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Millimeter Wave Cellular Communication Performances and Challenges: A Survey

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Abstract

The demand for high data rates, combined with the exponential growth of mobile data trafficking, and has prompted the use of millimeter-wave (mm-wave) spectrum for 5G mobile communication. So, for constructive assessment, this study employed various research publications, institutional reports, and other materials given at the conference. This survey article investigates the features of the mm-wave propagation channel and highlights the main challenges, solutions, and benefits associated with their utilization, as well as an analysis of their performance. The researchers observed that by reducing the difficulties and significant losses with various strategies, mm-wave cellular communication may extend up to 200m in a single cell and densification is essential for vast area coverage. The article also examines the right technical implementation approach, as well as the economic benefits and existing and predicted market situation of mm-wave cellular communication from the operator's perspective. The outcome will be useful information for any operator or stakeholder in mm-wave communication.

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1. Introduction

The explosion of mobile data traffic has resulted from the evolution of wireless data applications and the rising popularity of smart devices, posing significant difficulties to mobile service providers, as observed in Fig.1 [1]. This dramatic increase necessitates a significant increase in mobile network capacity beyond present 3G/4G networks and into the next generation of wireless radio technologies.

The upcoming mm-wave 5th generation (5G) is a technology that integrates existing wireless communication methods into a completely new air interface [2, 3]. New network needs are likely to rise as a result of the large increase in connected devices expected, as well as the significant increase in traffic volume forecast in the near future.

End-user key performance indicators are used to provide prospective solutions that analyze radio link needs based on underlying technical problems generated from user-related concerns [4]. Traffic volume density, latency, dependability, experienced end-user throughput, and availability are only a few of the characteristics [5].

The foundations for 5G are new systems that skillfully leverage developed technology and incorporate fresh methodologies. Significantly increased bandwidth is the most important potential technology for increasing the performance of 5G wireless networks. There is plenty of capacity available in the mm-wave frequency bands that will be needed to support 5G cellular networks. As a consequence, this study assessed a number of research articles, report papers, and review journals in order to investigate end-user key performance indicators of mm-wave mobile communication.

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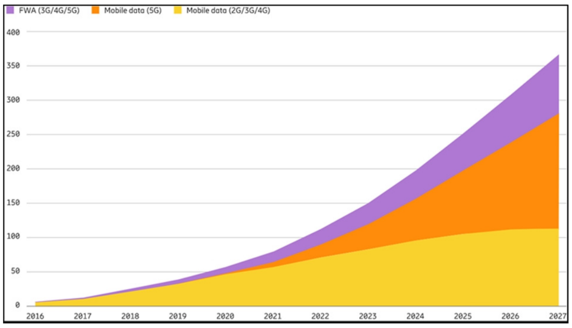

Figure 1. Global mobile data traffic of the world

2. Benefit of mm-wave

The frequency spectrum between 30 to 300 GHz, known as mm-wave frequency, provides several benefits in next-generation mobile communication. Nowadays, the majority of existing mobile communication systems is deployed in the sub-6GHz spectrum, which is known to be congested. The focus of radio system designers has shifted to higher frequencies in order to deliver the requisite data rates and throughput while also avoiding congestion. As the Shannon equation as stated (equation 1), the data rate is determined by the available bandwidth for transmission (BW) and the signal to noise ratio (SNR). Increasing bandwidth is a straightforward approach to increase channel capacity.

$$C(\frac{bits}{s}) = BWxlog_2(1 + SNR) \tag{1}$$

Another advantage of mm-wave technology is that it allows a large number of antenna components to be packed into a compact physical space, resulting in a bigger aperture and high antenna array gains. Massive multiple input multiple output (MIMO) and femtocells, might be the key to future mm-wave 5G mobile communication. However, in order for such a system to become a reality, various concerns and questions must be addressed [6]. Due to their high penetration and route loss, mm-wave signals must operate over small distances. This is beneficial for frequent reuse as well as improved security and privacy. In a nutshell, mm-wave communications provide a number of benefits in next-generation mobile communication.

3. Implementation Challenges

Despite this, the mm-wave frequency appears to be a promising contender for the next-generation 5G cellular technology, which is predicted to accommodate several Gb/s data speeds. However, using mm-wave necessitates dealing with the high-frequency bands' propagation characteristics and channel limitations. Higher route loss owing to higher carrier frequency, lower scattering, which limits available diversity, and greater effect of blockage due to poorer non-line-of-sight pathways are all major hurdles to mm-wave transmission. Furthermore, because of the use of higher bandwidths, the influence of noise power is more evident. This study provides an overview of the propagation difficulties, spectrum challenges, and interference control concerns.

3.1. propagation challenge

Unlike the microwave range, the mm-wave spectrum has a variety of propagation challenges. The first is that there is a considerable level of free space route loss, which leads to spectrum communication over a short distance. This frequency's signal is likewise impervious to obstructions and air absorption.

Free Space Path Loss (FSPL). The carrier frequency f_c affects the free space path loss. The free space path loss increases with f_c^2 as shown in equation 2. As a result, raising the carrier frequency f_c from 3 to 30 GHz will result in a 20 dB power loss, which independent of the distance between the transmitter and receiver.

$$FSPL = (\frac{4\pi d}{c})^2 x f_c^2 \tag{2}$$

In order to mitigate the effect of free space path loss, mm-wave frequency antenna arrays can be deployed. When arrayed, antenna elements are mechanically small but electrically large. In both base-station (BS) and user equipment (UE), increasing antenna aperture by constructing an electrically big antenna /antenna array gives enough antenna gain and directivity [7]. This will decrease path loss while maintaining a high signal to noise ratio (SNR) output.

Blockage. Microwave signals are less susceptible to interference, but diffraction causes them to fade. In contrast to microwave signals, mm-wave transmissions are more sensitive to blockades. They have a lot more penetration losses than the current microwave. This challenge can be solved by highly beamed antennas in terrestrial applications. The transmitter and receiver beam patterns are both focused across a narrower beamwidth to provide the required directionality.

Atmospheric and Rain Absorption. Attenuation caused by rain, vegetation, and air absorption is a severe barrier to mm-wave communications. Attenuation of the atmosphere as a result of oxygen absorption or

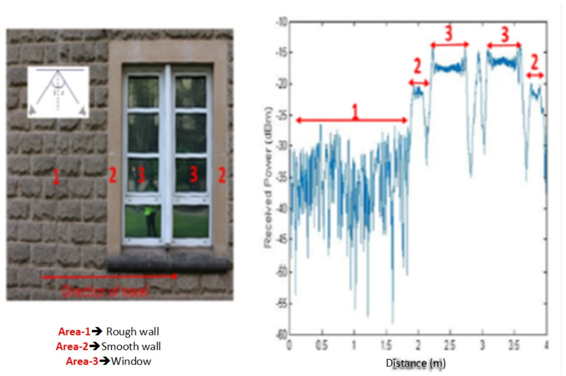

Figure 2. Results of diffuse scattering measurements at 60 GHz [8]

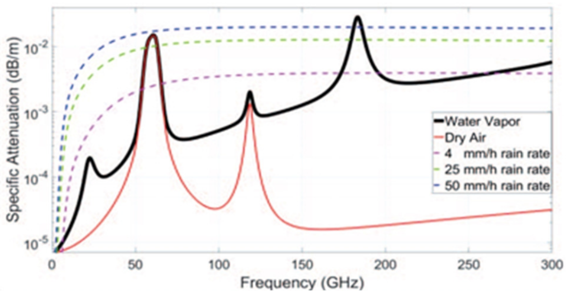

Figure 3. Specific Atmospheric attenuation and rain absorption at mm wave

severe pollution rain can be on the order of 10-20 dB/km [8].

As shown in Fig. 2 where smooth surfaces (e.g., windows) offer high correlation over distance, but signals from rough surfaces seem less correlated over distance
Fig.3 shows specific atmospheric attenuation and rain absorption of mm-wave. In order to minimize such absorption by atmospheric and rain mm-wave networks may be made highly dense to overcome obstructions, and can benefit from the present trend of shifting the cellular system to a more heterogeneous infrastructure that includes tiny cells and relays, which can be combined with the usage of adaptive steerable arrays [9]. The signal can able to move until 200 meters.

3.2. Interference management

Intra-Cell Interference. The interaction of user equipment (UEs) with other user equipment is a difficulty (UEs). It may be avoided with careful planning and beam forming design.

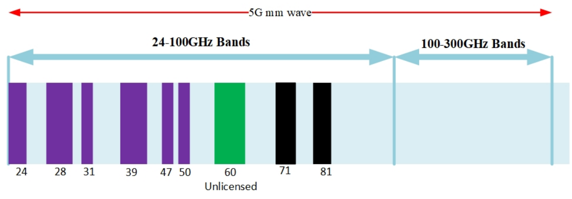

Figure 4. Available spectrums in different mm-wave bands

Inter-Cell Interference. Strong interference between cells occurs at the cell edge due to nearby cells. Scheduling based on time–frequency–space resource with fully-directional communication is used in mm-wave cellular networks to decrease it. A approach for managing interference on demand (UEs and BTs).

Inter-Layer Interference. It refers to interference between macro, micro, femto, and pico cells in distinct levels. This necessitates careful design of the pilots and control messages to minimize wasteful use of the limited resources.

3.3. Spectrum Aspects

Beyond the conventional prime spot of spectrum for wireless communications, which finishes at roughly 6 GHz, there is another 100 GHz of spectrum in the so-called mm-wave frequency band that is now mostly underutilized. This frequency band includes channel widths that allow for wireless data rates ranging from 10 to 50 Gbps [10].
5G cellular and WiFi connections might liberate a major piece of this vast radio spectrum. The intended frequency for 5G research is above 6 GHz, and research in this area should focus on electromagnetic field (EMF) features, connection budgets, propagation concerns, and channel model description. The available mm-wave band in the region of 20 to 100 GHz is presented in Fig4 [11].

There is 1.3 GHz available at 28 GHz. At 39GHz, around 2.1 GHz of spectrum is available. As seen in fig. 4, there is also a 7 GHz unlicensed band surrounding 60GHz. Furthermore, the International telecommunication union (ITU) has allotted lightly licensed 5GHz bandwidths for both the 71-76 GHz and 81-86 GHz bands for the purpose of developing high bandwidth wireless links [12]. Similarly, the band 92-95GHz has been designated for high bandwidth wireless communications. Although mm-wave technologies at 28 GHz and 60 GHz have the potential to be employed for early 5G deployment further debate about scenarios, use cases, and supporting technologies

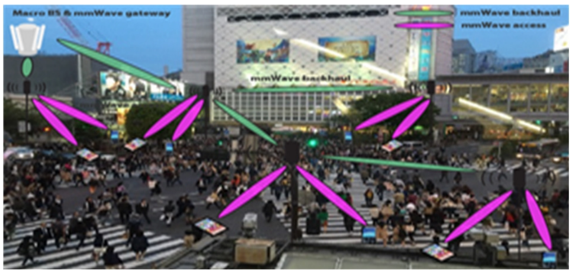

Figure 5. Dense urban scenario around Shibuya station in Tokyo [13]

is required.

4. Use case and scenario

Mm-wave might be used for low-latency applications as well as broadband applications with fixed, high-speed, and ultra-high-speed mobility users.

Indoor coverage scenarios. An isolated room and a wide public space are two interior scenarios. The isolated chamber has an exhibition hall, a workshop, and offices. A modest number of mm-wave Nano-cells might provide complete coverage of the space. A vast public area might be covered by a huge number of mm-wave Nano cells. Malls, retail complexes, sports facilities, airports, train stations, and businesses are all included.

Outdoor coverage scenarios. A very large urban scenario with traditional LTE/LTE-A base stations sharing the same area with mm-waves small-cells to supply localized high rate coverage.

Dense urban scenario. It is a location where users like to congregate and move as huge and dynamic crowds while maintaining cloud connectivity [13]. This is a key scenario in 5G. Due to the enormous traffic volume created by Smartphones and tablets, Sensors and wirelessly linked cameras, and others, numerous mm-wave access points are required. Open squares, streets, and train stations are typical settings as observed in Fig.5.

5. Coverage probability

The coverage probability which is equivalent to probability (p) of signal to interference noise ratio (SINR) greater than threshold P(SINR>Threshold SINR(T)) on targeted SINR as shown in equation **??**. The coverage probability is approximated as [14]

$$P(SINR \geq T) = \int_{-\infty}^{\infty} \int_{0}^{\infty} U(x,t) f_L(x) e^{(j2\pi t/T)-1} dx dt \tag{3}$$

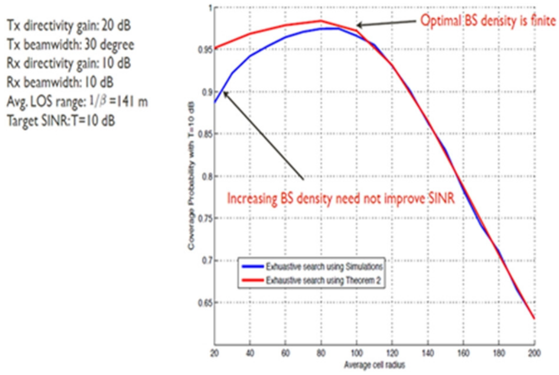

Figure 6. coverage probability on targeted SINR=10dB vs average cell radius [15]

Where $U(x,t)$ is a step function and

$$f_L(x) = -\frac{\partial e^{-\Delta(x)}}{\partial x} \tag{4}$$

Where:$\Delta(x)$ the change in distance of the interfering user to its serving BS Due to significant penetration losses and susceptibility to obstructions, mm-wave BS coverage zones are often tiny and uneven, as seen in Fig 6. This problem can be solved by increasing network density. When the BS density is low, BS densification reduces the distance to the serving BS and improves the likelihood that the serving BSs are line of sight (LOS) BSs.The simulated result of coverage probability mm wave with average cell radius is shown in Fig.6 as reported in [15].

This gives a normal user more serving power. The interference power, on the other hand, is unaffected since the interferers are still far enough away to be NLOS to the average user. As a result, densification typically benefits mm-wave systems by increasing SINR and rate coverage. After a certain threshold, however, there will be enough interferers in the LOS region to drastically decrease the SINR. When the average cell radius is far from the BS, the coverage probability will decreases. There is a chance of obtaining a targeted SINR up to 200m.

6. Capacity estimation

Enhancing channel capacity is one of the fundamental benefits of mm-wave communication. Fig.7 shows how capacity may be increased at 28GHz mm-wave communication by simply decreasing antenna beam width from 65 to 30 [16]. Mm-wave 5G networks will use multi-beam radio frequency (RF) transmissions with arbitrary beam widths significantly smaller than 30. As a result, it is projected that this reduction of antenna beam width transmission approach alone

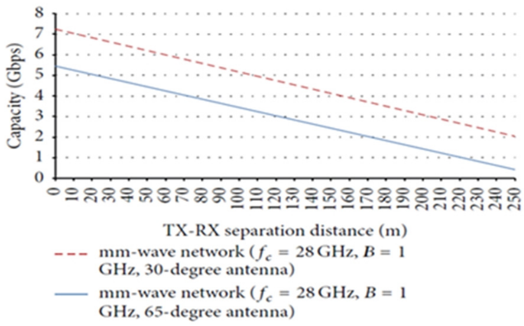

Figure 7. Capacity trend in Gbps for 28GHz mm-wave networks using $65^0 and 30^0$
transmitting antenna beam-widths

would greatly increase capacity and assist realize gigabit per second data speeds everywhere in the 5G network, even cell edges.
For indoor coverage, cell enhancers and in-building RF infrastructures may be needed to ensure providing acceptable received power levels inside buildings with satisfying in-building data rates, as stated in Fig.7.

7. Technical implementation strategy

To adopt mm-wave technology, the following basic tasks should be considered. Set the target and deployment area: At this point, the operator should decide where and when to apply the millimeter wave technology. The operator may choose a location near potential clients, densely inhabited regions, or other factors.
Mm-wave cellular network modeling: - Evaluation of mm wave performance in a given location. This will actualize the draft design across all design criteria. Modeling techniques that are most commonly used are:

- Stochastic Geometry tool for locate cells
- Poisons point process(PPP) for BS location distribution
- Use random shape theory to model buildings
- Building distribution by PPP
- User equipment distribution by PPP

Network optimization: The available human resource to run and optimize the technology should be acknowledged.

8. Market status of mm-wave

Because of its propagation properties and high frequency, mm-waves or the millimeter band are highly helpful in a broad range of applications such as delivering massive amounts of data through computers, cellular communication, and radar. Since vast amounts of data must be transmitted at all times, mm-waves are widely employed in the telecommunications sector, making it one of the most important applications globally. As a result of the higher frequencies supplied by mm-waves, they are a notable stable and efficient source for high frequency data transfer applications across computers, voice channels, or TVs [17]
The mm-wave technology market is segmented into five different levels, product, component, application, frequency band, and region[18]. According to the market study, mm-wave technology will grow exponentially until 2030 according to the US technology market, as shown in Fig. 8 [19].

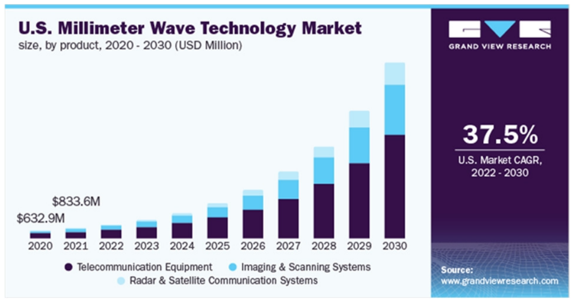

Figure 8. U.S. mm wave technology market from 2020-2030

9. Economic benefits

Because mm-wave technology is a new 5G component, the increased operating frequency will update all network topologies [20]. Furthermore, one of the answers for mm-wave difficulties is densification. All of this will boost operators' capital expenditure. However, mm-wave will only be implemented once to meet consumer demand for a high data rate. As a result, the following capital expenditure reduction alternatives will become available.

1. The regulatory body allow spectrum sharing it helps operators to reduce their expenses by sharing the license costs [21]
2. Industries have produced high efficient and low cost Silicon based mm wave radio frequency integrated circuit (RFIC), that replaces costly Gallium Nitrates (GaN) and Gallium Arsenate(GaAs)[22]
3. Infrastructure sharing reduces Operational Expenditure (OPEX) [23]

Because of the diversity of 5G applications and related service needs in unforeseen quality of service in terms of data rate, latency, reliability, and other criteria are met; the operator's income will improve [24, 25]. This will make the mm-wave operator lucrative. When the number of subscribers and the average income per user for the operator increases, the total profit will increase as stated in equation 5 [26, 27].

$$Profit = subscriber * ARPU - OPEX - CAPE5 \quad (5)$$

Where Average Revenue per User (ARPU), operational expenditure (OPEX) it includes utility services cost, overhead cost, manpower, and Capital Expenditure (CAPEX) includes initial investment cost for the technology including spectrum license cost. As a result, mm-wave communication is a very profitable market for operators since it will have a large number of connected devices with lower operational costs.

10. Conclusion

Due to its high cost, complexity, and perceived restrictions, early applications of millimeter wave communication were limited to specialist sectors. However, the necessity to satisfy high data throughput and low latency requirements in 5G communication has refocused attention on the mm-wave spectrum. Mm-wave cellular communication is a potential candidate to meet the upcoming 5G's high data rate requirement. Unlike microwave signals, mm-wave communications faces a substantial path loss, susceptible for blockages and sever atmospheric attenuation. This survey indicates a viable mitigations techniques of implementation difficulties such as building electrically large array, steerable antenna with narrow beamwidth, and utilizing already identified mm-wave bands which are less sensitive to atmospheric losses. The review also addresses coverage area, capacity estimation, and possible implementation stages for mm-wave communication. In the survey, the economic benefits and market situation of mm-wave communication were provided. To sum up, mm-wave communication be implemented in variety of scenarios to bridge the gap between client requirements and the operator's difficulty, which is the desire for high data rates.

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