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# A Comparative Study of mmWave vs. Sub-6 GHz 5G Networks for Urban Environments

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**ABSTRACT**

The performance of the millimeter-wave (mmWave) and Sub-6 GHz frequency bands for 5G networks are compared in this work, particularly for urban scenarios. Considering that the 5G technology is evolving, these two bands have their features providing specific opportunities and issues for populous regions. It assesses the utilization of KPIs such as data rate, coverage, latency, and penetration capacity that is significant in meeting smart city connectivity needs; mmWave bands have high data rate and low latency suitable for near real-time applications like self-driving cars and telesurgery, but its restrictive coverage and sensitivity to physical obstacles limit it when used in large areas. On the other hand, Sub-6 GHz frequencies offer wider coverage and better penetration through barriers for lower data rates. They are more suitable for general broadband internet and many other applications with acceptable delay. This paper explains using band-wise mmWave's and Sub-6 GHz's pros and cons in detailed graphical analysis and case studies while presenting a novel mixed model for mmWave and Sub-6 GHz bands to uncover their best attributes. These bands, when integrated, will help 5G networks meet multifaceted needs of connectivity in cities, providing high-speed connections in dense areas and sustaining steady links across vast distances. This has implications for future urban network planning; it brings into focus issues of intelligent network management and energy-efficient sustainable formations of infrastructure. The findings from this study offer meaningful recommendations for enhancing the utilization of 5G in urban settings to support smart city projects and future smart economy development.

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## Introduction

5G profound evolutions over current technologies expect higher data rates, lower latency, and support multiple device connections. These enhancements have opened new possibilities for earlier unfeasible applications, including the domains of medicine, transportation, fun, and industry. 5G is the most advanced wireless technology, which has the power to meet the never-stopping growth of data consumption in modern society and the burgeoning Internet of Things devices, each of which necessitates a steadfast and prompt connection. The framework of 5G Millimeter wave (mmWave) and Sub-6 GHz, the primary spectrum bands, is critical. Comparing the bands, they have various features that must determine how well they can meet consumers' needs while operating in densely populated urban areas – where connectivity issues are most severe. Frequency bands in mmWave frequency usually start from 24GHz and above with capabilities of very high data rates, although with restricted range and penetration. Sub-6Sub-6 GHz frequencies are below 6 GHz, where the coverage is wider and has better penetration but at standard rates. The two bands are quite different, and understanding these differences is important in determining the best course of action when planning for cities and deploying networks.


**Figure 1:** 5G Evolution

## Background

The evolution of 5G technology has been driven by the pressing need to address several critical demands [1]. Mobile broadband is a new generation of wireless communication technologies, the growing numbers of IoT devices, and the emergence of real-time services. Contrary to precedents where generations succeeded, always creating a more progressive and sophisticated system, 5G was envisioned as a revolution or as a new generation of connectivity required and expected by the society that develops as digitalized. One of the improvements characteristic of 5G is that it provides a higher data rate, allowing unlimited and synchronous high-definition (HD) video streaming, supporting complex real-time services. For example, high data transfer rates are possible, enabling high-quality, remote surgeries, an application requiring interruption, and latency-free connectivity. Further, 5G brings a lower level of latency, an important factor for applications that require low response time, like self-driving cars and telerobotics. Reduced latency, as it lets the connected devices interact instantly, increases the reliability of the devices that need to respond quickly. Also highly important is the concept of massive connectivity, a characteristic of the 5G, which means there are as many connected devices within cities as possible. This capability is critical because today's cities are implementing smart structures using smart infrastructure to connect with smart citizens through smart products like street lamps, traffic lights, wearables, and smart homes.

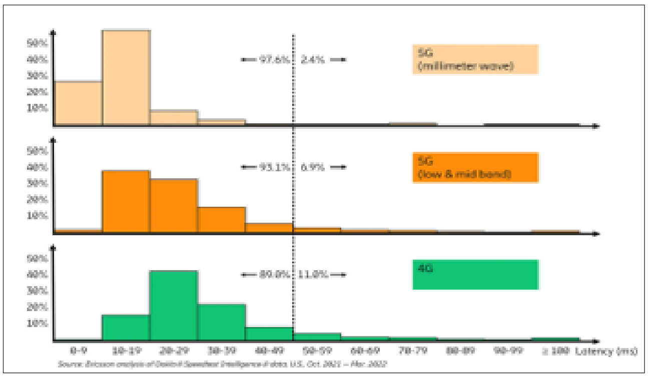



**Figure 2:** Sub-6 GHz 5G vs mmWave 5G

## Objectives

The main purpose of this work is to provide a comparative evaluation of the mmWave and Sub-6 GHz 5G networks and determine the advantages and disadvantages of the two networks. By assessing these facets of an operation, the study aims to provide a general understanding of when each frequency band is preferable to the other in light of present-day urban use. One objective of this study is to provide a quantitative investigation of the data rate, latency, and coverage of the deployed mmWave and Sub-6 GHz networks. This comparison will explain how each band can satisfy applications with diverse needs, such as high capacity compared to large coverage. Furthermore, the research will evaluate whether mmWave and Sub-6 GHz are appropriate in various urban settings, noting that some applications, such as smart city systems, may be more effective in utilizing the specific characteristics of one band over the other. This research reveals that particular problems relate to various technologies when implemented in the urban setting. For instance, the limited transmission range and vulnerability to interference in the case of the mmWave spectrum may not be as efficient in large cities, while the Sub-6 GHz band may experience network overcrowding in densely populated areas. In achieving these objectives, the study hopes to provide insights to aid the provision of knowledge for the planning and deploying the 5G network [2].

## mmWave 5G Networks

Millimeter-Wave (mmWave) 5G technology is one of the strategic developments introduced in the telecommunication industry, which has conjured opportunities for massive urbanized areas. The text of this section looks at various aspects of 5G mmWave, including its features, strengths, limitations, and an example of how it can be used to construct a smart city. For frequency bands above 24 GHz, Taiwanese mmWave provides particularly beneficial data rates and densities better suited for urban settings flooded with consumers.

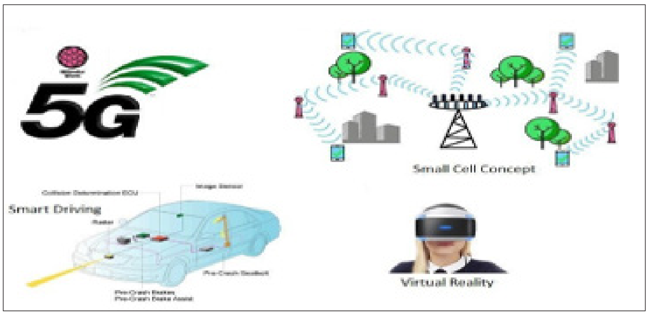



**Figure 3:** Millimeter Wave Technology

## Characteristics

The attributes of mmWave 5G make it unique compared to other 5G frequencies, especially sub-6 GHz. Due to features such as frequency, data rates, and bandwidth, it is appropriate for high-density applications. However, the same characteristics also put some restrictions.

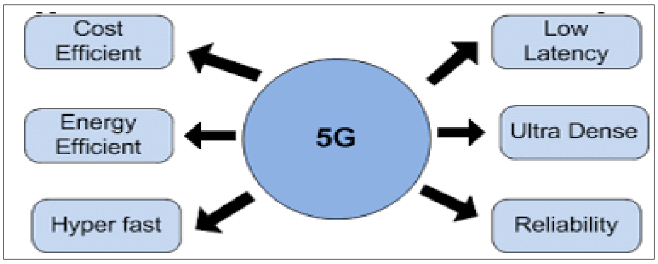



**Figure 4:** Distinguishing Features of 5G

- **Frequency Range:** mmWave technology uses the range of 24 GHz—100 GHz, which is significantly higher than that of Sub-6 GHz, which is below 6 GHz [3]. Such density facilitates great data transmission capacities because greater amounts of information can be transmitted within this range because of the short wavelengths.
- **Data Rates:** mmWave 5G, at its best, can deliver data rates above 10 Gbps. This high speed sets mmWave apart for real-time data transfer applications, such as Ghosh et al [3]. Thus, large magnetization for FMC with high-velocity communication can be supported by applications such as HD video streaming and VR, which are in the large-volume data exchange environment of urban areas.
- **Bandwidth Availability:** The carrier bandwidth available to support operation in the mmWave frequency range is much bigger than the sub-6 GHz range, enabling better capacity and throughput. Due to the higher allowed frequency range, there will be a higher number of users supported in mmWave networks, but at the same time, there will be higher data rates. This high capacity is still especially important in the areas of the highest user density, such as major cities, because congestion in a lower network frequency is often observed [3].

All these characteristics together define mmWave as a valuable tool for some specific city applications. However, the high frequency and short wavelength also influence some other disadvantages, which are explained in the next sections. These include limitations in the range of transmission and poor penetration power.

**Advantages**
The greatest advantages of applying mmWave 5G technology are its ability to handle a large amount of information and very low delay [4]. Therefore, the technology will be great for big cities with significantly high traffic.

- **High Capacity:** The wider bandwidth in the mmWave frequency band implies the ability to support more users and connection-bearing devices simultaneously. This is especially important in areas with higher population concentration, such as business districts, urban centers, and crowded places, because the ability to transmit data is not prejudiced by high user density [3]. Since offering more network capacity, mmWave networks can accommodate demanding services such as video call connections, cloud services, and IoT applications.
- **Low Latency:** mmWave, by design, provides low latency that, in many instances, can be below one millisecond. Such ultra-low latency is critical for real-time operations where instant and accurate responses are decisive, like self-driving cars, telesurgery, and smart industries. Coordinating with real-time data transfer, mmWave networks are suitable for use in areas where a delay might cause operational loss or jeopardy [3]. In modern cities, incorporating smart technologies executed based on various systems makes it significant to apply the extremely low latency options inherent in mmWave 5G.

**Challenges**
However, mmWave 5G technology comes with several challenges, especially those related to the technology's coverage range and penetration [5]. These things affect its utilization and dampen its efficiency in specific urban conditions.

- **Limited Range:** There is no doubt that one of the major drawbacks of mmWave 5G is low coverage. While long transmission ranges characterize lower frequency bands, mmWave signals have a less effective transmission range, less than 500 meters under the best circumstances [3]. Since mmWave signals transmit much more frequently than other frequencies, it is fragile to attenuation, which is the reduction in signal strength with distance. This characteristic means that mmWave networks require a denser population of these small cells or base stations in the urban environment than lower frequency bands, thus adding to the overall cost and roll-out problem.
- **Penetration Issues:** A well-known issue of mmWave technology is its inability to penetrate deeply through buildings and various obstacles. Like all other high-frequency signals, mmWave fails miserably when it comes to indoor penetration because they do not penetrate through walls or other opaque objects. Conversely, environmental impacts such as rain, foliage, atmospheric conditions, and so on all add to the degradation of mmWave signals, making this technology problematic in less controlled settings [3,6]. These penetration issues reduce the application's practicality of mmWave networks in densely built-up cities with numerous physical barriers, which require the integration of Sub-6 GHz networks for indoor and larger coverage.

**Example Application**
Since the mmWave 5G offers higher capacity and lower latency, its most suitable application is in smart city infrastructure, such as Traffic Management Systems, which require real-time analysis.

- Smart City Infrastructure: The high data rates and the low latency of the mmWave technology are suitable for smart city applications such as smart traffic systems [7]. In a smart city context, traffic lights, cameras, and sensors always produce large amounts of data to be processed in real-time to improve traffic flow and reduce traffic congestion. Thanks to the low latency provided by mmWave networks, those systems can quickly react to traffic conditions and make roads safer and more efficient in urban environments [3]. Given the ability of mmWave to provide high bandwidth and low latency, it is in a position to provide sufficient data throughput required for smart city applications, including real-time change of direction for ambulance and fire tenders and traffic flow prediction. The incorporation of mmWave networks into smart city structures is a progressive approach to city development that attempts to enhance the quality of life of people within a specific city through the effective utilization of data.

**Table 1: Overview of mmWave 5G Network Characteristics, Advantages, Challenges, and Applications**

| Section | Key Points | Details |
|---|---|---|
| Characteristics | Frequency Range | Operates between 24 GHz and 100 GHz, allowing for substantial data transmission capabilities due to shorter wavelengths (Ghosh et al., 2014). |
| | Data Rates | Achieves data rates exceeding 10 Gbps under optimal conditions, making it ideal for applications that require high-speed data transfer in urban environments (Ghosh et al., 2014). |
| | Bandwidth Availability | Offers larger bandwidth than Sub-6 GHz, supporting more users simultaneously without compromising data speeds (Ghosh et al., 2014). |
| Advantages | High Capacity | Suitable for densely populated urban areas, ensuring efficient data transmission even with high user density. Supports applications like video conferencing and cloud computing (Ghosh et al., 2014). |
| | Low Latency | Provides latency below 1 millisecond, essential for applications needing real-time response, such as autonomous vehicles and industrial automation (Ghosh et al., 2014). |

| | | |
|---|---|---|
| Challenges | Limited Range | Effective range is typically less than 500 meters, requiring a dense network of small cells or base stations to ensure coverage in urban settings. Increased deployment complexity and cost (Ghosh et al., 2014). |
| | Penetration Issues | Poor ability to penetrate solid obstacles, such as buildings, and highly susceptible to interference from environmental factors like rain and foliage. Limits effectiveness in indoor or obstructed environments (Ghosh et al., 2014; Gill, 2018). |
| Example Application | Smart City Infrastructure | Ideal for real-time data processing applications in smart cities, such as intelligent traffic management systems. Enables real-time adjustments to improve traffic flow and safety by utilizing mmWave's high data rates and low latency (Ghosh et al., 2014). |

**Sub-6 GHz 5G Networks**

With the world being ahead on the line of a highly connected society, the features of 5G technology are imperative to provide optimum speed networks [8]. Regarding the main 5G frequency bands, Sub-6 GHz is particularly important and relevant in cities as it provides optimal speed and coverage compromises. The characteristics, advantages, challenges, and applications of Sub-6 GHz 5G networks are presented and compared with those of the mmWave frequencies, as well as a discussion on the differences in coverage, penetration, and capacity between both.

**Characteristics**

Sub-6GHz in 5G is strategic to support data rate, coverage, and reliability as the band is promising for urban and suburban areas. This band comprises the low-band and mid-band spectrums to get a wider area than mmWave but generally a lower data rate.

- **Frequency Range:** Sub-6 Ghz refers to frequencies below 6 GHz, in which subcategories include low-band at below 1GHz and mid-band frequencies ranging from 1 to 6 Ghz [9]. These ranges enable the Sub-6 GHz frequencies to cover even more vast distances than those offered by mmWave while serving large populations common in urban settings.
- **Data Rates:** For Sub-6 GHz 5G, it is possible to achieve data rates of at least 100 Mbps to as high as 1 Gbps [10]. Though this remains much slower than mmWave frequencies, it is much faster than 4G LTE networks and should be adequate for most consumer and business use cases. This data rate level is useful for things like streaming video, playing video games, or almost any web surfing that a person might do.
- **Coverage:** Another essential benefit of sub-6 GHz frequencies is that their range is significantly wider than that of a millimeter wave and can range from several hundred to several kilometers, depending on the availability of supporting infrastructure. Compared with mmWave, Sub-6 GHz can cover a larger area with fewer base stations to be deployed in urban scenarios and thus has lower deployment costs [11]. This characteristic also makes Sub-6 GHz networks reliable and ubiquitously deployable in different terrains.

The properties of Sub-6 GHz frequencies represent a balanced and versatile 5G experience, which is useful for a wide range of applications that demand high speed and coverage, together with reasonable costs.

**Advantages**

As delineated beneath, the Sub-6 GHz band has unique attributes that make it suitable for deployment in urban areas and beyond. mmWave supports high speed but lacks coverage and poor penetration; sub-6 GHz has extensive connectivity and stronger penetration, which are important when deployed in cities.

- **Wider Coverage:** Sub-6GHz can reach far-ranging, and as such, it can be deployable for rural and suburban areas and the urban setting coupled with the dense population. This broad coverage reduces the need for a high density of base stations in urban areas, thus favoring carriers and allowing users to stay connected over large areas. This broad-based capacity improves the level of access for residents as well as for businesses.
- **Improved Penetration:** A part of sub-6 GHz can pass through the buildings and other barriers that are quite challenging for mmWave frequencies, and this is important in urban environments with high-rise constructions [10]. Frequencies are to be used to penetrate deeper into the building and indoor areas to provide better continuity of signals when there are barriers such as walls, trees, or other structures in the direct visions of transmission. This advantage makes Sub-6 GHz ideal for residential and business broadband, where indoor connectivity is a big consideration.
- The Sub-6 GHz frequency compromises wide-area coverage and indoor penetration, making it suitable for most technologically enhanced urban requirements where constant end-to-end connectivity is paramount.

**Challenges**

There are also significant disadvantages of Sub-6 GHz frequencies that mainly affect densely populated regions. The main difficulties are lower channel capacity and possible network loading, which decreases the overall network's availability with increasing request amounts.

- **Lower Capacity:** Sub-6 has less bandwidth than mmWave frequencies and, as such, cannot support the amount of data that networks [11]. Consequently, wireless Sub-6 GHz networks may face performance issues in densely populated areas for densities that outstrip the networks' throughput. This capacity limitation can be a significant issue, especially for those organizations operating in large urban regions where customers often connect simultaneously.
- **Congestion:** With the restricted bandwidth and high application, Sub-6 GHz is congested at some heavily populated sites [12]. In cities with high demand for connectivity, several networks may get congested, resulting in slow data speeds and poor service quality for users. The congestion of the available networks can also impact the scalability of the Sub-6 GHz networks, which implies that there is a need to add more infrastructure or use smarter techniques to manage the congestion to meet the expected service levels.

While sub 6 GHz is effective for most applications, these challenges suggest that it may not be effective in high-density environments where ultra-high speeds are needed. These are typical for large cities, and their management typically entails many efforts and the usage of adequate networks.

### Example Application

Among the many deployment scenarios of Sub-6 GHz networks, home broadband access is one of the most significant in urban areas [13]. Due to its coverage and penetration range, Sub-6 GHz is very useful in delivering fast internet connections to households and businesses within urban and suburban areas.

- **Broadband Connectivity:** Sub-6 GHz 5G frequencies are specifically well suited for residential broadband services as they provide a harmonious mix of speed, reliability, and price [10]. Because the networks can support streaming, browsing, and other typical internet use, Sub-6 GHz networks can serve as broadband substitutes for wired broadband, where installing fibers or cables is expensive or impossible, such as in urban centers. It also enables service providers to deploy broadband connectivity easily and at a low cost and enhance internet availability and quality of service in cities.

Apart from the home, Sub-6 GHz networks provide numerous other urban applications that require reliable connectivity, including smart cities, IoT, and public safety applications. With the help of the Sub-6 GHz campaign, urban analysts and network suppliers can build a heterogeneous connectivity environment that will efficiently satisfy the requirements of urban dwellers.

**Table 2: Overview of Key Characteristics, Advantages, Challenges, and Applications of Sub-6 GHz 5G Networks**

| Aspect | Description |
|---|---|
| Frequency Range | Up to 6 GHz (includes low-band and mid-band frequencies) |
| Data Rates | Generally between 100 Mbps and 1 Gbps |
| Coverage | Greater coverage area than mmWave, spanning several kilometers depending on infrastructure |
| Advantages | - Wider Coverage: Suitable for urban, suburban, and rural areas due to extensive reach |
| | - Improved Penetration: More effective at penetrating buildings and obstacles in urban settings |
| Challenges | - Lower Capacity: Less bandwidth compared to mmWave, leading to potential bottlenecks in high-demand areas |
| | - Congestion: Prone to congestion in densely populated regions due to limited bandwidth |
| Example Application | Broadband Connectivity: Ideal for residential broadband in urban areas, offering a balanced solution for speed, reliability, and affordability |

### Comparative Analysis

Millimeter-wave and Sub-6 GHz 5G networks provide heterogeneous performance in terms of key parameters, which determine their suitability for use in cities [14]. This work aims to compare these differences, considering aspects such as data rate, coverage range, latency, and penetration. Further, trends in performance are presented graphically, and there is also a block diagram that gives an understanding of 5G network architecture and the specific engagements of mmWave and Sub-6 GHz in urban areas.

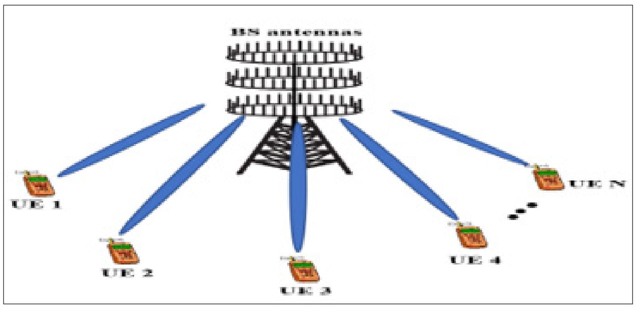



**Figure 5:** Massive MIMO Scenario

### Performance Metrics

The objectives of 5G networks are best characterized by parameters such as data rate, coverage range, latency, and penetration. All these metrics help us understand the relevance of both mmWave and Sub-6 GHz frequencies for some selected urban use cases [15].

- **Data Rate:** Data rate is one of the performance indicators that set mmWave against Sub-6 GHz. In the finest circumstances, mmWave capability can offer connections beyond 10 Gbps, a giant leap from the customary 100 Mbps to the 1Gbps range advertised for Sub-6GHz technologies [16]. Therefore, to support such applications like HD streaming, virtual reality, and cloud-based, mmWave offers a high data rate suitable for such uses. Nevertheless, the data rate of mmWave is affected by environmental profile and depends on LOS conditions. On the other hand, Sub-6Ghz, with comparatively far lesser data rates, is not influenced much by obstacles and can provide a reliable connection over a large area, making it suitable for applications where the exceedingly high data rate is not mandatory, such as general mobility broadband.
- **Coverage Range:** Another important parameter is the coverage range, which is substantially shorter, especially in the case of mmWave, which is in the higher frequency range with distances normally below 500 meters [16]. Sub-6 GHz, however, can stretch up to 5 kilometers depending on the frequency of this band. This is because mmWave cannot penetrate through obstacles obstructing its path, such as buildings and other structures found in urban areas, hence the shorter range. In dense user environments, mmWave can only offer connectivity at a fairly limited range, meaning that small cells need to be deployed denser to support the connection. On the other hand, Sub-6 GHz has the upper hand in both urban and suburban scenarios because it can extend a wide coverage with fewer base stations; hence, it is economical and practical for overall urban deployment.
- **Latency:** Another essential requirement for 5G is low latency, especially for self-driving cars, telemedicine, and other remote industrial controls. Low latency of up to 1 ms is supported using mmWave technology in the best-performing environment and is a key factor for real-time applications

[12]. Sub-6GHz, which can provide far lower latency than 4G networks, usually floats between 1 to 10 milliseconds. This is a benefit for applications that require quick exchange of data, and it is well known that with mmWave, latency is much lower. Sub-6 GHz with moderately higher latency is unsuitable for ultra-reliable low-latency communication applications but can be effective for most urban internet traffic.

- **Penetration:** Another suitable parameter is the ability of a frequency band to penetrate through obstacles, particularly walls and buildings typical for urban environments; conventional canopy suffers from poor penetration due to mmWave's high frequency which is easily absorbed or reflected by structures, providing rather poor indoor coverage. Sub-6 GHz, on the other hand, can penetrate through walls and other obstacles more effectively, thus offering better indoor connectivity than mmWave in the urban environment [12]. This penetration advantage makes Sub-6 GHz more suitable for offering continual coverage over different urban topographies, including indoors and subways, densely packed high-rise buildings that would greatly diminish mmWave signals.

**Table 3: Comparative Performance Metrics of mmWave and Sub-6 GHz 5G Networks in Urban Environments**

| Metric | mmWave | Sub-6 GHz |
|---|---|---|
| Maximum Data Rate | > 10 Gbps | 100 Mbps - 1 Gbps |
| Coverage Range | Short (< 500 m) | Medium (1-5 km) |
| Latency | Low (< 1 ms) | Moderate (1-10 ms) |
| Penetration | Poor | Good |

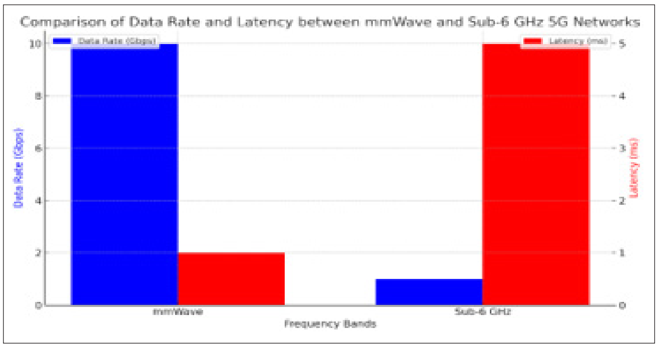
### Graphical Representation

Based on the analysis above, one way to differentiate between mmWave and Sub-6 GHz is by plotting graphs showing performance over distance and latency [17]. In the first graph, the data rate is plotted in terms of distance over both bands of frequency. As for mmWave, it should be noted that data rates are introduced very high, 10 Gbps, but quickly drop with distance over several hundred meters. The rapid drop is attributed to mmWave's limitations in terms of range and interference by surrounding structures. The 5GTALastly, Sub-6 GHz depicts the opposite trend from what CA has shown, with constantly decreasing data rate as it covers a larger range, albeit with lower peak speeds.

The second graph shows mmWave and Sub-6 GHz latency disparity under different conditions. As evident, mm-Wave has an ultra-low latency within the limited coverage area, and the latency usually stays below 1 ms under the line of sight (LOS) condition. Therefore, while Sub-6 GHz has low latency, it does not achieve mmWave's minimum values and shows higher latency if the distances are extended or there are separation barriers. One of the significant differences between mmWave and Sub-6 GHz is that the former is best for latency-sensitive applications in the near field. At the same time, the latter can cover moderate applications that do not require extremely low latency. Both graphs underscore the trade-offs in deploying these two technologies: mmWave works best over short distances and in high-density areas where low latency is desired. At the same time, Sub 6GHz is used where broader area coverage is needed with a moderate data rate and slightly higher latency [15].

### Graphical Representation

- **Graph 1:** Data Rate vs. Distance for mmWave and Sub-6 GHz
- **Graph 2:** Latency Comparison between mmWave and Sub-6 GHz




### Block Diagram

A conceptual block diagram furnishes a conceptual view of the 5G network architecture in terms of both mmWave and Sub-6 GHz [18]. Some of the core equipment that make up this architecture are Radio Access Network (RAN), Core Network, and User Equipment (UE). In that regard, the RAN in urban 5G networks will comprise many small cells, particularly mmWave, which requires immense density when deploying the network since its coverage is limited. Due to the high vulnerability of mmWave to external interferences and to avoid compromising its short coverage radius, it is vital to have many small cells distributed densely. Subsequently, Sub-6 GHz works with fewer cell sites due to the extended coverage range. Sub-6 GHz small cells could cover a larger area and extraneous infrastructure, thus lowering deployment costs. The Core Network is another subsystem that controls data transmission and forwarding in the transition between the RAN and other networks. For Sub-6 GHz and mmWave, the Core Network manages data flows and allocates resources related to network handling, while in some cases, especially when high data rate and low latency application is needed, additional processing of the signals is required for mmWave.

The block diagram also points to the integration between mmWave and Sub-6 GHz when implemented under a hybrid 5G deployment strategy. In such architectures, mmWave may be used abundantly, specifically for high-traffic areas such as business or event halls requiring dense deployment. In contrast, Sub-6 GHz is used to cover all areas in urban areas. This type of combined model of the choice of frequency band allows network providers to achieve the advantages of each frequency band in compliance with the requirements of the urban environment and to build a solid and diverse 5G experience. The comparative analysis shows that Sub-6 GHz has advantages that supplement each other. In contrast, mmWave has a high data rate and low latency and is perfect for communications in highly populated areas but incurs high infrastructure costs. Due to wide coverage, better penetration, and moderate data rate, Sub-6 GHz becomes conducive for more general urban connectivity as it offers people a secure and stable version of urban internet experience in different urban settings [18].

### Factors Related to Urban Still Environment

The strategic deployment of 5G technology in functionality in smart cities is a challenge, as are the consequent requirements when comparing the mmWave and Sub-6GHZ frequency bands. Due to the high population density and fixed structures, the networks in urban areas need to be well planned. This concerns the deployment requirements and the regulatory and environmental requirements specific to mmWave and Sub-6 GHz 5G in city environments.

### Infrastructure Requirements

5G networks need to be deployed in urban environments, and deep investment into a system of networks is called for by the huge throughput of data and low latency that this technology holds [8]. Infrastructural requirements vary with frequencies of mmWave and Sub-6 GHz because mmWave has high range, low penetration, and is easily affected by interference, while Sub-6 GHz has low range, good penetration, and is least affected by interference.


**Figure 6:** 5G System Overview for Ongoing Smart Applications

### Density of Small Cells

The major constructional imperative affecting mmWave 5G networks is continuous small cell deployment density. Because mmWave has a high operation frequency range of 24 to 100 GHz, the signal can only propagate a short distance before the signal power is significantly damped [19]. This limited range makes mmWave networks more likely to need a larger number of small cells or base stations with a small coverage area. In urban areas, such small cells are mounted on structures, for instance, lamp posts or traffic lights, or on the facades of buildings to offer the required densification. Nevertheless, this conurbation of small cells also increases installation costs significantly. Each small cell must be positioned to have maximum coverage and ensure reception continuity in such congested structures common in urban areas.

Signals in the band below 6 GHz — known as Sub-6 GHz — can easily cover a much larger area owing to its lower frequency, making signals travel farther before they are attenuated [20]. That is why it is easier to invest in Sub-6 GHz since there are fewer cells required to deliver broad coverage. For the urban environment, this feature of Sub-6 GHz to offer wider coverage capability is more beneficial because it has to cover almost all users within multiple regions without having to install loads of base stations. Therefore, although mmWave inherently needs more base stations and rigorous planning to guarantee sufficient coverage, Sub-6 GHz could provide the necessary signal quality when utilizing fewer small cells; thus, this makes Sub-6 GHz more practical for broad city coverage [19].

### Backhaul Considerations

This leads to the other key requirement for the successful deployment of mmWave 5G solution: the backhaul network that links the small cell and the main network. Because of the high data rates in mmWave ranging from over 10Gbps, backhaul networks must support large amounts of data traffic with low latency. Fiber backhaul is advantageous for mmWave networks as it offers bandwidth and reliability for high-speed data transmission. However, in urban areas, deploying fibers is costly and cumbersome since city plans are usually intricate, and the installation could interfere with other utilities.

Conversely, Sub-6 GHz, which typically supports lower data rates for delivery, has flexibility in the available backhaul types. Using fiber for backhaul remains an advantage for ensuring high performance. However, Sub-6 GHz networks also leverage microwave backhaul because it costs less and is easy to deploy in specific urban environments. These multiple options for backhauling are conducive for Sub-6GHz to fit more urban environments because it can be deployed in myriad ways, especially where fiber may not be possible. Therefore, the fiber backhaul is optimal for mmWave networks to perform best, while Sub-6 GHz networks can bear a relatively lower cost and even more diverse backhaul options.

### The Regulatory and the Environmental Environment

To infrastructure, the following regulations and environmental factors are critical to 5G network rollout in urban environments. Regulatory authorities define how spectrum is to be used, and cities' physical nature creates unique issues that affect both mmWave and Sub-6 GHz.

### Spectrum Availability

The opportunity to use frequency bands for 5G networks is different around the world [21]. At the same time, various authorities gave priority to mmWave and Sub-6 GHz for network implementation, depending on their priorities and technology opportunities. For example, the FCC in the United States has assigned different spectrum bands for both mmWave and Sub-6 GHz, where specific licenses are needed for that particular frequency band to avoid interferences while guaranteeing optimum use of the frequency space. This regulatory framework is essential for controlling the pressure on multiple operators in urban areas, hence the demand for 5G services. mmWave operates at a low spectrum availability; hence, licensing this band can also be very expensive, restricting its deployment. The potential licenses may take a long time to obtain, and the operators have to go through several hoops to obtain them, thus the expenses and the duration it takes to deploy mmWave in urban areas. Conversely, Sub-6 GHz ranges from a greater number of frequencies and more normally recognized standards, which these companies can use in densely populated terrains. This makes Sub-6 GHz more deployable and has fewer regulatory concerns, making it ideal for urban 5G network applications [13].

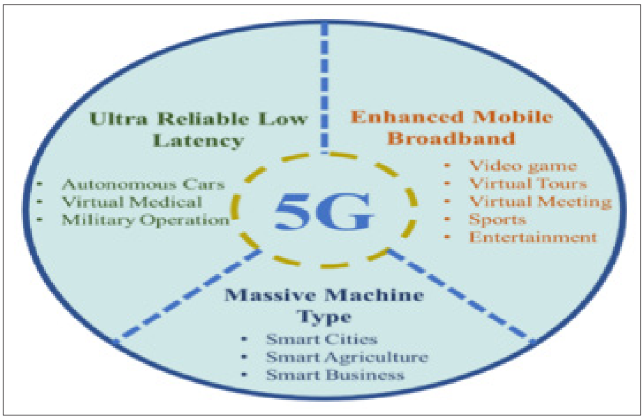



**Figure 7:** Survey on Joint Paradigm of 5G and SDN Emerging Mobile Technologies

### Environmental Challenges

In some ways, all these conditions are endemic to the urban environment and interfere with the performance of 5G networks, especially for mmWave frequencies [22]. Due to severe path loss, mmWave signals experience losses of tens of dBs due to buildings, trees, or any obstruction, thus defining hot and cold zones. For instance, using mmWave signals in large buildings in urban areas will be a challenge since the signals cannot penetrate and reach users on the opposite side or in the building. This sensitivity to physical barriers means that mmWave small cell placement is critical to avoid holes in the coverage of the small cells, and this can be problematic in areas with dense constructions.

Operating conditions also come into play, particularly in the performance of the mmWave 5G networks. For example, rain sometimes leads to signal attenuation because of the high frequencies used, meaning there would be low connectivity when it rains. This weather sensitivity poses a major challenge to mmWave, which is important for constant connectivity within cities for services like public safety and transportation. Unlike those in the Sub-6 GHz band, the signals in the mmWave range are more vulnerable to blockages by solid objects and adverse weather conditions in dense environments. Thus, Sub-6 GHz networks can benefit from the reliability and coverage that those frequencies offer in the urban environment, which has the ability to enter a building and to work in short and in adverse weather.

Huge improvements in data rates and latency are possible using mmWave. However, its dense small cells, reliable backhauls, and high-level regulatory and environmental problems are to be solved in urban areas. It also derived that Sub-6 GHz gives a more feasible solution for urban 5G networks regarding coverage and environment sensitivity despite having less capacity and lower speed than mmWave. These two frequency bands will have their disparity in terms of pros and cons, and there might be a need to offer a combination of the two for effective 5G implementation in urban areas [23].

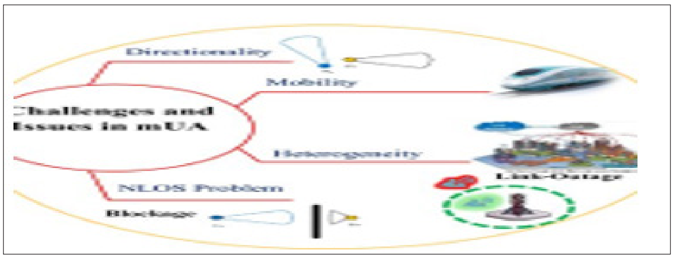



**Figure 8:** Challenges and Issues of UA Mechanism in mmWave Systems

## Future Directions

Future studies must investigate how the mmWave and the Sub-6 GHz bands may be jointly deployed to enhance urban connectivity [24]. Such ways allow the strengths of mmWave, which provides high speed and low latency in dense areas, to be used while remaining consistent in stability over distance with the help of Sub-6 GHz [10].

### Optimizing Network Coverage and Capacity

Le Corbusier argued that the overriding problem of urban connectivity is the proper establishment of coverage and capacity. Although mmWave provides data rate benefits, its range and sensitivity to obstruction by solid objects affect coverage [15]. For its part, Sub-6 GHz has a larger coverage and more inlet at the cost of a lower data rate. Such benefits may be combined using the Sub-6 GHz for ordinary coverage and mmWave in hot zones or any other application that requires bandwidth, for example, AR/VR. Future studies may also suggest efficient arrangements for both high-band and low-band networks to achieve the greatest range and facilitate speedy switches between bands to minimize pulse delay.

### Intelligent Network Management and Spectrum Allocation

Deploying 5G in a hybrid architecture requires effective network management and action-based spectrum control. That is why intelligent algorithms for assigning the traffic to mmWave or Sub-6 GHz depend on the density of the users and their applications. They may help predict the usage intensity in overloaded areas and adjust bandwidth usage in real-time. More studies could include creating algorithm-driven, dynamic AI models of network performance for discovering spectrum, optimizing it, and automatically controlling it during high-traffic periods without congesting a specific band.

### Enhancing Device Compatibility and Interoperability

Another essential criterion for systems of both types of frequency bands is compatibility with devices. PST needs to work outstandingly on mmWave and Sub-6 GHz and integrate between these two bands to avoid interference and latency. This is quite tasking given that the different bands demand different signal processing and hardware demands [25]. As such, future studies should concentrate on multi-band antenna technology, signal processing algorithms, and energy-efficient methods to make the system a dual-band. These improvements would be especially relevant as smart cities develop, with various devices depending on both frequency bands to convey information.

### Urban Environment Modeling and Simulation

Deployment of hybrid networks necessitates elaborate urban modeling. Reflections, diffractions, and absorptions that the signals undergo in an urban setting and other factors differ greatly. A perfect representation of the microenvironment and considering the architectural density of buildings, vegetation, and dynamic objects such as moving cars will be highly useful for predicting signal interactions and infrastructure layout. These types of simulators could help researchers try such mixed approaches in realistic contexts that could help improve network designs due to the problem specifics of the urban area.

### Energy Efficiency and Sustainability

Energy management is always a big issue in hybrid networks, especially given the issues of global warming and other environmental challenges that are growing in the world today [26]. Leveraging mmWave and Sub-6 GHz would mean more energy consumption if regulated improperly. More studies should be directed at the effective power control processes that reduce power usage while the equipment is in standby mode or control power according to the load demand. The advancement in existing low-power methods contributes towards having green energy sources for use in urban connectivity, as shown by Liang et al, which could make hybrid networks bear a lesser impact on the natural environment.

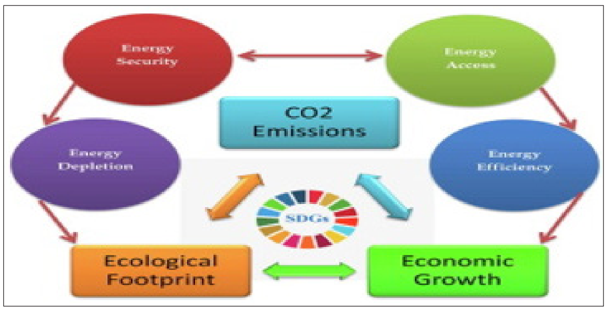



**Figure 9:** The Need for Energy Efficiency and Economic Prosperity in A Sustainable Environment

**Addressing Security and Privacy Challenges**

In the handoff scenario, hybrid networks pose distinctive security and privacy issues that differ from those of earlier bands [27]. In addition, each band's collective vulnerabilities might differ, and transitions escalate the overall risks of data leakage or unauthorized access [5]. Future research could aim at the expected ciphering schemes and user authentications to guard transitions between mmWave and Sub-6 GHz while preserving the confidentiality and integrity of users' data. However, since mmWave can provide high bandwidth, some situations require special security measures, especially where flow interception threats may be highly risky.

**Testing and Pilot Programs in Real-World Urban Settings**

These final real-world tests through pilot programs will be required to prove the best practices for hybrid strategies and identify performance issues. Such a dense deployment of hybrid networks in different setups of urban areas, mainstream business districts, and transport systems would provide useful information on the ability of the system to maintain connectivity, establish data latency under actual load, and its vulnerability to physical interference. These pilot studies would identify some of the major challenges in implementation; thus, the hybrid networks' approaches would be refined, and large-scale implementation practices would be directed effectively.

**Economic and Policy Implications**

The financial and policy implications of different forms of hybrid deployment should be defined [28]. Maintaining two infrastructures can be expensive, and telcos require models that compare the costs and benefits of having parallel infrastructures [15]. New policy areas will also influence hybrid network formation, such as spectrum allocation and privacy regulations. Possible future work can be to analyze how governments and policymakers should approach such crucial concerns as Fairness and privacy alongside the development of sustainable telecommunications infrastructure to create the policies and environment to support the mix of both fixed (such as fiber) and mobile connectivity. Integrated solutions based on mmWave together with Sub-6 GHz apply promising approaches to enhance urban connectivity. However, much research is required in network management, interworking, energy-saving, security, and policies to exploit them fully. Specific pilot projects suitable for belief scales in urban environments will be important for checking these concepts and real-world concerns and preparing prognoses for the future development of steady, efficient, and effective urban communication systems to meet modern urban requirements.

**Conclusion**

This paper offers a comparative analysis of mmWave and Sub-6 GHz 5G networks and determines the applications in which each network performs best in urban settings. Since 5G networks are becoming increasingly important for urban connections, it is crucial to understand the characteristics of these two frequency bands. The study also shows that mmWave networks provide highly superior data rates and low end-to-end latency. The networks are suitable for high-traffic services like smart city systems and real-time systems. Today, data rates have surpassed 10 Gbps, and the latency level is often below 1 ms, making mmWave very effective where data transmission rate is extremely important. These capabilities make mmWave suitable for LAA and other applications such as self-driving cars, remote medicine, and intelligent traffic networks. Nevertheless, the deployable disadvantage of mmWave is that it suffers very poor penetration through obstacles, hence restricting its deployment to large or heavily obstructed urban areas. It also means it is based purely on line-of-sight that suffers from environmental influences like rain and foliage. As a result, mmWave networks must use densely placed small cells; this adds to the network's physical expenses and presents challenges in deployment at an enormous scale.

Sub-6 GHz networks have a wider coverage area and can penetrate through various obstacles, making the networks ideal for several urban uses. While most Sub-6GHz networks offer a peak data rate of (100Mbps to 1Gbps), they sustain this rate over large distances and through geographical barriers such as buildings and walls. For this reason, Sub-6 GHz is strategically suitable for offering extensive coverage and a clean indoor experience in urban environments like broadband to homes and mobile communications. This is also true for Sub-6 GHz, which is less susceptible to environmental interferences and is further applied to stationary, large-scale Broadway solutions rather than those that need high bandwidth and low latency. Nevertheless, the disadvantage of Sub-6 GHz is its lower data transmission rate and network crowding issues in regions with an increased population density, reducing its efficiency for high bandwidth applications.

The observations imply that using mmWave and Sub-6 GHz bands can provide the best 5G coverage in urban areas. In this model, mmWave can be used in hot spots or for applications that require ultra-reliable low-latency communication, while Sub-6GHz can be used for overall network coverage and indoor applications. It may then apply synergism to the best from each band where mmWave will be used for speed and low latency in selected application areas, and Sub-6 GHz will be used for coverage and reliability. They have considerable advantages as they cover the demand gap in such a complex and unpredictable environment by providing electricity to cities based on renewable sources.

Subsequent studies should optimize the application of hybrid deployment models that incorporate different values concerning networking, compatibility, and power. Intelligent network management algorithms that allow the mmWave and Sub-6 GHz network resources to be shared or dynamically, according to the capacity demand and environment, would also improve the overall network performance and Radio users' experience. Furthermore, enhancements in device connectivity, including dual band antennas and efficient and seamless handover features for both the 3GPP bands, will be indispensable to support user demands. It is also crucial to address consumption issues for energy efficiency, especially due to the additional equipment needed to support the new mmWave network architecture [29]. The combination of mmWave and Sub-6 GHz bands offers an option to improve urban connectivity by satisfying the demands of modern urban society. As a result, urban areas will be able to obtain high-speed and low latency in those specific locations required, coupled with consistent coverage of vastly expansive areas.

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