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ORIGINAL PAPER

A study on the ambient electromagnetic radiation level of 5G base stations in typical scenarios

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Abstract

Knowledge of the electromagnetic radiation characteristics of 5G base stations under different circumstances is useful for risk prevention, assessment, and management. This paper selects several typical scenes (Open spaces, building concentration areas, user and building intensive areas) for electromagnetic radiation monitoring, and analyzes the relationship between ambient radiated power density and base station background. The results show that the factors that have significant impacts on the environmental radiation power density of 5G base stations including transmission distance, base station distribution, user density, building reflection superposition and so on. The radiation energy decays rapidly with distance. When the density of the building distribution is too large, the superposition effect caused by the reflected wave is concentrated at the distance of 50-70 meters. When the user density decreases (the superposition effect of reflected waves decreases), the 5G monitoring value follows the direct wave attenuation law and decreases rapidly with the increase of distance. Points with higher measured radiation in the simple access condition also had higher measured radiation in the high-speed download condition. With the popularization of 5G mobile phones and the increase of user density, the resource utilization of a single user will decline to the normal operation state, and the radiation environmental impact will be further reduced.

Keywords 5G base station · Environmental electromagnetic radiation · Typical scene · Radiation intensity

Introduction

Because of its higher data transmission rate and faster response time, fifth-generation mobile communication network (5G for short) created a series of typical application scenarios with commercial value and opened the digital era of interconnection of all things [1–3]. Researches show that the data transmission rate of 5G is up to 10 Gbit/s, which is 100 times faster than that of previous 4G LTE cellular networks [4], and the network delay of 5G is less than 1 ms, while that of 4G is 30–70 ms [5].

Base station is the core equipment of the 5G network, providing wireless coverage and realizing the wireless signal transmission between the wired communication network and the wireless terminal [6, 7]. Compared with the working mode of traditional mobile communication base stations, the evolution of 5G base stations in working mode is mainly reflected in two aspects: one is the intelligent Massive MIMO antenna technology, which is based on TD-LTE and TD-SCDMA intelligent antennas and is more in line with the technical requirements of 5G system in terms of structure, protocol and antenna

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equipment in details, 5G Massive MIMO antenna consists of multiple horizontally and vertically aligned sub-arrays, unlike TD-LTE (4G) system which supports beam assignment, spatial diversity and spatial multiplexing transmission scheme, 5G communication system only adopts the transmission scheme of beam assignment, which makes the use of frequency band resources more efficient. Second, the active antenna unit (AAU) technology, which integrates RF pull-away unit (RRU) and antenna equipment together to form AAU equipment, effectively supports MIMO diversity reception capability and more intelligent antenna deployment, while reducing antenna loss, facilitating the construction of large-scale mass distribution of 5G base stations. 5G base stations apply the large-scale MIMO technology (transformation from traditional multi-frequency antenna to array antenna) to multiplex more wireless signal streams to improve network capacity [8]. In addition, by using beamforming technology (transformation from directional radiation to multi-beamforming that can be realized by software) [9], the network coverage capability is greatly improved. Therefore, with the significant changes in the form of base stations and air interface characteristics, the electromagnetic radiation characteristics of 5G base stations have also changed greatly. Driven by the "new infrastructure" strategy of Chinese governments, 5G is undergoing a new process of large-scale deployment and application innovation, and the number of base station construction and users has also continued to rise [10]. Data from the 2022 World 5G Conference shows that China has built and opened a total of 1.968 million 5G base stations, and the three major operators have 5G The number of package users is close to 1billion, accounts for more than 60% of the world [11–13].

The large-scale commercial construction of 5G base stations, while promoting the new process of infrastructure in China, may have a negative impact on the electromagnetic radiation environment and even result in the local electromagnetic radiation environmental quality and the planned capacity of the electromagnetic radiation environment cannot meet the requirements of the national standard limits [14, 15], triggering negative public opinion in society.

Due to the major changes of 5G base station, the electromagnetic radiation characteristics of the corresponding base station have also changed greatly. How to grasp the electromagnetic radiation characteristics of 5G base stations scientifically, comprehensively, and accurately is an urgent problem to be solved for the base station construction units, government departments and ordinary people [16, 17]. Knowledge of the electromagnetic radiation characteristics of 5G base stations under different circumstances is useful for risk prevention, assessment, and management [18].

Previous empirical studies have investigated electromagnetic radiation level of 4G or 3G base stations in different micro-environments; collecting data by a qualified technician enables one to adhere strictly to a measurement protocol and control data quality, provided possibility for large scale modeling simulation [19–22]. However, little is known about the variation of electromagnetic radiation level of 5G base stations in different micro-environments. To fill the above research gap, we set two application scenarios, simple use and high-speed download, based on smart beam technology and high-frequency electromagnetic wave transmission principle, to monitor the 5G base station environment electromagnetic radiation under typical situations in daily life (open use environment, use environment with more concentrated users, use environment with high user and building density) and compare it with the base station background data, trying to explain the regular changes of 5G base station environment.

Experimental

Typical scene selection

According to the regional functions and user density, three typical areas are set for 5G base station electromagnetic radiation monitoring: open scenes (Yuzui Wetland Park and South Square of Nanjing railway station), more concentrated scenes (liujiacun residential community in Yuhuatai District and Mingji hospital on Taishan Road), and scenes with high density of users and buildings (the headquarters campus of Southeast University and the business district of Xincheng science and Technology Park), At the same time, the background data of the base station in the corresponding period shall be recorded.

In order to understand the distribution law of electromagnetic radiation impact of 5G base stations under typical technical parameter conditions in extreme scenarios, base stations with two antenna erection modes, namely rooftop glorification antenna (Base Station A) and floor-to-ceiling landscape tower (Base Station B), are selected to study the degree of attenuation of the narrow-wave intensity with distance. The continuous high-flow downlink transmission operation of 6 mobile terminals is defined as an extreme case data transmission application scenario. The mobile terminals used are Huawei mate20 cell phones with 5G SIM test cards, and the six terminals are kept in the data download state during monitoring and are centrally placed 1.5 m behind the monitoring site.

5G base station selection and background data recording

To analyze the relationship between the measured value of 5G base station and background data, 5G base stations of China Telecom were selected, and its operating frequency band is 3400–3500 MHz, the power is 200 W, and the gain is 25 dBi. Meanwhile, the operator is well-trained to adjust the antenna direction to ensure that it can be monitored in the main lobe range.

The background data reading interval of China Telecom 5G base station is 15 min, the monitoring experiment time is 6 min, and it ensures that the monitoring period is within the interval of background data reading of the base station, to obtain complete and continuous background monitoring data.

To clarify the relationship between the measured electromagnetic radiation value of 5G base station and background data, the relationship between 5G frequency selection radiation value and single user resource utilization under simple access and high-speed download conditions of terminal (5G mobile phone) in different scenarios is studied. Among them, single user resource utilization (%) refers to the average utilization (%) of 5G NR downlink PRB of base station antenna divided by the average number of users.

Monitoring instruments and weather conditions

The instrument used in this study is the SRM-3006 frequency selection analyzer (Nada, Germany), and the measurement instrument was metrologically calibrated before the measurement, and the instrument calibration certificate was obtained. The frequency selection analyzer consists of a mainframe and several omnidirectional measurement antennas in different frequency bands, which can perform omnidirectional measurement of all signal field strengths in the range of 9 kHz–6 GHz. After the frequency band (such as 3.4 GHz–3.5 GHz), the peak power density and the average power density under the frequency band are measured by peak detector and root mean square (RMS) detector, respectively, and the measurement spectrum is recorded at the same time, and the measurement probe has a built-in orthogonal three-axis antenna, so that the antenna has good isotropy, which can ensure that the monitoring results are independent of the direction of incidence and polarization of electromagnetic waves. The mobile terminal adopts mate 20 cell phone (Huawei, China) with 5G SIM test card, which can realize unlimited flow rate traffic and long time (not less than 15 min) stable data download.

According to the requirements of 5G mobile communication base station monitoring technology method, monitoring instrument and monitoring experiments was carried out in line with Monitoring Method for Electromagnetic Radiation Environment of 5G Mobile Communication Base Station (Trial) (HJ1151-2020) under the weather conditions without rain and snow.

Layout of mobile terminals and monitoring points

For the typical scenes around 5G base station, set three monitoring points in the unobstructed space between 5G base station and base station antenna according to the distance. During monitoring, 5G mobile terminal (Huawei mate20 with 5G SIM card) is placed 1.5 m behind the monitoring point, which is located between the mobile terminal and 5G base station (Fig. 1a), respectively, monitors the radiation value of 5G frequency selection during simple access of 5G terminal and large flow continuous data transmission operation (extreme download) of 5G terminal. Figure 1b is a typical spectrum diagram of 6-min average value continuously monitored in the range of 400–4000 MHz.

Results and discussion

Radiation level change of 5G base station in open scene

Figure 1 shows the relationship between 5G radiation monitoring values and single user resource utilization in the open scenes of the park (Nanjing Yuzui Wetland Park) and the square (South Square of Nanjing railway station). As can be seen from the figure that when the mobile terminal is simply connected, the 5G measured value in the park decreases with the increase in distance (and then remains stable); When the terminal downloads at high speed, the power density in the park also decreases rapidly with distance (and then increases slightly). Both cases show the characteristics of rapid attenuation of radiation energy with distance. In addition, the single user resource utilization rate in the park is very close to the change trend of its environmental radiation power density, showing a good correlation between the two.

For the scene in the square, both the environmental radiation power density and the resource utilization rate of single user show the characteristics of no change or little change. The analysis shows that compared with the park, the passenger flow in the railway station square is very large, there is more than one 5G base station set around, and the measured values are relatively stable in the range of tens to hundreds of meters. At the same time, the 5G measured value and single user resource utilization rate of the square are significantly lower than the measured value and average utilization rate in the park, which also indirectly proves that the setting of more 5G base stations is very beneficial to reducing the environmental radiation level.

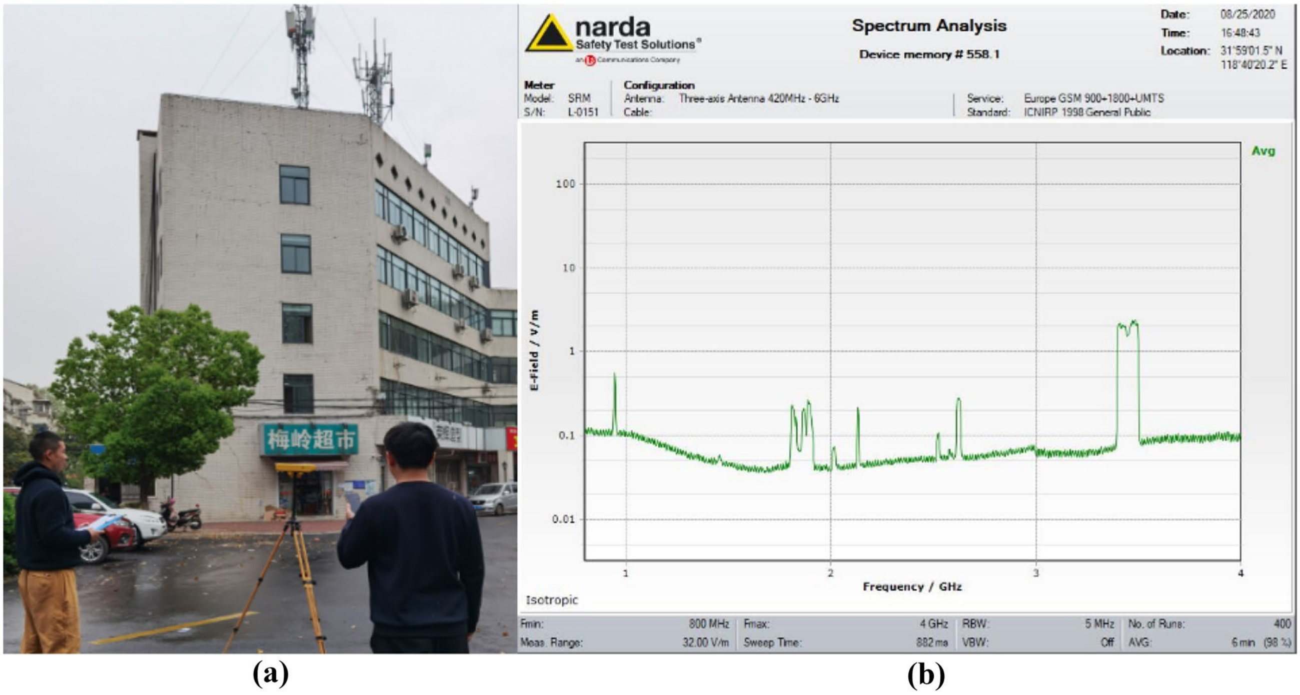

Fig. 1 **a** Electromagnetic radiation monitoring site; **b** typical monitoring spectrum

Comparing Fig. 2a and b, it can be found that the environmental radiation power density and single user resource utilization are much higher than those under the condition of simple access. It shows that when downloading at high speed, the signal strength is greater, and the average utilization rate of NR downlink PRB for 5G antenna is also higher.

Radiation level of 5G base station in building concentration scene

Figure 3 shows the relationship between 5G monitoring values of hospitals and residential areas (residential areas) and single user resource utilization under the scenario of dense buildings but low user density, simple access, and high-speed download. As can be seen from Fig. 3a, when the mobile terminal is simply connected, the 5G measured values of hospitals and residential areas first increase and then decrease with the change of distance. It is considered

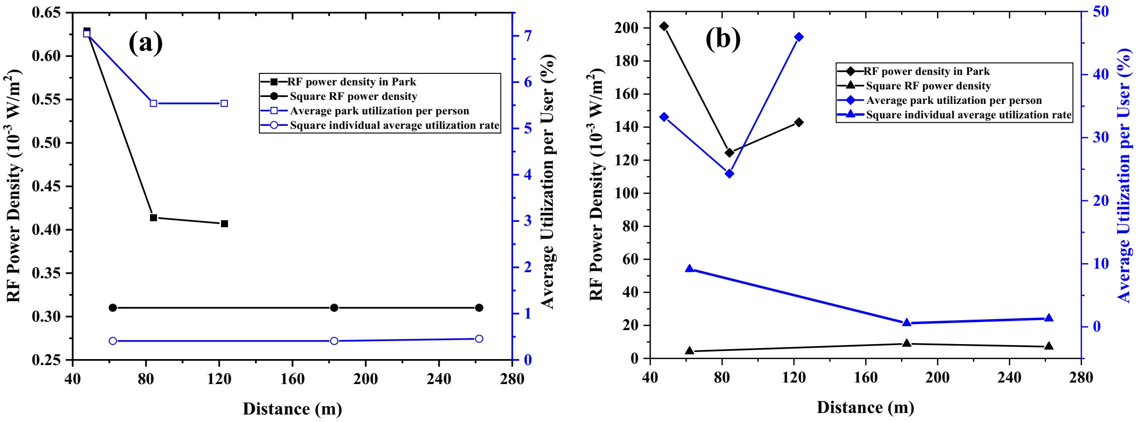

Fig. 2 Relationship between 5G monitoring power density and single user resource utilization under open scenario: **a** simple access; **b** high-speed download

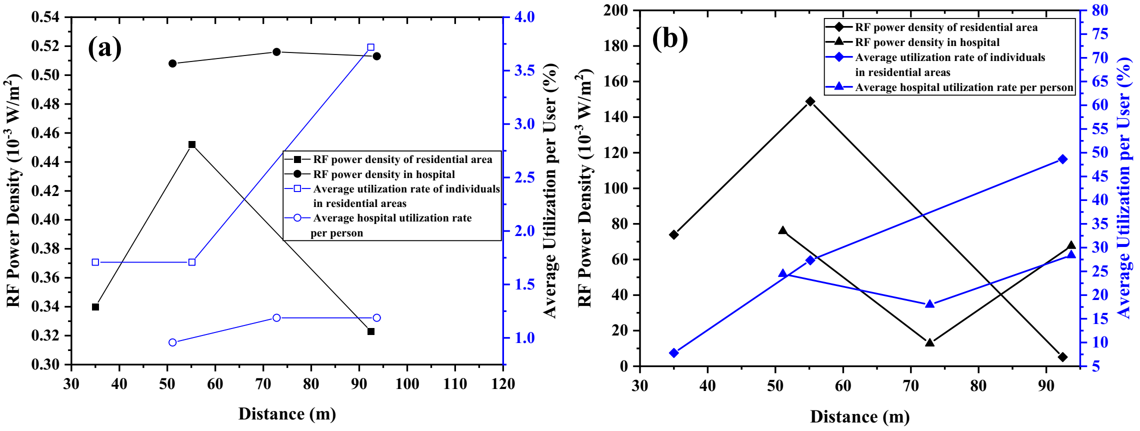

Fig. 3 Relationship between monitoring values of building centralized scenes and single user resource utilization: **a** simple access; **b** high-speed download

that this is caused by the superposition of electromagnetic wave reflection caused by dense buildings, and the situation is more obvious in small residential areas. Further comparing the radiation power density of the two environments during high-speed download, it is found that the larger value appears in the range of 50–60 m. It is speculated that based on the characteristics of electromagnetic wave transmission and energy attenuation, the superposition of direct electromagnetic wave of the base station and reflected wave of the building is in this distance range.

For single user resource utilization, whether it is simple access or high-speed download, the residential area environment increases with the increase in distance, showing the phenomenon that the utilization rate increases due to the decrease in radiant energy with the decrease in distance. It shows that when the user demand is relatively stable, the decline of radiant energy leads to the increase in average utilization rate. For the single user resource utilization in the hospital scenario, there is little change under the conditions of simple access and high-speed download.

Radiation level of 5G base station in the scene with large building and user density

For the scenario with dense buildings and high user density, the university campus and business district are selected as the research objects. Figure 4 shows the relationship between the monitored radiant power density and single user resource utilization in this scenario.

It can be seen from Fig. 4a that during simple access, 5G monitoring values of university campuses and business districts first increase and then decrease (or slightly increase) with the increase in distance, which is the reason for the relatively large building density in this scenario and the

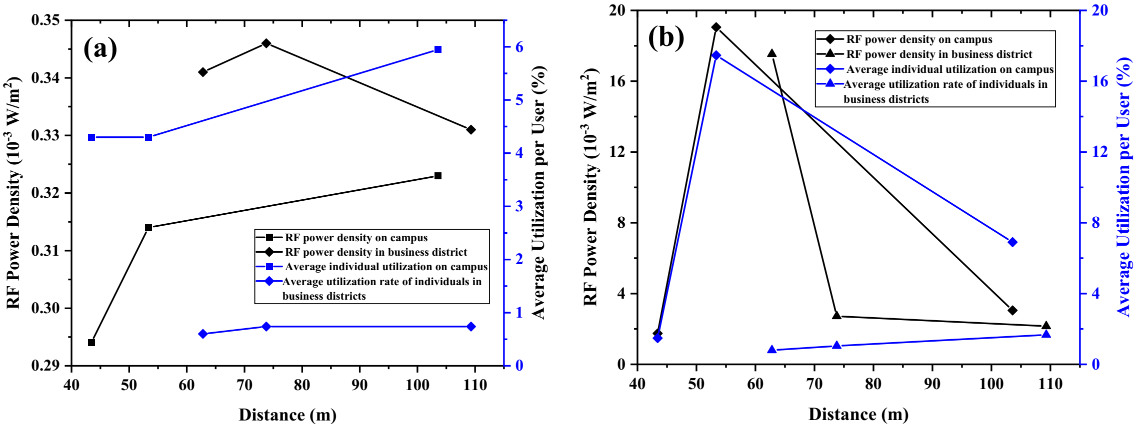

Fig. 4 Relationship between monitoring values and single user resource utilization in scenes with high density of users and buildings: **a** simple access; **b** high-speed download

superposition effect of direct and reflected electromagnetic waves within a certain range. When the distance increases further, the building density decreases, the superposition effect of reflected waves decreases, and the 5G monitoring value follows the attenuation law of direct waves and decreases rapidly with the distance. This change of ambient radiation power density also occurs under the condition of high-speed download, as shown in Fig. 4b.

Comparing Fig. 3b with Fig. 4b, it can be found that the ambient radiation power density of the former is significantly higher than that of the latter, which is related to the specific beamforming effect of 5G base station according to the change of user density. When there are few users around the 5G base station, the shaped beam will be transmitted to the terminal for high load applications (such as large flow and high-speed download), resulting in large local electromagnetic radiation; When there are many users around, the shaped beam is dispersed, and the influence of electromagnetic radiation becomes smaller. Further comparison shows that, like the situation in Fig. 3, the larger value of environmental radiation power density appears in the range of 50–70 m. Therefore, combined with the data in Fig. 3, it can be considered that when the building density is large, the superposition effect caused by the reflected wave is in the range of 50–70 m.

For the university campus and business district environment, the single user resource utilization during simple access does not change significantly with distance, as shown in Fig. 4a. For the working condition of high-speed download, as shown in Fig. 4b, the resource utilization rate of single user shows different trends in campus and business district. The resource utilization of single users in the business district environment increases slightly with the distance (the change is not obvious), while that of the campus first increases and then decreases (the change is very large). It is considered that this is related to the different number of base stations set in the two environments. As a key service area with high user density, the campus has a higher density of 5G base stations installed in the area to ensure communication quality. When the distance is long, the single user resource utilization decreases when multiple base stations are served/covered.

Similarly, comparing Fig. 4a and b, it can be found that, like Figs. 2 and 3, under the scenario of high user and building density, the environmental radiation power density and single user resource utilization during high-speed download are significantly higher than those under the condition of simple access.

It can be seen from the above research that the measured values of various typical scenes fluctuate greatly. In fact, the corresponding background data such as the average number of background users of 5G base station and the average utilization rate of NR downlink PRB also change accordingly. To clarify the relationship between monitoring values and background data, a broken line diagram of the corresponding relationship between the environmental radiation power density measured under the above various scenarios and working conditions (calculated from 5G measured values) and the average utilization rate of a single user (single user resource utilization rate) is established, as shown in Fig. 5.

It can be seen from Fig. 5 that under the two working conditions of simple access and high-speed download, the change trend of both environmental radiation power density and single user resource utilization shows good consistency. The points with higher measured values under simple access conditions also have higher measured values under high-speed download conditions; under the simple access condition, the single user resource utilization rate is higher, and under the high-speed download condition, the single user resource utilization rate is also higher. The environmental radiation power density and the average utilization rate of a single user show a good correlation

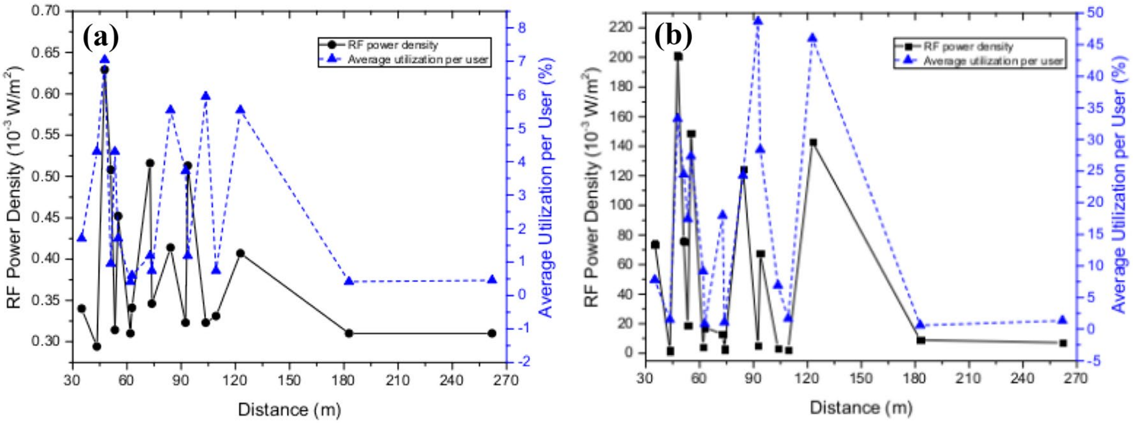

Fig. 5 Relationship between single user resource utilization and 5G electromagnetic radiation level: **a** simple access; **b** high-speed download

with distance. In addition, no matter what kind of working condition, overall, the points with large 5G measured value (environmental radiation power density) also have significantly higher resource utilization rate of single user. It can be inferred that the impact of electromagnetic radiation of 5G base station is related to the utilization rate of single user resources. The higher the utilization rate is, the greater the impact of electromagnetic radiation may be. Therefore, it can be determined that there is a strong correlation between single user resource utilization and radiation intensity, which can be used as a working condition characterization factor.

Therefore, according to the change of resource utilization rate of single user, the above monitoring data are further combed, and the results are shown in Table 1. It can be seen from Table 1 that in the monitoring of each typical scenario, the 5G measured value (power density) and single user resource utilization rate under the simple access scenario of 5G terminal are low, indicating that when the 5G terminal around 5G base station is not used or only used for light applications, it has little impact on the surrounding electromagnetic radiation. When carrying out continuous large flow data transmission (high-speed download), 5G measured value and single user resource utilization rate increase significantly. In fact, the average traffic consumption in this scenario is 20.3 gb per 6 min, which belongs to the high-speed use scenario of a single terminal, and it will hardly appear in daily life. From the range of single user resource utilization, under the condition of high-speed download, the number of occurrences is less than 20% (accounting for 61.1%), while the number of occurrences below 30% accounts for 83.3%. Therefore, it can be conservatively determined that the 30% resource utilization rate of a single user is the general condition of the normal operation of the 5G base station.

Table 1 Comparison of 5G electromagnetic radiation impact and single user resource utilization in typical scenarios

Working condition	Number of resource utilization intervals of single user (Times)		5G frequency selection power density (w/m^2)
Simple access	> 10%	0	–
	5–10%	4	0.323–0.629
	2–5%	3	0.294–0.323
	1–2%	4	0.340–0.508
	< 1%	7	0.310–0.957
High-speed download	> 50%	0	–
	40–50%	2	5.162;142.906
	30–40%	1	201.092
	20–30%	4	67.646–148.846
	< 20%	11	1.749–19.051

It should be noted that due to the early promulgation of the Chinese national standard "Electromagnetic Environment Control Limits" (GB8702-2014), the measured data in the high-speed download scenario all exceeded the standard public exposure control limit of 0.4 W/m^2, and even in the simple application scenario, some of the measured values exceeded the limit. However, compared with the standard limit of 40 W/m^2 in the ICNIRP "Guidelines for Limiting Electromagnetic Field Exposure" (100 kHz–300 GHz) (2020), all measured values in the simple application scenario meet the limit, and only some measured values in the high-speed download conditions exceed the limit. The measured data in this research are only for the study of the changing pattern of electromagnetic radiation environment of 5G base stations, and cannot reflect the general situation of daily use of 5G base stations.

Like the results in Fig. 5, when the measured value is large, the resource utilization rate of single user is generally high. On the contrary, when the resource utilization of a single user is low, the measured value is generally small. The resource utilization rate of a single user is inversely proportional to the number of users around the 5G base station. The more users, the lower the personal utilization rate. When the 5G radiation is concentrated on the user, it will cause less local radiation to the base station, such as when the 5G radiation is concentrated on the user; when there are many surrounding users, the shaped beam is dispersed, so the influence of electromagnetic radiation becomes smaller. It can be inferred that with the popularity of 5G mobile phones, the number of users will increase, the utilization rate of single user resources will decline, and the radiation environmental impact will be further reduced.

Radiation level of 5G base station in building extreme scene

It can be seen that for the conventional 5G base station, in the application scenario where 6 mobile terminals are simultaneously in the operation of high traffic data transmission (Table 2 and Fig. 6), the measured value of the 5G band at 40–50 m from the antenna can satisfy the public exposure control limit value of 0.4 W/m^2 in the electromagnetic environment control limit value (GB 8702-2014). During the monitoring process, the background data of the measured base station were synchronously tracked and recorded, and the average utilization rate of NR downlink PRB of the corresponding antenna reached a range of 65.88–98.58%, and the effective throughput rate of cell downlink was 885.29–1147.30 Mbps, and it can be considered that this monitoring can reflect the electromagnetic radiation intensity of the stable and strong narrow wave during the measurement time.

Table 2 Summary of 5G base station electromagnetic radiation monitoring results and background data

Distance to antenna (m)	5G base station A			5G base station B		
	5G frequency selection power density (W/m^2)	Average NR downlink PRB utilization rate (%)	Cell downlink effective throughput rate (Mbps)	5G frequency selection power density (W/m^2)	Average NR downlink PRB utilization rate (%)	Cell downlink effective throughput rate (Mbps)
40	0.779	88.01	1045.51	0.398	98.57	953.15
50	0.306	89.38	1009.37	0.243	98.58	922.44
60	0.354	77.28	958.07	0.149	98.58	967.58
70	0.215	95.72	983.38	0.095	98.40	932.92
80	0.160	65.88	920.30	0.053	98.58	938.93
90	0.099	93.61	912.46	0.036	98.58	885.29
100	0.130	97.08	1147.30	0.079	98.43	919.25
110	–	–	–	0.029	98.43	919.25

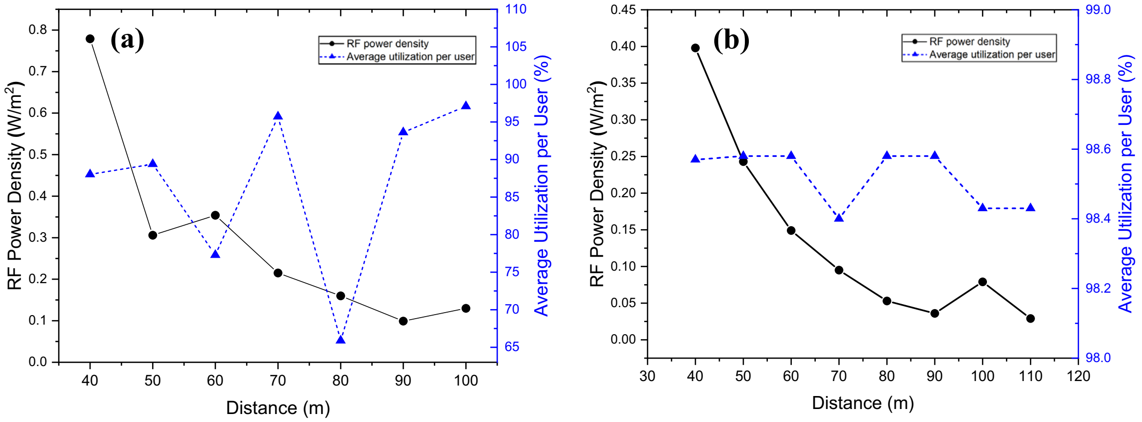

Fig. 6 Relationship between distance to antenna and single user resource utilization and 5G electromagnetic radiation level on **a** 5G base station A; **b** 5G base station B

Conclusions

(1) In different scenarios, the environmental electromagnetic radiation level of 5G base stations is affected by many factors. The factors affecting the radiation power density mainly include transmission distance, base station distribution, user density, building reflection superposition, etc., while the change of single user resource utilization is strongly related to base station distribution, user density, download traffic, etc.

(2) When the building density is large, the superposition effect caused by the reflected wave is concentrated in the distance of 50–70 m.

(3) The single user resource utilization rate of 5G base station has a strong correlation with the radiation intensity, which can be used as the working condition characterization factor. It is conservatively considered that 30% of the single user resource utilization rate can characterize the working condition of 5G base station during normal operation.

(4) When there are few users around the 5G base station, the shaped beam will be transmitted to the terminals for high load applications (such as continuous downloading), resulting in large local electromagnetic radiation; When there are many users around, the shaped beam is dispersed, and the influence of electromagnetic radiation becomes smaller. With the popularity of 5G mobile phones and the increase in the number of users, the resource utilization rate of single user will drop to the general working condition, and the radiation environmental impact will be further reduced.

(5) With the development and construction of the Internet in industry, medical care and transportation, 5G base stations may form short-time strong electromagnetic narrow waves in a special area or a specific direction, and it is recommended to carry out targeted theoretical simulation and actual test analysis for 5G base station application scenarios and terminal working

conditions in the next step, so as to promote the healthy development of the electromagnetic environment in the era of the Internet of everything.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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