New Mid-Band for 6G: Several Considerations from the Channel Propagation Characteristics Perspective

Jianhua Zhang, Haiyang Miao, Pan Tang, Lei Tian, and Guangyi Liu

Abstract

To realize the sixth-generation (6G) vision may require additional spectrum to support the framework and objectives. The sub-6 GHz of fifth-generation (5G) can be used for spectrum refarming, but we also need to find more spectrum with larger bandwidth. This article focuses on the new mid-band (6–24 GHz) that 6G is concerned with, and gives several considerations from the channel perspective. First, we review the global efforts in recent years to study the candidate frequency bands for 6G, as well as spectrum-related works and views of the different organizations. Second, from large/small-scale fading and new characteristics, the recent research findings and considerations are investigated for the channel of the different bands. The channel characteristics of the new mid-band and the influence on the system performance are discussed in depth. Some views and suggestions on the reasonable utilization of the new mid-band for 6G communication systems are put forward. Finally, open issues and future research directions for the 6G spectrum are pointed out. This article sheds light on the more reasonable use of the new mid-band for 6G.

Introduction

In the evolution of each generation of mobile communication, some new frequency bands are usually considered to meet the needs of communication. For example, the frequency ranges with appropriate data rates and coverage were divided according to frequency characteristics in the fifth-generation (5G) era. The high-band (above 24 GHz) was used in communication environments with extremely high data rate requirements. The band below 2 GHz was classified as the low-band, which allowed wide coverage. Currently, the data rate demand of communication systems has been exponentially increasing, which will continue in the sixth-generation (6G) mobile communication services. In June 2023, the 44th meeting of the International Telecommunication Union-Radiocommunication Sector (ITU-R) WP 5D described the 6G overall objectives and trends. This meeting proposed six usage scenarios of International Mobile Telecommunications (IMT) for 2030 and beyond (IMT-2030) [1], including Immersive Communication, Massive Communication, Integrated Sensing and Communication (ISAC), and so on, which will bring the demands for the high data rate and wide coverage. However, these demands may require more new spectrum resources for the communication systems.

As we all know, the sub-6 GHz spectrum has become one of the main bands for 5G commercial applications, which is widely used in Europe, China, and other regions. In the 5G era, the researchers carried out a lot of research work in the sub-6 GHz band to support the better use of this spectrum. The multiple-input-multiple-output (MIMO) technology plays a more important role for 5G due to the high communication rate requirements, and the array antenna is expanded from the azimuth to the elevation dimension in various deployment scenarios. As a prerequisite for the design of communication systems, the 5G standard channel model introduces elevation dimension information to meet the research needs of three-dimensional (3D) MIMO and massive MIMO technology [2]. The academia and industry come together to drive the development of 3D MIMO. There are some exploration and finding about the 3D MIMO channel. The 3D array antenna is used to carry out channel measurement, and the elevation-azimuth-time-frequency joint statistical channel modeling is put forward. Compared with 2D MIMO, the 3D MIMO can bring higher channel capacity gain [3], providing an experimental basis for the application of 3D MIMO. In addition, the channel characteristics and model of massive MIMO antenna arrays are compared at 3.5 and 6 GHz bands [4]. It can be seen that the channel research is not only very important for the use of key technologies, but also provides support for reasonable spectrum study.

Recently, the ITU released the 6G vision framework, and the 6G spectrum work has begun. However, if there is to be a global consensus on the 6G spectrum, it is necessary to combine various aspects of research. In this article, the support for 6G spectrum research is considered from the underlying physical layer channel. Three issues need to be answered: What are the views of different regions and organizations on the 6G spectrum? What are the considerations and suggestions for the new mid-band (6-24 GHz) from the channel perspective? What are the open issues and future directions for the 6G spectrum? The main features and contributions are summarized as follows:

Jianhua Zhang, Haiyang Miao (corresponding author), Pan Tang, and Lei Tian are with Beijing University of Posts and Telecommunications, China; Guangyi Liu is with China Mobile Research Institute, China.

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Based on the development of the 5G antenna, the higher the frequency band, the greater the technical limitation of antenna production, such as mmWave or terahertz band, which puts forward higher requirements for microchip and device performance.

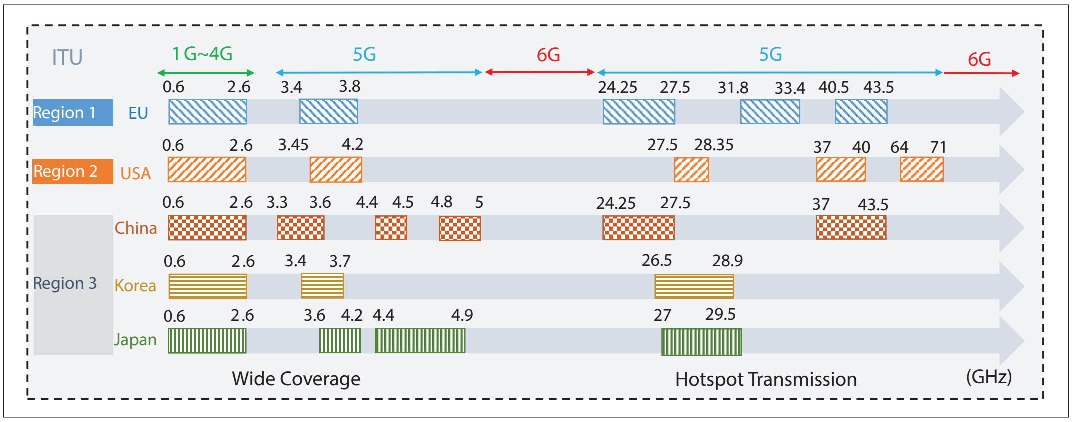

FIGURE 1. The operating and potential spectrum in ITU regions.

- We provide an overview of the global efforts in recent years to allocate the potential 6G frequency bands and the work associated with the spectrum, including the views of some regions and organizations on the 6G spectrum.
- Based on the new mid-band channel research, some considerations are put forward. The inspiration and corresponding suggestions are given for the new mid-band research and applications for 6G.
- Several open problems, and future research directions are pointed out for the spectrum research of the 6G communication systems. For example, the channel research on new technologies in the different spectrums, such as Extreme MIMO (E-MIMO).

Views on the 6G Spectrum

To negotiate the global frequency spectrum, the world is divided into three ITU regions. Figure 1 shows the spectrum planning for some countries in the regions. From first-generation (1G) to 5G, it can be observed that frequency bands of mobile communication are distributed below 6 GHz and above 24 GHz.

Why Consider the New Spectrum?

Immature Technology: On the one hand, as one of the most important parts of all communication equipment, the quality of the antenna is directly related to the communication ability and working efficiency of terminal hardware. Based on the development of the 5G antenna, the higher the frequency band, the greater the technical limitation of antenna production, such as mmWave or terahertz (THz) band, which puts forward higher requirements for microchip and device performance. On the other hand, the collaborative communication across multiple frequency bands can efficiently use low and high frequency resources, which has broad application potential in the 6G era. However, as the frequency span increases, the channel characteristics usually differ more significantly. The difference of channel characteristics brings great challenges to the wireless networking across multiple frequency bands. As a result, the frequency span should not be too large, and it is better to concentrate on adjacent frequency bands. These problems put forward the demand for the frequency band of 6G.

High Investment: From 1G to 5G, it can be seen that the upgrading of each generation of systems requires high investment in all aspects, improving performance and adapting to changing market demands. For example, the system of over-the-air (OTA) testing mechanism is mainly set for market products. In the 5G era, there are few devices above 6 GHz on the market, and the test system for antenna calibration covers almost only below 6 GHz. The upgrading of the frequency band of the system requires high investment and technical difficulties. The channel model is very important for the performance evaluation of the equipment, and it is also necessary to determine whether the target test environment is correctly constructed and ensure the effective test results. Therefore, timely exploration of the spectrum range of the 6G communication system will be more helpful to the advance deployment of the system.

Upgrading of Infrastructure: At present, the base stations of global operators are mostly deployed in the sub-6 GHz band. It is difficult to update infrastructure hardware equipment, which is an important problem faced by operators. Due to the differences in channel characteristics at different frequency bands, it is challenging for low-frequency infrastructure to upgrade to high-frequency bands such as mmWave. As a result, if a more suitable frequency band can be found in the mid-band, it will be beneficial to the updating of mobile communication system infrastructure, attract the investment of operators, and promote the development and evolution of 6G.

Recent Standardization Efforts in New Mid-Band

Previously, due to the larger bandwidth and more available frequency bands, the high-frequency research of 5G is mainly concentrated in the mmWave band. However, according to the results of commercial and deployment, the mmWave band has large propagation loss and high construction costs. Therefore, some new 6G spectrum needs to be considered. To facilitate the research and development of 6G, the organizations are actively searching for suitable frequency bands with global consensus. The various regions and organizations have made corresponding efforts and put forward their views on the new mid-band in Table 1.

In June 2022, the 3GPP RAN Plenum adopted a standard modification proposal for the band of 5925-7125 MHz, and the band was introduced into 5G-Advanced Rel-18. In the World Radiocommunication Conference 2023 (WRC-23), the 6 GHz band was identified for mobile use in every ITU region, and the agenda for WRC-27 was defined. The new WRC cycle will focus on the following bands for IMT: 4400-4800 MHz, 7125-8400 MHz, and 14.8-15.35 GHz. In December 2023, the 3GPP TSG RAN Rel-19 discussed the research work in 7-24 GHz band. Besides, some companies have proposed their considerations for the 6G spectrum shown in Table 1.

Organization	Views
WRC	WRC-23 identified the 6 GHz band. The new WRC cycle will focus on the following bands for IMT: 4400–4800 MHz, 7125–8400 MHz, and 14.8–15.35 GHz
3GPP	The 3GPP RAN#96 plenary meeting focused on the 5925–7125 MHz band
WiFi Alliance	The WiFi 6E standard will further support the 6 GHz band
Company	**Views**
Samsung	An in-depth study is needed on how to use the 7–24 GHz for 6G [5]
Ericsson	The 7–15 GHz range is necessary to realize the capacity-demanding use cases in 6G networks [6]
China Mobile	The considerations on 6 GHz bands for 5G-Advanced and 6G
Nokia	The new pioneer spectrum blocks for 6G are expected to be at mid-bands 7–20 GHz for urban outdoor cells
Qualcomm	The 7–16 GHz range has been widely identified for 6G consideration
Government department	**Views**
Ministry of Industry and Information Technology	All or part of the 6425–7125 MHz frequency band for IMT (including 5G/6G) systems
Federal Communications Commission	Expanding use of the 12.7–13.25 GHz band for mobile broadband or other expanded use

TABLE 1. Some views on the new mid-band.

Frequency bands [GHz]	Scenarios	Antennas	Channel characteristics	Reference
3.3, 6.5, 15, 28	Outdoor/ O2I	SISO	Path loss, RMS DS, K-factor, cluster, etc.	[7]
6, 12, 18, 24	Outdoor	MIMO	Capacity gains, signal-to-noise ratio, etc.	[8]
8, 9, 10, 11	Indoor	SISO	Path loss model, co-polarization, etc.	[9]
3.5, 6, 14, 23, 26, 28	Indoor	SISO	Path loss, RMS DS	[10]
6, 26, 132	Indoor	SIMO	Channel sparsity	[11]

TABLE 2. Channel characteristics covering the new mid-band.

Considerations and Suggestions for New Mid-Band

In this section, the research findings of channel in different frequency bands are discussed and compared with the 3GPP channel model [2]. Some channel characteristics covering the new mid-band are shown in Table 2 Based on the analysis of the influence of channel on system performance, this section gives some considerations and suggestions as to whether the new mid-band has the advantage of becoming the operating spectrum of the next-generation communication system.

Large-Scale Parameters

Propagation Loss and Delay Domain: From sub-6 GHz to high bands such as mmWave, some observations and comparisons can be made in some typical frequency bands. With the free space path loss (FSPL) model, the coverage performance of the new mid-band is better than mmWave and higher bands. From the measurement campaigns [7], it is found that with the increase of frequency, the path loss is significantly greater in non-line-of-sight (NLoS) environment. The frequency-dependent coefficient is larger than that of the free-space path loss model [7]. It is worth considering the coverage of different frequency bands. Besides, the frequency dependency was not consistently remarked on channel parameters such as delay spread, which is a statistically significant difference from the 3GPP standard channel model TR 38.901 [2, 12].

Considerations: In [7], the frequency-dependent coefficient of path loss is 29.02 in NLoS environment from sub-6 GHz to mmWave bands and the coverage capability of high-frequency signals is very challenging, but the path loss factor in line-of-sight (LoS) environment is almost the same as that in free space. The results show that the utilization of mid-band needs to pay attention to the problem of coverage in the NLoS environment. Compared with the mmWave band, the cell coverage radius of the new mid-band is larger. In dense urban scenarios, it is challenging to provide satisfactory coverage at high frequencies due to occlusion [8]. As the frequency increases, the coverage is greatly reduced, and the penetration loss has the tendency to increase [8]. For high-band such as mmWave, it is necessary to increase the number of base stations or improve power with other techniques, especially in the NLoS environment with many obstacles. The measurement data was used to adjust path loss prediction models for indoor environments at 8–11 GHz [9]. In adjacent bands, path loss does not increase significantly with the increase of frequency.

In Fig. 2, the frequency-dependent model of root mean square (RMS) delay spreads is displayed at multi-frequency bands in outdoor environment [7]. The signal propagation attenuation will be larger when the frequency increases. The multipath component power will decay, which causes some multipath with large delay to disappear. The RMS delay spread tends to decrease with the increase of frequency. To the system design, it indicates that the orthogonal frequency division multiplexing guard interval at new mid-band can be set smaller than that of sub-6 GHz spectrum, to increase the transmission data rate of useful information. Compared with the standard model, it can be found from Fig. 2 that the RMS delay spread obtained by the actual measurement is smaller than the 3GPP channel model. This difference may be caused by different propagation environments. However, high-frequency wideband channels are introduced, which bring more degree of freedom (DoF) and rich scattering effect. In addition, it can be seen that the delay spread does not change monotonically in indoor scenarios [10], which covers multiple typical frequency bands. This may be caused by the abundance of multiple paths in an indoor closed environment.

The channel characteristic parameters should be adjusted to the new model considering the difference of the real environment when using the 3GPP channel model at the new mid-band.

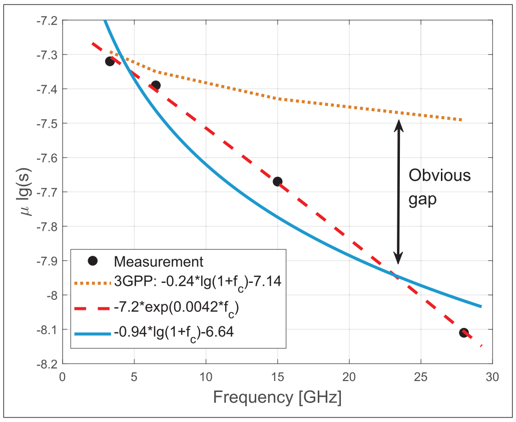

FIGURE 2. The frequency-dependent model of delay spread [7].

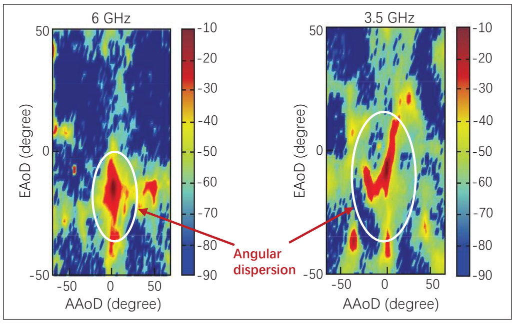

FIGURE 3. The power angle spectrum with 256 Tx [4].

Suggestions: As the frequency increases, there is a greater additional path loss. The new mid-band has better coverage than mmWave and THz bands. With the same cell coverage area, the new mid-band requires fewer base stations, while the number of base stations at the mmWave band is several times compared with the new mid-band. In addition, we find that the delay spread of the adjacent frequency points does not monotonically decrease as the frequency increases. Only when the frequency span increases, the delay spread will show an obvious frequency-dependent model. The channel characteristic parameters should be adjusted to the new model considering the difference of the real environment when using the 3GPP channel model at the new mid-band. To sum up, in terms of propagation loss, the new mid-band has enough advantages compared with mmWave band, and the base station deployment cost is lower, which is attractive for operators.

Small-Scale Parameters

Spatial Domain and Capacity Gain: For small-scale parameters, the angular domain and cluster characteristics are generally concerned. It can be found that in some measurements and literature [7], the multipath effect becomes less obvious as the frequency increases. However, it can also be seen that as the bandwidth increases, the data transmission rate increases. In [11], with the increase of frequency, the channel sparsity becomes more prominent. However, the sparsity of the channel matrix derived from the 3GPP channel model is similar regardless of the frequency band, which leads to inaccurate prediction results for different frequency bands. The difference of sparsity in different frequency bands has a great impact on the system design.

Considerations: In Fig. 3, the beamwidth of the base station is about 18° at 6 GHz, while the beamwidth is over 30° at 3.5 GHz. Compared with the 3.5 GHz base station MIMO antenna, the base station antenna has a narrow beam, good directivity, and higher spatial resolution at the 6 GHz band, which can distinguish small targets closer together and is more conducive to MIMO beam-forming technology. With the increase of antenna array, the channel capacity increases due to the decrease of spatial correlation. The deficiency of the standard model to characterize sparsity arises from the model allocating cluster power equally to the rays within the cluster. An intra-cluster power weight distribution model is proposed to accurately model sparsity on geometry-based statistical modeling (GBSM) framework based on the measurement [11]. It can be proved that compared with the 6 GHz band, the multipaths are very sparse and the power attenuation is larger at mmWave and sub-THz band. In addition, if more bandwidth can be allocated in the new spectrum, it is very attractive to improve the data rate of 6G communication systems.

Suggestions: Due to the prominent channel sparsity of mmWave and higher bands, the additional loss is greater according to the frequency-dependent model. In multi-frequency coordinated communication, the new mid-band can support more complex outdoor environments and ensure the wide area coverage capability of 6G mobile communication. More importantly, the new mid-band can provide greater channel capacity and data rate in the same bandwidth compared with the low-band. Compared with the narrow band at low frequency and prominent channel sparsity at high frequency, the new mid-band has the potential to be part of the 6G spectrum, complementing and coordinating with sub-6 GHz, mmWave and THz bands.

New Channel Characteristics

Near-Field Effect and Spatial Non-Stationarity: With the increase in the number of antennas and carrier frequencies, the near-field region of E-MIMO will be expanded by orders of magnitude. For example, a 7.3-meter-long virtual linear array is adopted, and the Rayleigh distance is 945 meters at 2.6 GHz, which is much larger than the radius of the typical cell (200 meters). Therefore, near-field MIMO communication will become the basic component of 6G mobile networks in the future, and the far-field and plane-wave front assumptions of traditional channel models are no longer applicable to E-MIMO. To investigate the spatial evolution of clusters, a measurement campaign was carried out at 3.5 GHz with a 256-element virtual array [13]. The clusters mainly appear or disappear in one path in LoS condition and this main path is formed by the LoS condition, most of clusters focus on it, while those distribute in different degrees in NLoS condition [13]. When the frequency increases, the decrease of rich scattering characteristics and the increase of channel sparsity were shown in higher frequency bands [11]. These channel characteristics will reduce some performance indicators of the system, such as bit error rate and data rate. Besides, with the increase of frequency band and the decrease of array element size, the scale of array antenna can be deployed larger. In [14], we observed the near-field effects and spatial non-stationarity on most major paths. These characteristics pose great challenges to the accuracy and complexity of E-MIMO channel modeling methods.

Considerations: To reduce the complexity of E-MIMO channel modeling, a channel modeling framework is proposed based on the capture and observation of multipath propagation mechanisms [14]. In Fig. 4, the different channels are viewed from the visible region (VR) on the base station (BS) array. The spatial non-stationary characteristic is observed in massive MIMO channels since the objects in the scenario may no longer serve as complete scatterers for the entire antenna array with its aperture increasing. When the size of the base station antenna array and the carrier frequency increases from sub-6 GHz to new mid-band, the range of near-field region increases. The users are located in the near-field region, and near-field effects and spatial non-stationary characteristic may occur in both LoS and NLoS environments. In [15], it can be seen that the near-field propagation is a double-edged sword (i.e., it brings both challenges and potentials to 6G communications). The existing 5G transmission methods specific for far-field suffer from severe performance loss in near-field regions, but exploiting the potential of near-field propagation can improve communication performance. The spatial multiplexing gain of MIMO communications increases with the transition from far-field to near-field. The DoFs increase when the BS-UE distance decreases, so the increased spatial DoFs can act as an additional spatial multiplexing gain, which opens up new possibilities for enhanced capacity [15]. Compared with the traditional channel model, the near-field channel model needs to consider more characteristics.

Suggestions: With the increase in the carrier frequencies and number of antennas in the future 6G systems, near-field effects will become more and more significant. Compared with the sub-6 GHz bands, the new mid-band antenna size is smaller, more array elements can be deployed in the limited space, greatly increasing capacity. The new mid-band E-MIMO will bring new channel characteristics, such as near-field beam split effect and beamfocusing, which are able to serve multiple users at the same angle. The spatial multiplexing gain of MIMO communications increases with the transition from far-field regions to near-field regions. Therefore, we can take advantage of the new channel characteristics to improve the 6G communication system performance.

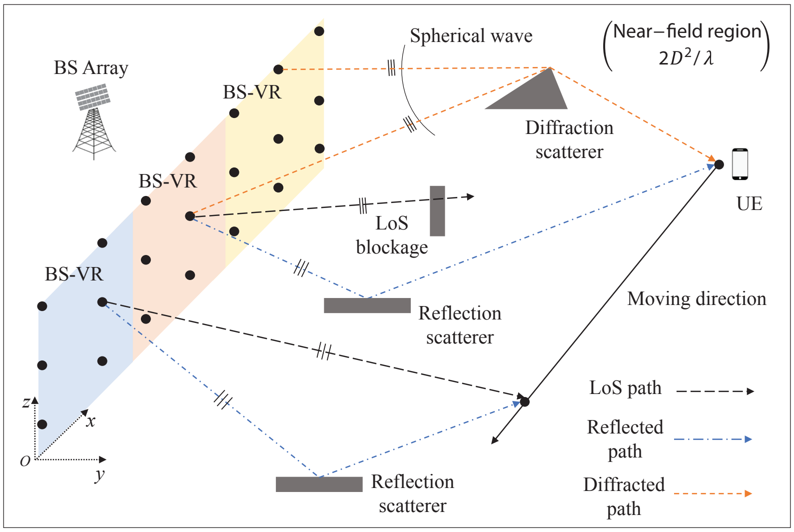

FIGURE 4. The near-field propagation with spherical wave and spatial non-stationary characteristic.

Open Issues and Future Directions of Spectrum toward 6G

With the rapid development and wide applications of radio technologies, the contradiction between the supply and demand of spectrum resources is becoming increasingly prominent. The spectrum management departments need to consider various factors in the spectrum planning.

Open Issues and Solutions

Network Coverage: The goal of the 6G network should not only meet urban scenarios, but also consider rural areas to achieve full coverage. This is a huge challenge, especially in terms of spectrum allocation. For a country with densely populated zones with hundreds of millions of people living in rural areas distributed over a very large area. The spectrum of 6G communication should include a variety of frequency bands in different scenarios, the current allocation of spectrum is not enough to meet the demand. High-frequency bands with wider radio bandwidth are required for ultra-high data rate transmission, but it is necessary to consider the existing research and development and mass production capacity of high-band equipment, the cost and cycle time. More importantly, large area coverage requires more frequency bands with lower propagation loss. At present, the new mid-band has not been connected to terrestrial mobile communication, which has the potential to be a solution to the problem of the new spectrum strategy.

Spectrum Allocation: The issues related to frequency allocation need to be mentioned, and the licensing of spectrum for commercial use is expensive. This poses a great challenge for promoting the development of 6G, expanding mobile coverage and meeting the sustainable development goals of 6G. Therefore, the allocation of spectrum at new mid-band should be planned as soon as possible to ensure that the spectrum can be allocated at a large bandwidth and low price. The spectrum can be used more efficiently, making operators more willing to upgrade and deploy networks.

Potential Technology: For the development of the future mobile communication industry, the research of technology is the necessary work. It is significant for spectrum research to master the characteristics of potential technologies in different frequency bands.

E-MIMO: E-MIMO would be deployed with new types of antenna arrays, much larger-scale antenna arrays, and distributed mechanism. Compared with the commercial sub-6 GHz, the size of the array element becomes smaller with the frequency band higher. More antenna array elements can be deployed in the same space, but the technical challenges of high frequency antennas also need to be considered. In addition, with the increase of MIMO scale and frequency, Rayleigh distance increases, and some new characteristics will appear, such as near-field effects.

ISAC: The applications of sensing mainly include positioning, posture recognition, and environment reconstruction. It is very important to obtain the angular domain information. The power angle spectrum will be sparse with the frequency increasing, which is beneficial to beamforming [11]. Compared with higher bands, the new mid-band has more multipaths and stronger multipath interference, which is a challenge to the sensing accuracy. Although the sensing ability of higher bands is stronger, the propagation loss is relatively larger. Therefore, the suitable spectrum is essential for ISAC applications.

Future Research Directions

This section will point out several potential research directions for the 6G spectrum.

Channel Research: At the new mid-band, more channel measurements about 6G potential technologies are needed to understand more channel characteristics. The channel is the basis of system design, network optimization and performance evaluation. To realize the 6G wireless communication network, it is urgent to carry out in-depth research on the channel.

Spectrum Sharing: Primary allocations to the mobile and fixed services at the new mid-band exist today in the International Telecommunication Union Radio Regulations, such as satellite communications. In the case of limited spectrum resources, spectrum sharing becomes important. To ensure that the spectrum sharing between different systems or services does not interfere with each other, it is necessary to solve the problem of spectrum contention and interference.

Bandwidth Division: Compared with sub-6 GHz, the new mid-band has a larger bandwidth. However, it needs to allocate bandwidth reasonably to different systems or services at a frequency band. This may involve the design of dynamic bandwidth allocation, channel division, and scheduling algorithms to meet the needs of different systems and optimize network performance.

Unified Standards: By formulating relevant standards such as ITU which are globally unified, the development of multi-frequency communication technology can be effectively promoted. From the regulatory perspective, it is vital to perform solid research in these bands, including the compatibility with currently used services.

Conclusion

This article compares the global state of spectrum allocation and illustrates the critical importance of reaching a consensus on the future 6G communication frequency band allocation. Some inspirations and suggestions are put forward for the application of the new mid-band in next generation communication systems. Several open issues of spectrum-related work, attractive solutions and future research directions are also highlighted. The new mid-band spectrum is a very attractive frequency range for the future mobile communication systems, with better coverage than higher band, especially at lower edge of the spectrum, and with the considerable bandwidth.

6G brings a lot of new features to the spectrum, and it is a trend to make spectrum access more open while strengthening the management. Compared with the narrow band at low-frequency and prominent channel sparsity at high-frequency, the new mid-band has the potential to be part of 6G systems, complementing and coordinating with sub-6 GHz, mmWave and high bands. This article hopes to provide some references for regulatory institutions to formulate spectrum regulation policies.

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Biographies

Jianhua Zhang (jhzhang@bupt.edu.cn) is a professor and Chairperson of China IMT-2030 tech group. She was the Drafting Group Chairperson of ITU-R IMT-2020 channel model. Her researches include mid-band, mmWave channel modeling.

Haiyang Miao (hymiao@bupt.edu.cn) is a Ph.D. candidate. His researches include massive MIMO, mid-band channel modeling.

Pan Tang (tangpan27@bupt.edu.cn) is an associate professor. His researches include mmWave, THz channel modeling.

Lei Tian (tianlbupt@bupt.edu.cn) is an associate professor. His researches include mmWave channel measurements.

Guangyi Liu (liuguangyi@chinamobile.com) is a 6G lead specialist. His researches include 6G technology.