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Coverage Analysis and Proposed Cell Sizes to Enhance the Performance of the 5G Cellular System

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Keywords:
IMT-2020; 5G; Micro cell; mmWave; Spectral Efficiency.

Highlights:

- *ITU standard channel model has been used.*
- *FR1 and FR2 coverage investigation of 5G NR has been done.*
- *Minimum ITUs technical requirements for spectral efficiency has been evaluated.*
- *Suitable cell size is proposed for each frequency band.*

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Abstract: The global demand for more digital data motivates the evolution of mobile communication systems from 2G and 3G to 4G and 5G to support high data rate applications. The International Mobile Telecommuication-2020 (IMT-2020) defined the minimum technical performance requirements and guidelines for evaluating the 5G mobile cellular system. The New Radio (NR) millimeter wave (mmWave) and massive Multiple Input Multiple Output (mMIMO) antenna systems are technologies used in the 5G cellular system. Therefore, this paper studies the performance of the mmWave system combined with the mMIMO antenna system using the IMT-2020 channel model in a dense urban microenvironment, considering different frequency bands and numbers of elements at the Base Station (BS) antenna array. The performance is evaluated through system-level simulation in terms of Signal power to Noise power Ratio (SNR), Spectral Efficiency (SE), and cell edge user SE. A cell size reduction technique is proposed to meet the target requirements set by IMT-2020. Simulation results showed that the sub. 6 GHz frequency bands achieve the target SE of IMT-2020, while in the mmWave frequency range, the target SE requirement can be achieved using a high number of antenna elements at the BS antenna for some frequency bands.

تحليل التغطية وأحجام الخلايا المقترحة لتحسين أداء النظام الخلوي الجيل الخامس

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الخلاصة

يحفز الطلب العالمي على المزيد من البيانات الرقمية تطور نظام الاتصالات المتنقلة من الجيل الثاني والثالث إلى الجيل الرابع والخامس لدعم التطبيقات ذات معدل البيانات المرتفع. حددت الاتصالات المتنقلة الدولية - ٢٠٢٠ (IMT-2020) الحد الأدنى من متطلبات الأداء الفني والمبادئ التوجيهية لتقييم النظام الخلوي المتنقل الجيل الخامس. تعد الموجات المليمترية للراديو الجديدة (mmWave) وأنظمة الهوائي متعددة المدخلات الضخمة (mMIMO) من التقنيات المستخدمة في النظام الخلوي الجيل الخامس. لذلك، يدرس هذا البحث أداء نظام mmWave المقترن بنظام هوائي mMIMO باستخدام نموذج قناة IMT-2020 في بيئة حضرية صغيرة كثيفة مع مراعاة نطاقات تردد مختلفة وعدد مختلف من العناصر في صفيف هوائي المحطة الأساسية (BS). يتم تقييم الأداء من خلال محاكاة مستوى النظام من حيث قوة الإشارة إلى نسبة قوة الضوضاء (SNR) والكفاءة الطيفية (SE) ومستخدم حافة الخلية SE. تم اقتراح تقنية لتقليل حجم الخلية لتلبية المتطلبات المستهدفة التي حددها IMT-2020. أظهرت نتائج المحاكاة أن الجزء الفرعي. تحقق نطاقات التردد ٦GHz الهدف SE المستهدف للاتصالات المتنقلة الدولية -٢٠٢٠، بينما يمكن تحقيق متطلبات SE الهدف في نطاق الترددات بالموجات المليمترية باستخدام عدد كبير من عناصر الهوائي في هوائي المحطة الأساسية لبعض نطاقات التردد.

الكلمات الدالة: الاتصالات المتنقلة الدولية - ٢٠٢٠، الجيل الخامس، خلية صغيرة، الموجات المليمترية، الكفاءة الطيفية.

1.INTRODUCTION

Mobile communications systems and sociotechnical advances are closely related and serve as the foundation of civilization in 2020 or beyond [1, 2]. There has been a significant increase in demand for more connected devices and reliable and high data rate systems worldwide [2-4]. By the end of 2025, 39 billion active connections will be used in different applications, such as smart healthcare, smart cities, self-driving cars, and smart energy systems [5, 6]. The concept of wireless transmissions has changed with the introduction of the Fifth Generation (5G) mobile communications. In addition to several technological advancements over the Fourth Generation (4G) Long Term Evolution (LTE) communication system, the 5G New Radio (NR) broadens using mobile communications to new business sectors [7]. The International Mobile Telecommunications-2020 (IMT-2020) specifications, which outlined forming 5G mobile communication standards, were established by the International Telecommunication Union-Radio communication sector (ITU-R) [8, 9]. According to (Series M) [1], IMT-2020 applications fit into the three main usage scenarios: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and massive Machine-Type Communications (mMTC) [1, 10]. Fig. 1 shows eight significant qualities set by ITU-R for IMT-2020 technologies out of thirteen capabilities and compares them with the IMT-Advanced specifications. According to IMT-2020, the 5G network supports a peak data rate from 10 Gbps up to 20 Gbps, depending on the operation scenarios and conditions. The spectrum efficiency in IMT-2020 is three times higher than IMT-Advanced. IMT-2020 is anticipated to support an area traffic capacity of 10 Mbps/m². The network energy efficiency is desired to improve 100 times the IMT-Advanced system. IMT-2020 supports over-the-air latency of 1 ms for very low-latency applications. Additionally, IMT-2020 is anticipated to provide high mobility up to 500 km/h with adequate Quality of Service (QoS) intended for high-speed trains. Finally, IMT-2020 is anticipated to allow a connection density of up to 10^6 Devices /km² [1, 11].

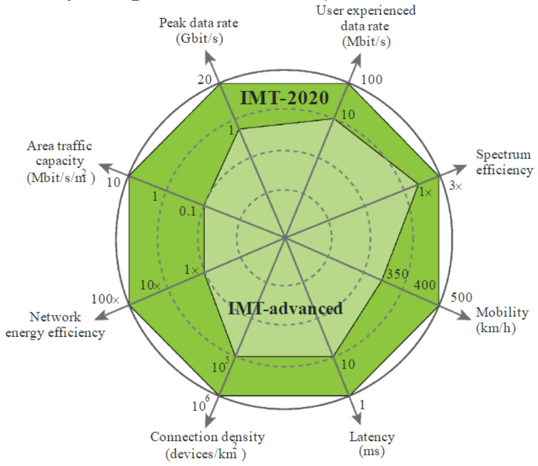


Fig. 1 Enhancement of Key Capabilities from IMT-Advanced to IMT-2020 [1].

The global shortage of frequency spectrum for cellular communications motivates the world to move their attention to millimeter Wave (mmWave) frequency bands [12], where a vast contiguous spectrum is available for deploying the new generation mobile network [13, 14]. Release 16 of the 3GPP specification defines two frequency ranges: Frequency Range one (FR1) from 410 MHz to 7.125 GHz and FR2 from 24.25 GHz to 52.6 GHz. FR2 lies in the mmWave spectrum [15, 16]. However, moving up into the high-frequency range of the mmWave band brings unfavorable propagation effects for mobile comminutions, such as an increased pathloss and higher diffraction and absorption loss. A possible solution to overcome the higher propagation loss is to use high-gain antenna systems, such as antenna arrays at the Base Station (BS) and the User Equipment (UE) [13, 17]. Different studies have evaluated the performance of the mmWave mobile communication system. Lee and Oh [18] presented a system-level simulation study for a 2x2 MIMO system. Lee and Oh [18] evaluated a data rate of 4 Gbps theoretically considering the urban microenvironment in the downlink considering the FR1 band. A spherical coverage of the 5G network in mmWave band was characterized in Zhao et al. [13] based on the 3GPP specification. The study determined the impact of user body obstruction, antenna topologies, and device integration on the spherical coverage at different UE locations through modeling and measurement data. According to the results, the array performance was more sensitive to nearby objects in the mmWave band than the sub. 6 GHz band due to the high operating frequency. The link budget of mobile communications degraded due to the significant shadowing loss and unpredictable human body orientation in the mmWave frequency band. Coverage analysis for indoor and outdoor was conducted in Turkmen et al. [19] considering the FR2 range. The study investigated the BS transmit power, distance from the building, and construction wall material on the indoor coverage. The dielectric characteristics of the materials mostly determined the degree of the interference induced by the outdoor BS. In Refs. [7, 9], the evaluation of 5G's performance by the key performance metrics in ITU-R [20] has been accomplished. The works examined whether the minimal technical standards in ITU-R [21] were met. The studies have demonstrated that the IMT-2020 expectations were satisfied for certain simulation parameters. Salazar et al. [22] the coverage analysis and problems in the Urban 5G cellular system have been evaluated using the Ray tracing tool and the MATLAB simulation. None of the above studies considered various carrier frequencies in different bands, especially 5G NR, with a wide spectrum range. Also, none of the mentioned studies analyzed the system-level performance of massive MIMO in different frequency bands. Furthermore, the available studies have yet to evaluate system performance according to the minimum requirement of ITU specification for IMT-2020. Therefore, this paper studies the impact of different antenna elements at the BS massive antenna array in FR1 and FR2 and the carrier frequency between them. The study uses the ITU-R channel model with a standard environment for all transmission conditions. Also, cell reduction is proposed for the scenarios in which the minimum requirements cannot be achieved.

2.SYSTEM LAYOUT AND CHANNEL MODEL

The coverage analysis in this paper is performed for a dense Urban Micro (Umi) environment with a cell radius of 110 m and a BS antenna height of 10 m [20]. Fig. 2 shows the simulated system layout. The simulation scenario of this paper was set according to the ITU-R report [20]. The report provides guidelines for the procedure, methodology, and criteria for evaluating the candidate radio technologies against IMT-2020 requirements.

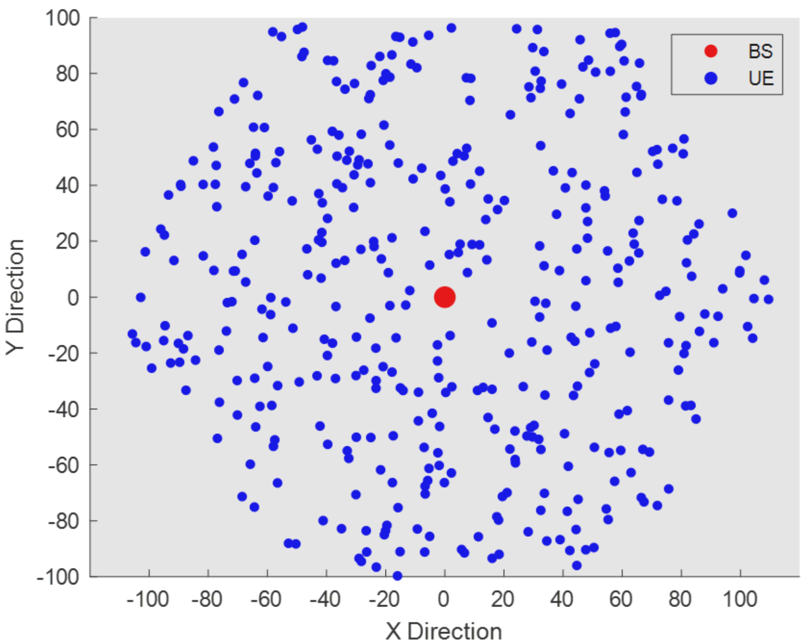


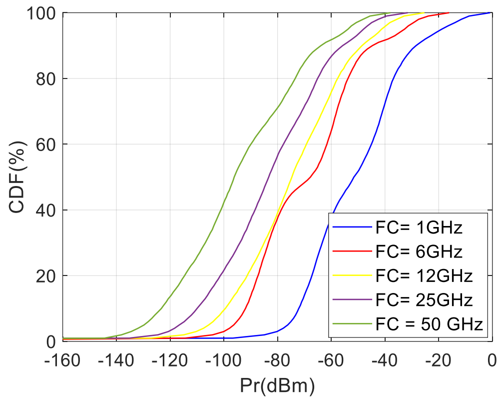
Fig. 2 Network Layout of the Simulated System.

Many BS-UE links' wireless channels were modeled using the IMT-2020 channel model [23]. ITU-R recommends this model for evaluating the candidates' Radio Interface Technology (RIT) for 5G specifications. The channel model can operate in a frequency band from 0.5 GHz to 100 GHz. The channel model is detailed more in the ITU document [20]. The simulation parameters were set according to the ITU-R and the 3GPP standard and documentation [15, 20, 24]. Carrier frequency (FC) of 1 GHz and 6 GHz were selected in the FR1 frequency band. 12 GHz was between the FR1 and the FR2 bands. 25 GHz and 50 GHz are selected for the FR2 band. Different numbers of antenna elements at the BS array were considered, while the UEs were considered to have a single antenna in all simulation scenarios. Table 1 summarizes the simulation parameters.

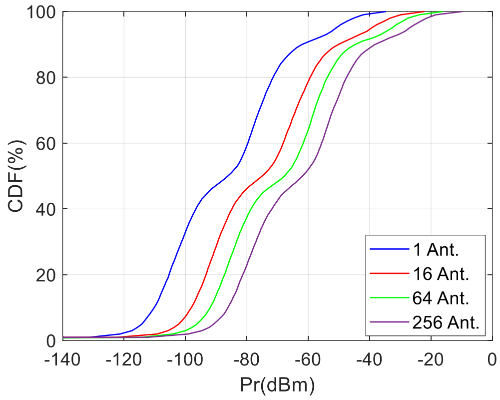
Table 1 Simulation Parameters.

Parameter	Value	
	FR1	12 GHz and FR2
Carrier frequency (GHz)	1 , 6	12, 25, 50
Number of antenna elements at BS	1, 16, 64 , 256	
Transmission power (dBm)	30	
Bandwidth (MHz)	10	50
Subcarrier Spacing (Δf) (kHz)	15	60
Number of resource blocks (NRB)	52	66
Number of Subcarriers (Nsc)	624	792
FFT size (NFFT)	1024	
Sampling frequency (MHz)	15.36	61.44
Noise Figure (NF)(dB)	7	10
Temperature (°C)	15	

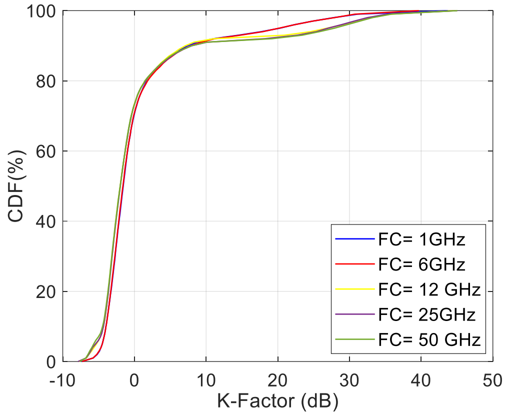
Fig. 3 shows the characteristic of the propagation channel in terms of Cumulative Distribution Function (CDF) of the total received power (Pr) in dBm, K-factor, Root Mean Square (RMS) delay spread, RMS Azimuth Angel of Departure (AOD), RMS Elevation Angel of Departure (EOD), RMS Azimuth Angel of Arrival (AOA), and RMS Elevation Angel of Arrival (EOA). In Fig. 3, the impact of different carrier frequencies is shown for several antenna elements of 64, while the impact of different numbers of BS antenna elements is shown for a carrier frequency of 6 GHz. Fig. 3 (a, b) shows CDF graphs for total received power at the UEs. As expected, the received power decreased as the carrier frequency increased, and the number of antenna elements at the BS decreased. The array gain of the antenna array at the BS decreases as the number of elements in the array decreases, decreasing the received power. Fig. 3 (c, d, e, g, h) shows negligible impact for the carrier frequency on the K-factor, RMS delay spread, RMS AOD, RMS AOA, and RMS EOA. A difference can be noticed in Fig. 3 (f) in the RMS AOD spread, where the angle spread at the FR2 band and 12 GHz were low compared to the angle spread of the FR1 band since higher frequency bands require a more directive antenna pattern.



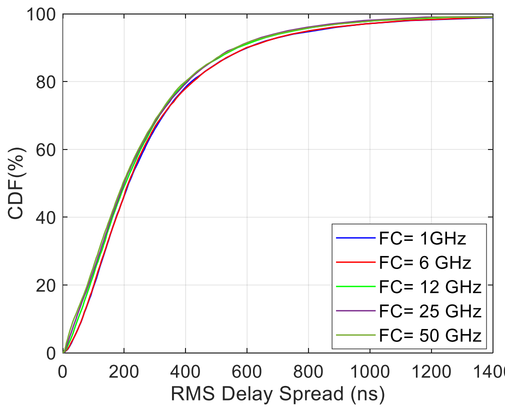
(a)



(b)



(c)



(d)

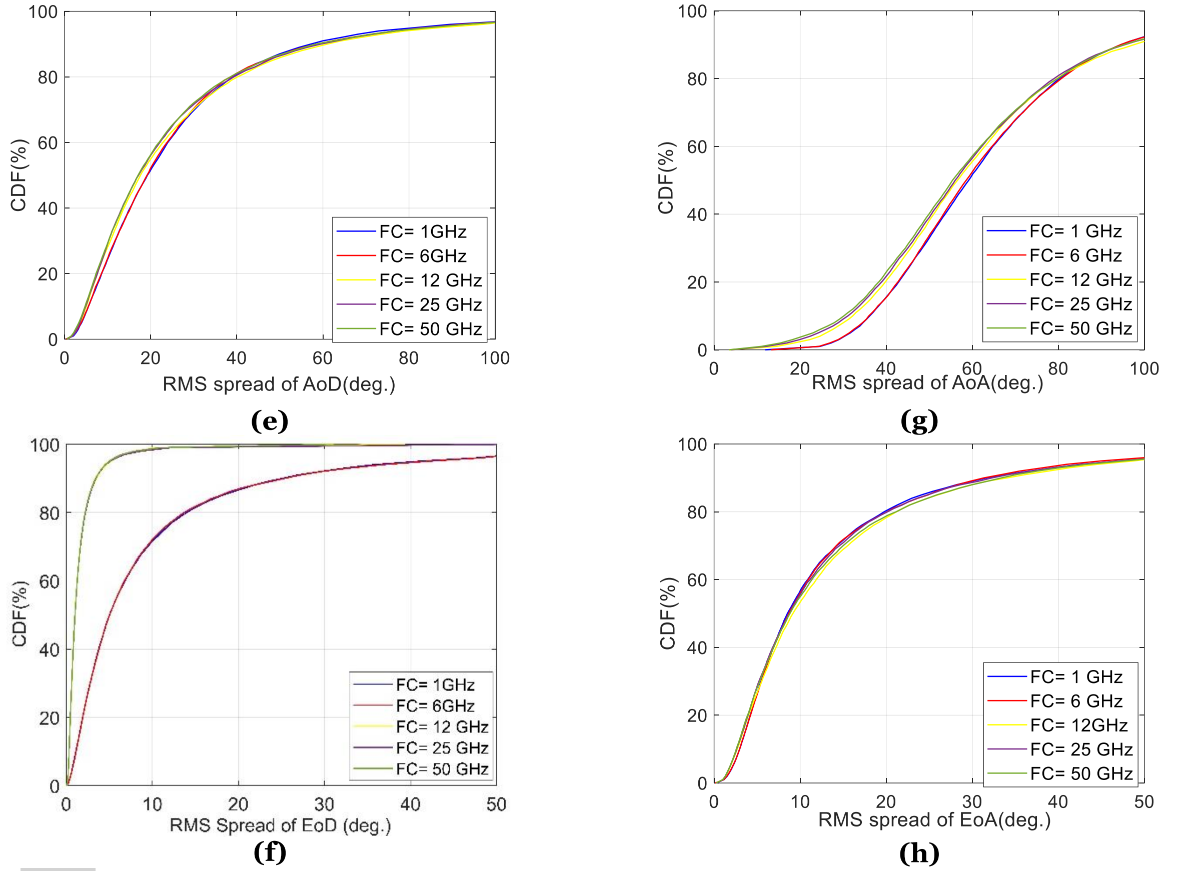


Fig. 3 Propagation Characteristics of IMT-2020 Channel Model, (a) Received Power for Different Carrier Frequencies, (b) Received Power for Different Number of Antenna Elements at the BS, (c) K-Factor for Different Carrier Frequencies, (d) RMS Delay Spread for Different Carrier Frequencies, (e) RMS AOD Spread for Different Carrier Frequencies, (f) RMS EOD Spread for Different Carrier Frequencies, (g) RMS EOD Spread for Different Carrier Frequencies, and (h) RMS EOA Spread for Different Carrier Frequencies.

3.SPECTRAL EFFICIENCY ANALYSIS

This section presents the system-level simulation performance analysis of cellular systems at different carrier frequencies and several antenna elements at the BS. The performance was evaluated regarding spectral efficiency considering the downlink channel in a dense micro-urban environment. The spectral efficiency (SE) in bps/Hz is calculated according to the Shannon ergodic capacity [25].

$$SE = log_2\left(det\left\{I_{N_R} + \frac{\rho}{N_T}\ H\, H^*\right\}\right) \quad (1)$$

In Eq. (1), N_T represents the number of antenna elements at the BS array, N_R is the number of elements at the UE antennas array (equal to 1 in this study), I_{N_R} is an $(N_R \times N_R)$ identity matrix, ρ is the received Signal power to Noise power ratio (SNR) at the UE locations in linear scale, H is an $(N_R \times N_T)$ channel matrix of the BS-UE links, and H^* is conjugate transpose of the channel matrix. The received SNR at the UE locations in dB, ρ_{dB}, is calculated using Eq. (2) [26].

$$\rho_{dB} = P_r - K \cdot T \cdot B - F \quad (2)$$

In Eq. (2), P_r is the average total received power at the UE in dBm, K is Boltzmann's constant, T is the temperature in kelvin, B is the effective bandwidth, and F is the noise figure in dB. Fig.4 shows the average spectral efficiency versus the BS-UE distance for the FR1 band, considering the different numbers of antenna elements at the BS array. The BS-UE distances were averaged over a distance range of 10 m. The SE decreased as the BS-UE distance increased for all the considered cases in Fig. 4. The SE performance improved as the carrier frequency decreased because the relation between the received power at the mobile station and a carrier frequency is reversely proportional, which means that using lower carrier frequency, the received power at the mobile station will be better, as shown in Fig. 3(a), producing higher SE values. Fig. 4 also illustrates that the SE performance improved as the number of antenna elements increased due to a proportional relationship between the number of antenna elements and received power, as shown in Fig. 3(b). Furthermore, Fig.4 shows that using 64 antenna elements at the 6 GHz band achieved SE performance higher than the 1 GHz band with a single antenna element. The antenna array gain of the 64 elements compensates for the excessive pathloss of the 6 GHz band compared to the 1

GHz band. A plot of average SNR versus the BS-UE distance is illustrated in Fig. 5. It can be noticed that the variation of SNR with distance for different carrier frequencies and different numbers of BS antenna elements confirms the average spectral efficiency results. Fig. 6 shows the SE CDF graphs for the simulation scenarios of Fig. 4. According to the ITU-R [21] the minimum average SE and cell edges users SE in the dense urban micro scenario were 7.8 bps/Hz and 0.225 bps/Hz, respectively. The cell edges SE represents the 5th percentile of the CDF of SE at the UEs (indicated by the black straight line in Fig. 6). It can also be observed that the CDF results of the lower frequencies were much better than higher frequencies. By increasing the number of elements in BS, the improvement of SE can be seen. The same approach was investigated from SNR and SE results in Fig 4 and Fig 5. Table 2 lists the average and the cell edges user SE for FR1 simulated scenarios. The 1GHz band achieved the minimum average SE and cell edge user SE requirements for all antenna element cases. However, the 6 GHz band achieved the target average SE using 64 and 256 antenna elements. Meanwhile, with 16, 64, and 256 antenna elements achieved the target cell edge user SE. The colored cells in the table indicate that the minimum requirements were not achieved. Fig.7 shows the average SE versus BS-UE distance for different numbers of antenna elements at the BS, considering the 12 GHz and FR2 bands. Comparing Fig. 7 with Fig. 4, it is obvious that the FR1 band's SE performance outperformed the 12 GHz and the FR2 bands' performance. Like the FR1 band, the SE performance increased as the number of antenna elements at the BS increased, and the SE decreased as the BS-UE distance increased. Also, the array gain of the BS antenna array compensated for the increased pathloss of the higher frequency bands. For example, the SE of the 25 GHz band with 256 antenna elements outperformed the SE of the 12 GHz band with 16 antenna elements.

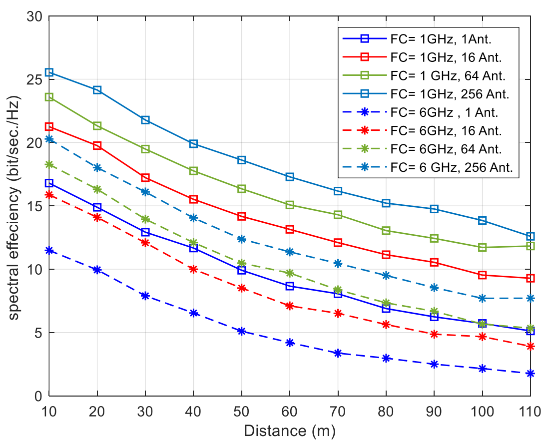


Fig. 4 Average Spectral Efficiency Versus BS-UE Distance for FR1 Band.

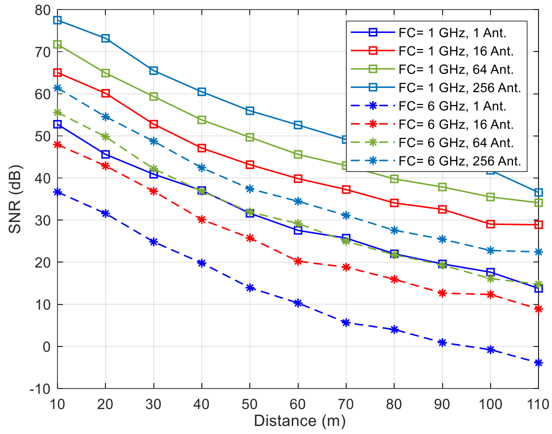


Fig. 5 Average SNR Versus BS-UE Distance for FR1 Band.

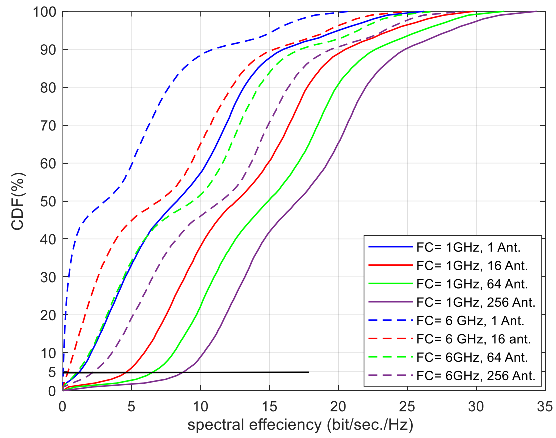


Fig. 6 CDF of Spectral Efficiency for FR1 Simulated Scenarios.

Table 2 Average SE and Cell Edge User SE of FR1 Simulated Scenarios.

Carrier frequency (GHz)	Number of BS antennas	Average SE (bps/Hz)	Cell edge user SE (bps/Hz)
1	1	8.75	1.21
	16	12.93	4.66
	64	15.06	6.57
	256	17.17	8.79
6	1	4.38	0.03
	16	7.44	0.37
	64	9.31	1.04
	256	11.28	2.23

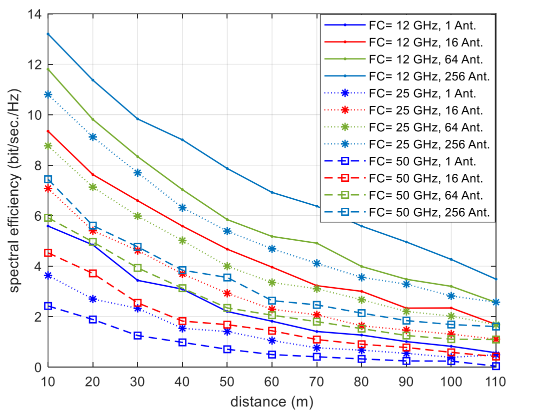


Fig. 7 Average spectral efficiency versus BS-UE distance for different numbers of antenna elements at the BS at 12 GHz and FR2 frequency bands.

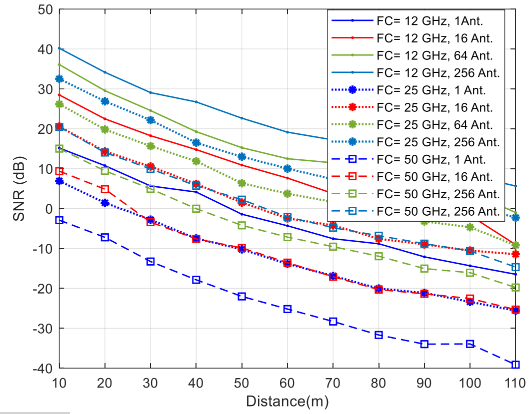


Fig. 8 Average SNR versus BS-UE distance for different numbers of antenna elements at the BS at 12 GHz and FR2 frequency bands.

Figure 8 shows the average SNR versus BS-UE distance. It is clear from the figure that the SNR results confirm the spectral efficiency results. Fig. 9 shows the CDF of SE for different numbers of antenna elements at the BS, considering the 12 GHz and FR2 bands. It is clear from Fig. 9 that all the graphs provide zero SE at the 5th percentile of the SE's CDF, which means none of the simulated scenarios of the 12 GHz and the FR2 bands provided the target performance of the IMT-2020 for the cell edge users.

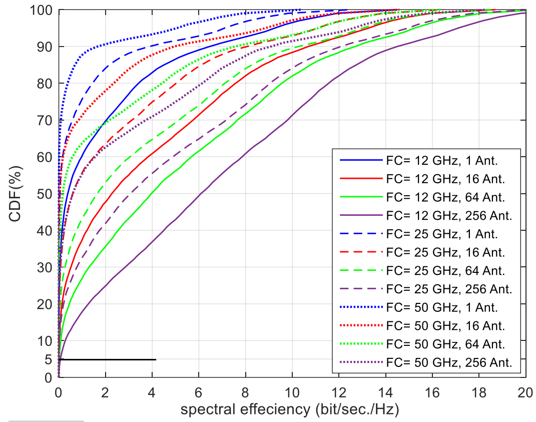


Fig. 9 CDF of Spectral Efficiency for 12 GHz and FR2 Simulated Scenarios.

Table 3 lists the average SE and the cell edge user SE for the 12 GHz and the FR2 simulated scenarios. As indicated, none of the scenarios satisfied the target SE performance.

Table 3 Average SE and Cell Edge User SE of 12 GHz and FR2 Simulated Scenarios.

Carrier Frequency (GHz)	Number of Antenna Elements at BS	Average SE (bps/Hz)	Cell Edge user SE (bps/Hz)
12	1	1.92	3.6×10^{-4}
	16	3.97	4.9×10^{-3}
	64	5.28	0.02
	256	6.83	0.07
25	1	1.09	2.8×10^{-5}
	16	2.53	5.2×10^{-4}
	64	3.60	1.67×10^{-3}
	256	4.77	7.4×10^{-3}
50	1	0.61	1×10^{-6}
	16	1.43	1.8×10^{-5}
	64	2.19	8.1×10^{-5}
	256	2.91	2.9×10^{-4}

4.PROPOSED CELL SIZE REDUCTION FOR SPECTRAL EFFICIENCY IMPROVEMENT

As shown and discussed in section 3, the target average SE and cell edge user SE do not satisfy the target performance requirement of the IMT-2020 for all the scenarios of 12 GHz and FR2 bands and some scenarios in the FR1 band. Therefore, this section proposes a cell size reduction technique for different numbers of antenna elements to meet the target performances. The proposed cell size reduction technique reduces the cell radius to improve the coverage performance of higher frequency bands. Table 4 lists all simulated cases' reduced cell sizes and average SE and cell edge user SE results. The applied cell size reduction algorithm reduced the cell's radius for each case until the target performances were achieved. It is clear from the table that the cell reduction technique was inefficient when the carrier frequency was high, and the number of BS antenna elements at the BS was low. It can be seen that by increasing the carrier frequency, it is required to reduce the cell size more and more for the same antenna element number; for example, using 256 elements at carrier frequency 12GHz, the cell radius is reduced to 81 meters, while at 25 GHz the cell radius should not be more than 47 m, and at 50 GHz the maximum cell radius that can be used was only 17 m. A larger cell size can be set for the same carrier frequency by increasing the antenna elements at BS.

Table 4 Cell Radius Reduction Results of Simulated Scenarios.

Carrier frequency (GHz)	Number of BS antennas	Cell radius (m)	Average SE (bps/Hz)	Cell edge SE (bps/Hz)
6	1	57	7.55	0.36
	16	105	7.56	0.42
12	1	12	Does not reach	0.3
	16	37	7.8	0.26
	64	58	7.9	0.226
	256	81	8.15	0.24
25	1		Does not reach	
	16	18	Does not reach	0.36
	64	29	7.89	0.37
	256	47	8.1	0.25
50	1	Does not reach		
	16	Does not reach		
	64	Does not reach		
	256	17	7.8	0.34

5.CONCLUSIONS

This paper performed a coverage performance evaluation of 5G NR in terms of SNR and spectral efficiency using the IMT-2020 channel model. The study is performed for different frequency bands and several BS antenna elements in dense urban micro scenarios. The results showed better spectral efficiency performance and higher coverage area for the FR1 band than for the FR2 and 12 GHz bands.

Performance improvement can be achieved by increasing the antenna elements at the BS array. The study also investigated the achievement of the minimum requirements in terms of average spectral efficiency and cell edge users' spectral efficiency set by the IMT-2020. A cell size reduction technique was proposed and applied to improve the performance and satisfy the target requirements. Higher average SE and cell edge user SE were achieved as the cell size decreased. The minimum requirement was unsatisfied in the FR2 even when the cell size reduction technique was applied.

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