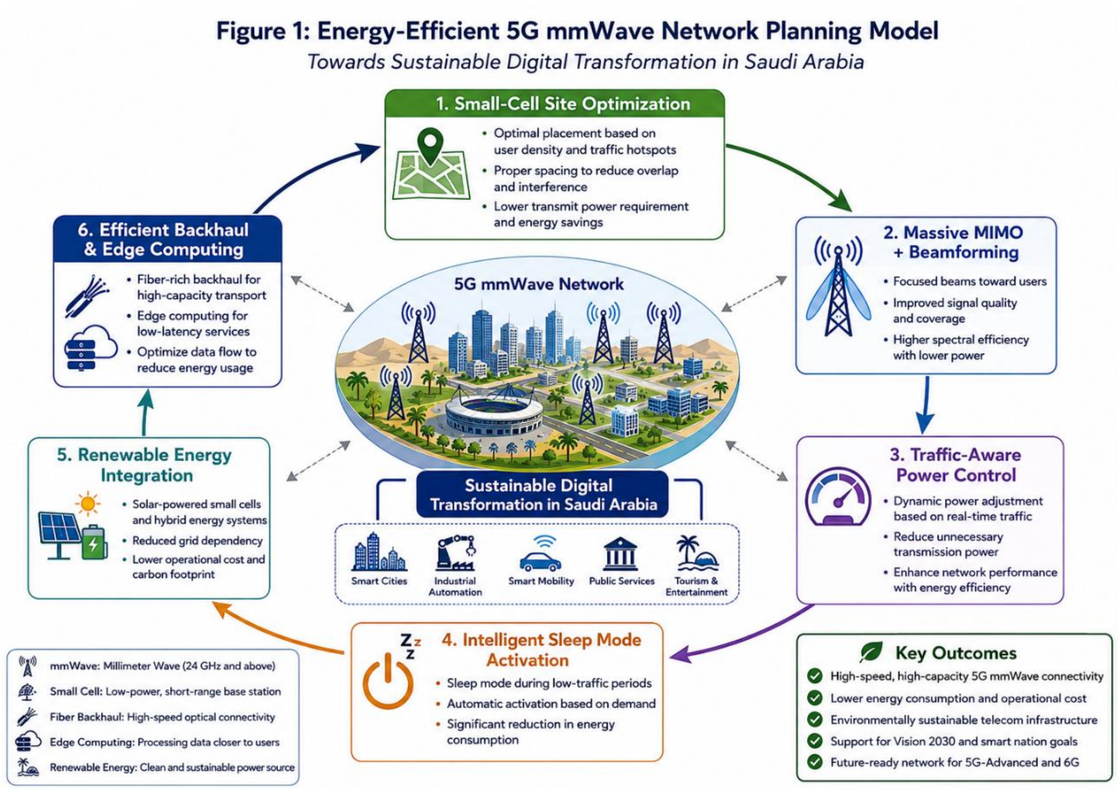

Figure 1: Energy-Efficient 5G mmWave Planning Model

5G mmWave Network Planning

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Small-Cell Site Optimization

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Massive MIMO + Beamforming

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Traffic-Aware Power Control

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Intelligent Sleep Mode Activation

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Renewable Energy + Efficient Backhaul

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Sustainable Digital Transformation in Saudi Arabia

3. Research Methodology

The proposed research will apply **a review-based qualitative methodology** in analyzing the aspects of energy-efficient 5G mmWave networks planning for sustainable digital transformation in Saudi Arabia. The reason for using a review-based qualitative research is that the topic being investigated is related to telecom planning, energy efficiency, mmWave deployment, digital infrastructure, and Vision 2030 sustainability goals. Thus, the review-based methodology is relevant to be used in the investigation.

The proposed methodology will consider five core dimensions. They include mmWave network requirements, energy consumption aspects, planning approaches, deployment conditions in Saudi Arabia, and sustainability benefits. The first dimension to be considered is the nature of mmWave communication which is highly technological. This kind of network possesses extremely high bandwidth and quick data transfer. However, mmWave networks should be densely deployed by using a lot of small cells due to the limited signal propagation range.

The second area examines energy consumption in 5G mmWave systems. Energy use is not limited to radio transmission only. It also includes radio units, antennas, baseband processing, fiber backhaul, edge computing equipment, power systems, cooling systems, and maintenance operations. In dense mmWave networks, the number of active sites can increase significantly, which may increase electricity demand and operational cost. Therefore, this study evaluates energy efficiency from a complete network-planning perspective rather than focusing only on individual base stations.

The third area looks at useful planning methods. These features consist of improving small-cell sites, using massive MIMO technology, directing signals with beamforming, having smart sleep modes, controlling power dynamically, using renewable energy, and managing the network based on traffic levels. Optimizing small cells is important because having too many sites too close together can waste energy and create more interference. Beamforming helps save energy by sending signals straight to users instead of spreading power in every direction. Smart sleep modes lower energy consumption when there is less activity. Using renewable energy can lessen the need for the power grid, particularly in certain outdoor areas, industrial zones, and smart city spots.

The fourth area shows how mmWave technology is being used in different parts of Saudi Arabia. Saudi Arabia has various connectivity requirements in its cities, tourist spots, industrial areas, transport centers, oil and gas sites, airports, sports stadiums, and large-scale projects. For instance, Riyadh and Jeddah need large urban networks, while NEOM and The Line need advanced smart infrastructure that is ready for the future. Airports and stadiums need to support a lot of people for a short time when they are really busy. Industrial areas need dependable, quick connections for their automation, monitoring, and safety systems. This study looks at these settings to find out where deploying mmWave can provide the most benefits while managing energy use effectively. The fifth area examines sustainability outcomes. The research looks at if planning for energy-efficient mmWave can lower operating costs, make the network more reliable, help with smart services, lessen environmental impact, and get the Kingdom ready for 5G-Advanced and upcoming 6G technologies.

This is important because Saudi Arabia's shift to digital technology should not just be about how fast the network is. It also needs to consider lasting sustainability, saving costs, and being responsible towards the environment. The process starts by figuring out the key technical problems that come with setting up mmWave technology. These problems include a short range for coverage, signals being blocked, difficulties getting signals inside buildings, the need for many sites close together, and the requirements for connecting different parts of the network. The next step is to find ways to save energy that can help lessen these problems. These features consist of turning on sleep mode, adjusting power use as needed, predicting traffic, placing cell towers in the best spots, and using renewable energy sources for power. Then, the research links these methods to examples from Saudi Arabia, including smart cities, automation in industries, tourism, logistics, and digital services for the public.

In addition, the methodology helps to create a framework to consider while deploying networks. The framework advises that mmWave networks deployed in Saudi Arabia should be considered from the angle of performance-energy balance. What this implies is that mmWave network deployments should consider not only locations that require high speeds, but also where high-speed deployments make economic sense. Locations to be considered include areas that have dense usage, highly valued digital services, or even mission critical needs.

Table 2: Methodological Framework for Energy-Efficient 5G mmWave Planning

Methodology Area	Main Focus	Evaluation Criteria	Saudi Arabia Relevance
mmWave requirements	Coverage, capacity, latency	Signal range, blockage, throughput	Smart cities, airports, stadiums, mega-projects
Energy consumption	Power use across network layers	Radio units, cooling, backhaul, edge systems	Reduces cost and supports sustainability
Planning strategies	Efficient deployment methods	Small cells, beamforming, sleep modes	Improves performance with lower energy use
Saudi use-case mapping	Local deployment environments	Urban, industrial, tourism, logistics zones	Supports Vision 2030 digital sectors
Sustainability outcomes	Long-term network impact	Cost, reliability, carbon footprint	Enables green digital transformation

Figure 2: Research Methodology Flow

Review of 5G mmWave Literature

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Identification of Energy Challenges

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Analysis of Network Planning Strategies

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Saudi Use-Case Mapping

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Performance-Energy Balance Framework

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Sustainable Digital Transformation Outcomes

This methodology provides a clear foundation for analyzing how Saudi Arabia can deploy mmWave networks in a technically strong, economically practical, and environmentally sustainable way.

4. Results and Discussion

The review findings show that energy-efficient 5G mmWave network planning is essential for Saudi Arabia because future digital services will require both high-speed connectivity and sustainable infrastructure performance. mmWave technology can provide very high data capacity, but if it is deployed without careful planning, it can increase energy consumption because of dense small-cell requirements, stronger backhaul needs, active antenna systems, and cooling demands. Therefore, the main result of this study is that mmWave deployment in Saudi Arabia should follow a targeted and demand-based planning model, rather than a wide-area deployment model.

The first major finding is that mmWave is most suitable for high-density and high-value zones. These include airports, stadiums, business districts, tourism destinations, industrial campuses, smart city districts, and giga-project areas such as NEOM and The Line. In these locations, many users, devices, and digital applications require large bandwidth at the same time. mmWave can support ultra-high-definition video, augmented reality, virtual reality, autonomous mobility, real-time monitoring, smart surveillance, and industrial automation. However, deploying mmWave in low-demand areas may not be energy-efficient because the short coverage range would require many small cells without enough traffic demand to justify the energy cost.

The second discovery is that **optimizing small** cells is one of the key strategies for saving energy. Because mmWave signals travel shorter distances, service providers require more small cells compared to the older macro networks. If small cells are set up too close to each other without careful planning, they can cause overlapping signals, interference, wasted power, and increased operating costs. Good site optimization can help save energy by putting cells in locations where there is a real need based on traffic demand, coverage gaps, and how many users there are. In Saudi Arabia, this is particularly helpful in smart neighborhoods, shopping centers, airports, and entertainment areas where traffic flows are easy to predict.

The third discovery is that **beamforming and massive MIMO** can enhance performance as well as energy efficiency. Beamforming directs radio signals towards particular users rather than sending power out in every direction. This helps to lower wasted energy and boosts signal strength, especially in mmWave networks where signal loss is significant. Massive MIMO enhances the use of available spectrum by enabling more users to be connected at the same time. These technologies are crucial for busy cities like Riyadh, Jeddah, and Dammam. In these places, a lot of users can lead to traffic jams if the network isn’t managed properly.

The fourth finding is that intelligent sleep mode activation can significantly reduce energy consumption. Traffic demand in mmWave zones is not always constant. For example, a stadium may need very high capacity during events but much less capacity on normal days. A business district may have high traffic during working hours but lower demand at night. Airports may experience changing traffic throughout the day. Intelligent sleep mode allows selected small cells to reduce activity or switch off during low-demand periods while maintaining minimum service through nearby cells. This approach can reduce power consumption without affecting service quality.

The fifth conclusion made by the authors is that renewable energy integration could facilitate sustainable telecom infrastructure development. Indeed, the country features excellent potential for solar energy utilization. Therefore, certain telecom stations could utilize the benefits of renewable energy solutions, which may be based on solar energy use, hybrid energy concepts, as well as battery storage technologies. Notably, renewable energy will not be sufficient to supply all mmWave sites; however, renewable energy integration could reduce the strain placed on the national grid system.

The sixth finding is that edge computing and efficient backhaul planning are essential for mmWave performance. mmWave access networks can provide high speed, but weak backhaul can create bottlenecks. Fiber backhaul is necessary for high-capacity transport, while edge computing can reduce latency by processing data closer to users. However, edge and backhaul equipment also consume energy. Therefore, operators should place edge nodes only in areas where real-time processing is needed, such as smart factories, autonomous mobility zones, healthcare systems, logistics hubs, and public safety operations.

In conclusion, the analysis reveals that Saudi Arabia should focus on integrating all aspects of performance, efficiency, and sustainability for its mmWave deployment. The best suited model for such an integration will be the performance-energy trade-off model, which ensures that mmWave is rolled out only in areas with evident demand, using intelligent power control, strategic small cell placement, renewable energy sources, and efficient backhaul infrastructure. Such a strategy will contribute to the realization of the Vision 2030 by facilitating smart cities and more.

7.2 Table 3: Results Summary for Energy-Efficient 5G mmWave Deployment

Key Result	Explanation	Impact on Saudi Arabia
Targeted mmWave deployment	mmWave should be used in high-demand zones, not everywhere	Reduces unnecessary energy use and cost
Small-cell optimization	Proper placement prevents overlap and wasted power	Improves efficiency in smart cities and venues
Beamforming and Massive MIMO	Directs signals toward users and improves capacity	Better performance with lower energy waste
Intelligent sleep modes	Reduces site activity during low-traffic periods	Saves energy in stadiums, airports, and business zones
Renewable integration	Uses solar/hybrid power where practical	Supports sustainability and lower emissions
Edge and backhaul efficiency	Places computing and fiber resources strategically	Supports low latency and reliable services

Suggested Visual Figure

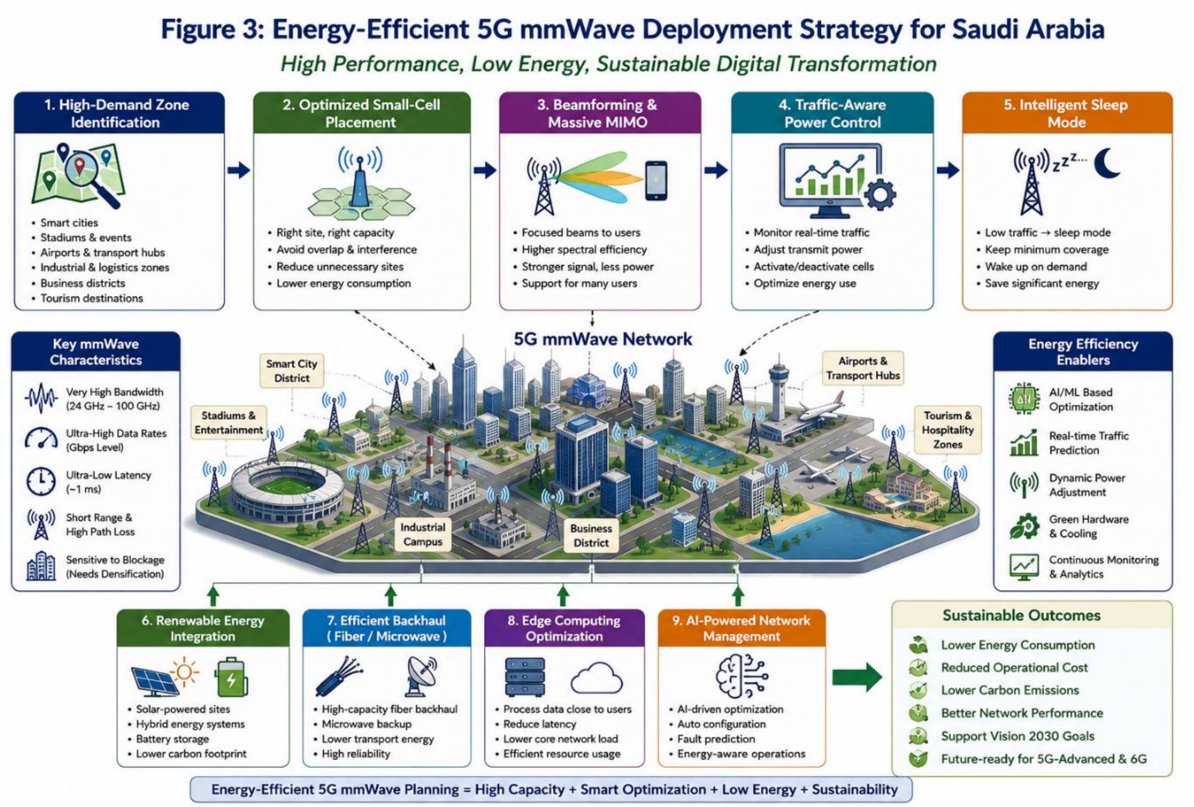

Figure 3: Energy-Efficient mmWave Deployment Strategy for Saudi Arabia

High-Demand Zone Identification
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Optimized Small-Cell Placement
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Beamforming + Massive MIMO
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Traffic-Aware Power Control
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Sleep Mode During Low Demand
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Renewable Energy + Efficient Backhaul
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Sustainable 5G mmWave Network

5. Conclusion and Future Recommendations

This study finds that planning energy-efficient 5G mmWave networks is important for helping sustainable digital growth in Saudi Arabia. mmWave technology can offer very fast wireless communication, very low delay, and a lot of network capacity. This makes it a great choice for smart cities, industrial automation, big projects, tourist spots, airports, entertainment places, and future smart infrastructure systems. The study also shows that using mmWave technology brings about major energy and infrastructure issues. This is due to its short signal range, the need for many small cells, high demands for backhaul, and added complexity in operations.

The results indicate that to successfully set up mmWave technology in Saudi Arabia, it is important to have a strategy that balances strong network performance with energy efficiency and sustainability. The best way to use mmWave technology is to focus on specific areas where there is a high demand for it, rather than trying to make it available everywhere in the country. This helps operators make the most of capacity in important areas while cutting down on extra energy use and lowering infrastructure expenses.

The research also points out how important it is to use advanced optimization technologies. These include beamforming, massive MIMO, smart sleep modes, power management that considers traffic, edge computing, and the use of renewable energy. These technologies can greatly lower the amount of energy used in operations while also making the network more reliable and enhancing the experience for users. Beamforming and massive MIMO make better use of the available signal space and cut down on unnecessary energy during transmission. At the same time, smart sleep modes help to save power when there is less demand. Telecom sites that use renewable energy can help protect the environment and reduce carbon emissions.

From a national development perspective, energy-efficient mmWave planning strongly supports Saudi Vision 2030 objectives. Smart cities, industrial digitalization, smart mobility, intelligent tourism services, healthcare innovation, and public digital infrastructure all depend on high-capacity wireless communication systems. Therefore, sustainable telecom planning should be considered part of the Kingdom’s long-term economic and digital infrastructure strategy.

In the case of future development, it is advisable for Saudi Arabia to make more investments in the development of 5G-Advanced technologies, AI-enabled telecommunication networks, eco-friendly infrastructure, and future 6G networks research. In addition, there needs to be an increase in investment in fiber deployment, cloud-native telecommunication systems, green hardware, and intelligent network operation.

Finally, from the findings of this research, it can be concluded that the use of energy-efficient 5G mmWave technology in Saudi Arabia will make great strides towards not only technological advancement but also environmental sustainability.

Table 4: Future Recommendations for Sustainable 5G mmWave Deployment

Recommendation Area	Strategic Focus	Expected Benefit
Smart deployment planning	Deploy mmWave mainly in high-demand areas	Better energy efficiency and lower cost
AI-assisted optimization	Use intelligent traffic and power management	Reduced operational energy consumption
Renewable energy integration	Increase solar-assisted telecom infrastructure	Lower emissions and sustainable operations
Fiber and edge expansion	Improve high-capacity low-latency connectivity	Stronger network reliability
5G-Advanced and 6G research	Invest in future wireless technologies	Long-term digital competitiveness
Green telecom infrastructure	Promote energy-efficient equipment and cooling systems	Sustainable network operations

6. Future Scope

Future opportunities for energy-efficient 5G mmWave-based networks in Saudi Arabia are directly tied to the country's ongoing digital transformation and future smart infrastructure initiatives. With the rise in demand for ultra-high-speed connections, it will be important for telecommunication companies to go beyond their conventional approach to network rollouts and embrace smarter, automated, and eco-friendly wireless environments. Future advances in 5G-Advanced and 6G technology would allow for improvements in spectrum usage, network intelligence, reduced latency, and energy savings.

One of the major future opportunities is the integration of **AI-driven autonomous network management systems**. Future networks will increasingly use artificial intelligence to monitor traffic patterns, predict congestion, optimize beamforming, control power usage, and activate sleep modes automatically. This will reduce operational energy consumption while maintaining strong network performance. AI-assisted optimization will be especially important in Saudi smart cities and giga-projects where millions of connected devices and sensors will require continuous high-capacity connectivity.

Another emerging area for the future will be the growth in private 5G industrial networks. Oil and gas industries, logistics services, manufacturing industry, mining industries, aviation, and ports are likely to implement their own private networks using mmWave technology for secure and low latency communications. Private 5G networks would enable automation, robots, intelligent monitoring, and many other applications. It would be critical to plan for energy efficiency since these industries could be operating 24/7..

The future development of **green telecom infrastructure** is also expected to become more important. Saudi Arabia has strong solar energy potential, and future telecom sites may increasingly use hybrid renewable energy systems, advanced battery storage, energy-efficient cooling systems, and low-power hardware designs. Sustainable telecom infrastructure can help reduce environmental impact while lowering long-term operational costs.

Future research may also focus on **6G communication technologies**, which are expected to support intelligent digital ecosystems, immersive communication, integrated sensing systems, satellite-terrestrial convergence, and advanced edge intelligence. Saudi Arabia has the opportunity to become a regional leader in next-generation wireless innovation by combining smart infrastructure investment with future telecom research and development.

7. Limitations of the Study

This study is based on reviews, so it doesn't have any live measurements taken from telecom sites in Saudi Arabia. Real mmWave performance can vary based on how many sites are nearby, the type of buildings around, the amount of users, the weather, whether devices can connect properly, the capacity of the backhaul, and how the network is set up by each operator. Another limitation is that mmWave and 5G-Advanced technologies are still developing, which means that future updates to regulations, new spectrum releases, and commercial trials could alter the priorities for their deployment. Future research can involve actual tests of network speeds, measuring energy use, comparing different operators, and looking at case studies from places like Riyadh, NEOM, Jeddah, airports, and industrial areas.

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