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Performance Analysis of Ultra-dense Networks with Frequency Reuse

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Abstract. Ultra-dense networks (UDN) have become a key technology in future communications systems by deploying a large number of low-power small cell base stations (SBS). However, ultra-dense deployment of small cells in the coverage area of conventional macrocells presents new challenges, such as inter-tier interference (interference between small cells (SC) and macro cells (MC)) and both-tier interference (interference between small cells), which may affect the overall network performance. In this work, in order to mitigate interference, frequency reuse is used. The simulation was performed with MATLAB software based on Monte Carlo methodology for discrete events, with the objective of evaluating the impact of ultra-dense networks within fixed infrastructure wireless networks. The main performance indicators are the Signal to Interference Ratio (SIR) and throughput.

Keywords: Ultra-dense network (UDN), frequency reuse, Throughput, Co-channel interference, Signal to Interference Ratio (SIR).

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1 Introduction

Due to the popularization of smart devices and applications, they demand higher network capacity. This large number of mobile devices and their diversity challenge the current communications network. It is expected that by 2025 there will be more than 50 billion connected devices. The next generation of communications is expected to connect a large number of users, support massive communications, enable up to a thousand-fold increase in data traffic, low latency, and 100% coverage and availability [1,2].

The current deployment of MC is already approaching its limit and further deployment of MC will not improve performance. The UDN is seen as a key factor in future communications networks, where access points and/or the number of communication links per unit area are densified. The main difference between an UDN and a traditional cellular network is the densification of access points or base stations (BS). In an UDN, there can be perhaps hundreds of access points per square kilometer, compared to a maximum of three to five in a traditional network. As a result, in an ultra-dense network only a limited number of users are connected to each access point or BS, whereas in a traditional network there may be hundreds or even thousands of users connected to an access point or BS [3,4].

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SC improve network capacity by offloading traffic from macro cells, balancing network loads and reducing congestion. In addition, these cells are capable of performing all the functions of a macro cell, but with lower power and in a smaller coverage area.
This paper is structured as follows: Section II works related to ultra-dense networks. Section III shows the equations involved in the downlink study of the network, Section IV shows the results obtained. And finally, it contains the conclusions.

2 Related Work

In our previous work, we studied the effect caused by the UDN network when it is superimposed on the macro network based on orthogonal frequency division multiple access (OFDMA). The UDN network consists of a large number of small cells within the coverage area of the OFDMA macro network. The main effect observed was co-channel interference, which significantly decreased network performance. We analyzed this issue from both the perspectives of the UDN network and the OFDMA. To mitigate interference from the UDN network, we reduced the transmission power of the small cell base stations. However, better strategies are needed to mitigate co-channel interference between small cells and macro cells.

In order to improve co-channel interference, Small Cell Base Stations (SBSs) in the network should be dynamically activated or deactivated based on appropriate criteria or strategies. In [5], it is proposed to assign UEs to the SBSs of the UDN, taking into account the UE preference. As a result, a set of SBSs that can be put into sleep mode is obtained. This is based on the number of UEs connected to each SBS, without considering the interference from the macro base station. Additionally, users who are no longer served by the SBSs are reassigned to other SBSs. In [6], the SBS outage is considered as a function of the number of users served by the SBSs, and the density of small cells in a specific region is increased by considering a non-uniform distribution of users. In [7], the authors consider the interference generated by each SBS of the UDN in order to suspend those that are causing more interference to the network. However, they do not take into account the interference from the macro cell. The purpose is to turn off and on the SBSs to save energy by not having all of them on at the same time. In these paper [8], the authors assign time slots, which are present duty and sleep cycles of the SBSs, to improve energy consumption and reduce co-channel interference. These duty cycles are estimated based on the network traffic. When the traffic is light, a longer sleep cycle is maintained. However, when the traffic is heavier, this cycle is reduced without considering interference effects.

Another strategy to mitigate co-channel interference is to apply frequency reuse to small cell base stations that are in close proximity to each other, so that the frequency reuse factor is greater than 1 and improves the SIR to ensure good transmission. In [9], a study is conducted on frequency reuse and the number of clusters in ultra-dense networks, analyzing the optimal number of clusters to achieve maximum user capacity in a UDN environment. In [10], fractional frequency reuse is applied to analyze multi-level interference, specifically the interference that the macro cell produces to the small cell and vice versa, although it is only applied to the macro cell. In [11], strict frequency reuse is applied, which is modeled according to 3GPP recommendations. Additionally, an analysis is performed on how interference increases with increasing small cell densification. In this paper [12], the performance of strict fractional frequency reuse and frequency reuse factor-3 is evaluated and compared according to the cell throughput. In these papers, interference improvements are reported when frequency reuse is used.

3 Models and Methods

Interference significantly affects the performance of both spectral efficiency and energy efficiency. We assume that, in MC coverage, SC are densely deployed. The SBS are omnidirectional antennas that coexist with the macro base station through shared spectrum access. This means that they operate in the same frequency band and with the same bandwidth [13].

Interference, especially inter-cell interference, has been shown to be the most important problem in wireless communication systems. To reduce inter-cell interference and have better network performance, each cell needs to allocate its own resources and, at the same time, reduce interference by simultaneously increasing spatial reuse.

In order to mitigate interference between small cell base stations, frequency reuse is implemented in small cell base stations to increase network performance by allocating resources to each cell. Frequency reuse implies that in the same coverage area there are cells using the same channel, these cells are called co-channel cells, and the interference generated between them is known as co-channel interference. To reduce this interference, base stations must be physically separated by a minimum distance that provides sufficient isolation. Frequency reuse aims at distributing the frequency band in such a way that two cells do not interfere with each other [14].

Another technique used to reduce interference is to suspend SBS from the network dynamically using appropriate criteria or strategies. Suspension can be done based on the number of users served by each SBS, because it is not feasible for a SBS to be active with a small number of users, generating interference to neighboring SBS. Another criterion for suspending SBS is according to the interference that each one brings to the network, by means of a threshold. As soon as the threshold is exceeded, the SBS should be suspended [15].

3.1 System Model

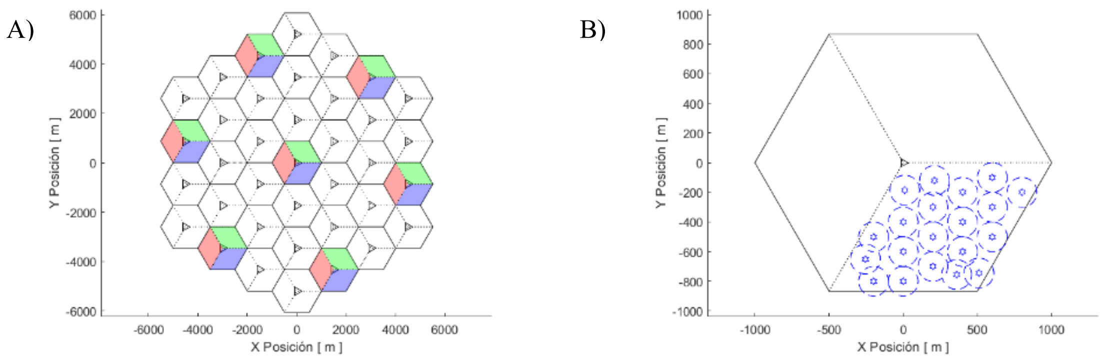

Figure 1. Representation of the UDN network (B) superimposed on the OFDMA network (A).

The model consists of a macro network called OFDMA and within a specific sector is the UDN network. The OFDMA network consists of 37 MC, each of which is divided into three 120° sectors. In such a network, the central cell is considered as the cell of interest and the rest of the 36 MCs as interferers as illustrated in Figure 1.

The UDN consists of 20 pico small cell base stations (PBS) considered as omnidirectional, so they are modeled in a circular shape as they are suitable for situations where users equipment (UEs) are in close proximity to the base station (BS).

The SC are deployed in an overlapping manner with the MC, forming a two-level network. Level 1 represents MC and level 2 represents SC. One of the challenges in UDN is interference between SC, thus degrading spectral efficiency.

The analysis is performed from two perspectives, from the OFDMA network and from the UDN network since both coexist and share the same resources. Therefore, the calculation of the SIR of the OFDMA network is performed with equation 1, which considers the UDN network as interfering. Similarly, the calculation of the SIR from the UDN perspective is performed with equation 2

$$SIR_i^{OFDMA} = \frac{\dfrac{G_{TXMC_{1,i}}(\emptyset)\varepsilon_{1,i}10^{\delta_{1,i}/_{10}}}{d_{1,i}^{\mu}}}{\sum_{k=2}^{N_{MC}} \dfrac{G_{TXMC_{k,i}}(\emptyset)\varepsilon_{k,i}10^{\delta_{k,i}/_{10}}}{d_{k,i}^{\mu}} + \sum_{n=1}^{N_{mc}} \dfrac{P_{FMC}\varepsilon_{n,i}10^{\delta_{n,i}/_{10}}}{d_{n,i}^{\mu}}} \qquad (1)$$

where

$\frac{G_{TXMC_{1,i}}(\emptyset)\varepsilon_{1,i}10^{\delta_{1,i}/_{10}}}{d_{1,i}^{\mu}}$ is the power received from the base station of the OFDMA MC of interest. $\sum_{k=2}^{N_{MC}}\frac{G_{TXMC_{k,i}}(\emptyset)\varepsilon_{k,i}10^{\delta_{k,i}/_{10}}}{d_{k,i}^{\mu}}$ is the sum of the interfering powers of the remaining BS of the MC in the OFDMA network and $\sum_{n=1}^{N_{mc}}\frac{p_{FMC}\varepsilon_{n,i}10^{\delta_{n,i}/_{10}}}{d_{n,i}^{\mu}}$ is the sum of the interfering powers of the UDN small cell base stations.

$$SIR_i^{UDN} = \frac{\frac{\varepsilon_{1,i}10^{\delta_{1,i}/_{10}}}{d_{1,i}^{\mu}}}{\sum_{n=2}^{N_{mc}}\frac{\varepsilon_{n,i}10^{\delta_{n,i}/_{10}}}{d_{n,i}^{\mu}} + \sum_{k=1}^{N_{MC}}\frac{p_{fmc}G_{TXMC_{k,i}}(\emptyset)\varepsilon_{k,i}10^{\delta_{k,i}/_{10}}}{d_{k,i}^{\mu}}} \tag{2}$$

where

$\frac{\varepsilon_{1,i}10^{\delta_{1,i}/_{10}}}{d_{1,i}^{\mu}}$ is the received power of the small cell base station of the UDN network of interest, $\sum_{n=2}^{N_{mc}}\frac{\varepsilon_{n,i}10^{\delta_{n,i}/_{10}}}{d_{n,i}^{\mu}}$ is the sum of the interfering powers of the rest of the small cell base stations in the UDN network, and $\sum_{k=1}^{N_{MC}}\frac{p_{fmc}G_{TXMC_{k,i}}(\emptyset)\varepsilon_{k,i}10^{\delta_{k,i}/_{10}}}{d_{k,i}^{\mu}}$ is the sum of the interfering powers of the base stations of the macro cells of the OFDMA network.

These equations are based on the Log-distance propagation loss model, which makes it possible to estimate the received signal considering antenna gains, distance losses, phenomena caused by the characteristics of the propagation terrain, the effect of multiple paths, the propagation frequency, etc [16].

Where $G_{TXMC_{k,i}}(\emptyset)$ is the transmit antenna gain, $\varepsilon_{k,i}$ is the losses caused by the multipath effect called fast fades modeled by a Rayleigh type variable, $10^{\delta_{k,i}/_{10}}$ models the slow fades, typically modeled through a log-normal random variable, $d_{k,i}^{\mu}$ is the distance between the user and the service base station and μ is the propagation loss exponent.

The calculation of the transmission rate R_i refers to the number of bits per second that can be transferred by an access point, and is the parameter of interest to know the network capacity. The definition of performance is expressed as

$$R_i = \begin{cases} \left(\frac{\omega_o}{\gamma}\right) SIR_i, & SIR_i < m\gamma \\ m\omega_0, & SIR_i \geq m\gamma \end{cases} \tag{3}$$

Where m is the modulation dimensionality, ω_o the network bandwidth, SIR_i is the signal interference ratio of the *i-th* user and γ is the bit energy to interference ratio [17, 18].

3.2 Frequency Reuse

OFDMA networks are flexible in terms of radio resource management techniques, which allows supporting different frequency reuse schemes that decrease inter-cell interference and increase network performance. In the macro OFDMA network, a frequency reuse of 7 is used with the objective of having a greater distance between co-channel cells, as shown in Figure 1. The same methodology is applied to assign a frequency reuse to the small cells of the ultra-dense network. In the simulation, a reuse of 3 and 4 was used for the small cells (Figure 2). The simulation is applied in MATLAB and the proposed methods are analyzed.

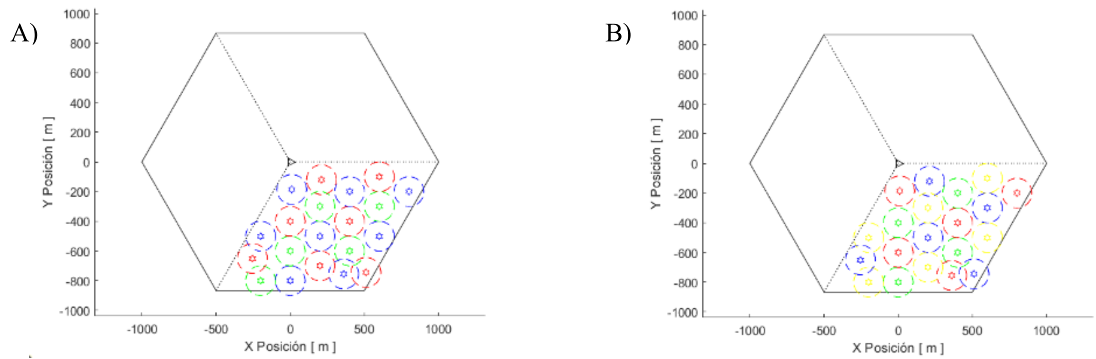

Figure 2. Representation of the UDN network with reuse 3 (A) and resuse 4 (B).

3.3 Dynamic On/Off

A small cell on/off switching algorithm was developed based on the interference contribution rate. First, the interference contribution rate of the SC is calculated using the reference signal values of the users' received power from their serving BS, and then the decision on which SC to turn on or off is obtained. The algorithm simultaneously takes into account the traffic load of the SC and the interference between SC.

We define the target signal strength R_{b_n} as the sum of the received powers at each user belonging to the serving PBS, and the interference signal strength $\bar{R}_{b_n}$ as the sum of the received powers at each user not belonging to the serving PBS of the n-th PBS of the UDN network. Consequently, the target signal strength of the n-th PBS can be defined as

$$R_{b_n} = \sum_{u_i \in U_{b_n}} \frac{P_{txmc_{n,i}} \varepsilon_{n,i} 10^{\delta_{n,i}/_{10}}}{d_{n,i}^{\mu}} \tag{4}$$

Similarly, $\bar{R}_{b_n}$ may be defined as

$$\bar{R}_{b_n} = \sum_{u_i \in U/U_{b_n}} \frac{P_{txmc_{n,i}} \varepsilon_{n,i} 10^{\delta_{n,i}/_{10}}}{d_{n,i}^{\mu}} \tag{5}$$

From the above analysis, we define the interference contribution rate of the n-th PBS of the UDN network as Γ_{b_n}, which can be calculated with eq.

$$\Gamma_{b_n} = \frac{\bar{R}_{b_n}}{R_{b_n}} \tag{6}$$

In order to effectively elicit the decisions of small cells in the UDN network to be turned ON or OFF, we define a dynamic interference contribution rate threshold calculated as

$$\Gamma_{th} = \frac{1}{|S_{on}|} \sum_{b_n \in S_{on}} \left(\frac{\sum_{b_m \in S_{on}/b_n} \left(\frac{P_{txmc_m} \varepsilon_m 10^{\delta_m/_{10}}}{d_m^{\mu}} \right)}{\frac{P_{txmc_n} \varepsilon_n 10^{\delta_n/_{10}}}{d_n^{\mu}}} \right) \tag{7}$$

Where S_{on} is the set of active PBSs. Using equation 7, we can easily calculate the dynamic interference contribution rate threshold of the network. By comparing the interference contribution rate value of a PBS with the threshold value Γ_{th}, the decision to turn on or turn off the PBS can be obtained.

4 Results

The simulation of the developed strategies, frequency reuse and on/off of small cells of the UDN network uses the Monte Carlo method of discrete events, which consists of repeating the behavior of a real system with the objective of imitating the behavior of the real variables, to analyze the operation and evolution of the network. The OFDMA network has a frequency reuse of 7, which means that only some MC are interfering. The performance of the network is analyzed with QPSK modulation, because it is the most robust modulation under the worst channel conditions.

The table 1 shows the parameters used for the simulation and evaluation of the network performance.

Table 1. Simulation parameters.

Parameter	Value
Macro cell radius	1 Km
Potency of transmission of MBS	50 dBm
Small cell radius	100 m
Potency of transmisión of PBS	20 dBm
ω_0	20 MHz
μ	4
γ	1, 2, 3, 4, 5, 6 dB
m	2
Frequency	3.5 GHz

This section shows the results obtained through simulation. The simulation of each strategy was performed separately. For the frequency reuse strategy, the comparison is made with a reuse 1, reuse 3 and reuse 4 in the small cell base stations.
For the dynamic on/off strategy for the SBS, the comparison is made with having all base stations on and turning off a percentage at random.

4.1 Reuse Frequency Results

Figure 3 shows the results from the perspective of the UDN network with different frequency reuses in the SBS. It can be seen that when using reuse 4, the performance of the UDN network improves by 5% with reuse 4 with respect to only considering the UDN network, while with reuse 3 it is very similar.

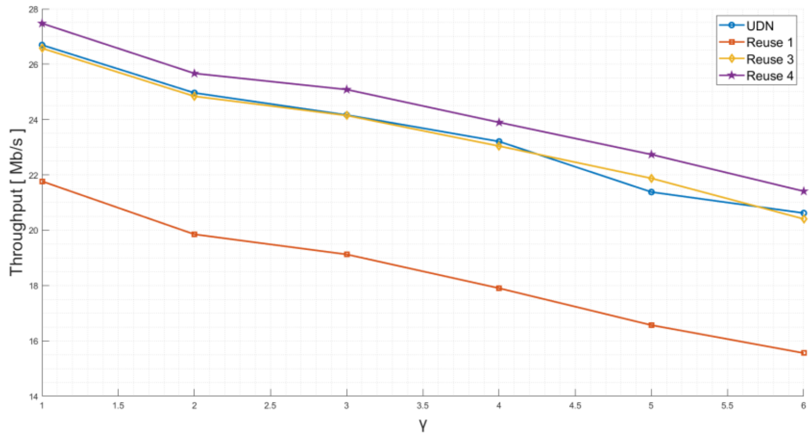

Figure 3. from the perspective of the UDN network at different frequency reuses.

Figure 4 shows the results from the perspective of the OFDMA network with different frequency reuses in the SBS. With reuse 1 in the UDN network, unemployment drops by 60% compared to just having the OFDMA network without the UDN network. Performance improves by 20% with reuse 3 and with reuse 4 it improves by 35% over reuse 1.

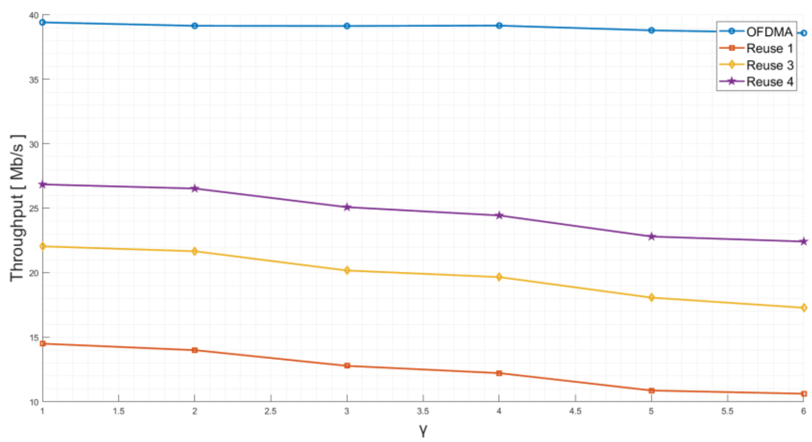

Figure 4. from the perspective of the OFDMA network at different frequency reuses.

4.2 Dynamic On/Off Results

Figure 5 shows the performance from the OFDMA network perspective, where it can be seen how the performance improves compared to having all the SBS on. It is evident that the performance is very low due to the interference caused by the large number of small cell base stations on.

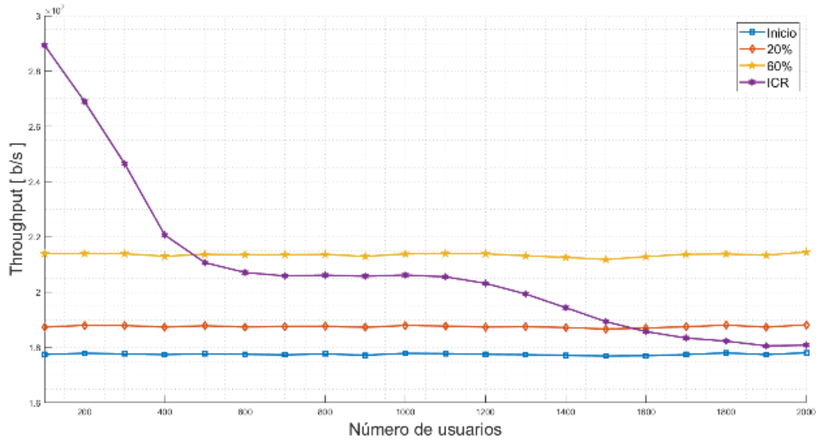

Figure 5. Performance from the perspective of the UDN network in relation to the number of EUs in the network.

Figure 6 shows the results from the perspective of the UDN network, as in the OFDMA network, there is an improvement compared to having all the small cell base stations on.

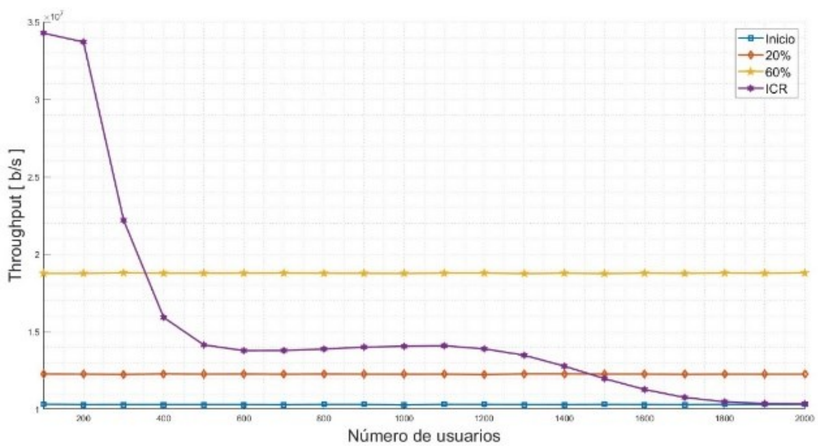

Figure 6. Performance from the perspective of the UDN network in relation to the number of EUs in the network.

Figures 5 and 6 show that as the number of users increases, the throughput decreases. This occurs because most of the SBS are turned on. It is also observed that the most affected network is the OFDMA network due to the large number of BS in the UDN network and the short distance between them. Both figures show how the random scenarios show favorable results, but it is not known if the SBS stations that were randomly turned off should be turned off, i.e., if their interference contribution is greater than the threshold or if they have a small number of users. The same is true, on the contrary, if those that are turned on have a large number of connected users.

5 Conclusions and Directions for Further Research

In this work, a simulation of an ultra-dense network coexisting with a macro network has been performed, analyzing how it affects the co-channel interference of the small cells of the ultra-dense network. As a strategy to mitigate interference, frequency reuse is used to improve performance. With this simulation, it is possible to provide a good insight into the performance of this type of network in terms of the maximum transmission rate.

Comparing the strategies between frequency reuse and dynamic on/off, it is possible to reduce interference more in the reuse strategy, improving the performance of the network. However, the energy consumption is not reduced as in the dynamic on/off strategy, because the load of each of the small cell base stations is not considered.
In the dynamic on/off strategy, when there are a large number of users, it is no longer possible to turn off several small cell base stations and because they all work at the same frequency, interference increases.
A future work would be the combination of both strategies, achieving interference mitigation and energy savings.

In the future, different strategies, or a combination of several will be required to reduce interference and high-power consumption in the network. These strategies include power control in small cell base stations and dynamic suspension of small cell base stations. In addition, it will be necessary to use other technologies such as artificial intelligence for an appropriate allocation of resources.

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References

1. Gupta, A., & Jha, R. K. (2015). A survey of 5G network: Architecture and emerging technologies. *IEEE Access, 3*, 1206–1232. https://doi.org/10.1109/ACCESS.2015.2461602
2. Kamel, M., Hamouda, W., & Youssef, A. (2016). Ultra-dense networks: A survey. *IEEE Communications Surveys & Tutorials, 18*(4), 2522–2545. https://doi.org/10.1109/COMST.2016.2571730
3. Fokin, G., Bachevsky, S., & Sevidov, V. (2020). System level performance evaluation of location aware beamforming in 5G ultra-dense networks. *2020 IEEE International Conference on Electrical Engineering and Photonics (EExPolytech)*, 94–97. https://doi.org/10.1109/EExPolytech50912.2020.9243970
4. Shabbir, M., Kandeepan, S., Al-Hourani, A., & Rowe, W. (2022). Access point selection in small cell ultra-dense network, with load balancing. *2022 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob)*, 1–6. https://doi.org/10.1109/APWiMob56856.2022.10014303
5. Venkateswararao, K., & Swain, P. (2020). Traffic aware sleeping strategies for small-cell base station in the ultra-dense 5G small cell networks. *2020 IEEE REGION 10 CONFERENCE (TENCON)*, 102–107. https://doi.org/10.1109/TENCON50793.2020.9293754
6. Shen, B., Lei, Z., Huang, X., & Chen, Q. (2018). An interference contribution rate based small cells on/off switching algorithm for 5G dense heterogeneous networks. *IEEE Access, 6*, 29757–29769. https://doi.org/10.1109/ACCESS.2018.2841044
7. Xu, H., Yu, W., Hematian, A., Griffith, D., & Golmie, N. (2018). Performance evaluation of energy efficiency with sleep mode in ultra-dense networks. *2018 International Conference on Computing, Networking and Communications (ICNC)*, 747–751. https://doi.org/10.1109/ICCNC.2018.8390302
8. Chopra, G. (2023). An efficient base station sleeping configuration for ultra-dense networks. *2023 International Conference on Emerging Smart Computing and Informatics (ESCI)*, 1–5. https://doi.org/10.1109/ESCI56872.2023.10100245
9. Kim, E.-H., Lee, J.-W., Kim, Y.-M., & Hong, E.-K. (2019). Analysis of the optimal number of clusters in UDN environment. *2019 IEEE VTS Asia Pacific Wireless Communications Symposium (APWCS)*, 1–4. https://doi.org/10.1109/VTS-APWCS.2019.8851643

10. Susanto, M., et al. (2023). Interference management using fractional frequency reuse for ultra-dense networks at downlink transmission. *2023 3rd International Conference on Smart Cities, Automation & Intelligent Computing Systems (ICON-SONICS)*, 142–146. https://doi.org/10.1109/ICON-SONICS59898.2023.10435086
11. Lam, S. C., Huynh, H. D., Nguyen, Q. T., & Sandrasegaran, K. (2018). Strict frequency reuse in ultra-dense networks. *TENCON 2018 - 2018 IEEE Region 10 Conference*, 1027–1032. https://doi.org/10.1109/TENCON.2018.8650328
12. Musa, A., Adekola, F. O., & Faruk, N. (2022). Performance evaluation of strict fractional frequency reuse and frequency reuse factor-3 in 5G networks. *2022 5th Information Technology for Education and Development (ITED)*, 1–5. https://doi.org/10.1109/ITED56637.2022.10051468
13. Petkova, R., Ivanov, A., & Poulkov, V. (2020). Challenges in implementing ultra-dense scenarios in 5G networks. *2020 Joint International Conference on Digital Arts, Media and Technology with ECTI Northern Section Conference on Electrical, Electronics, Computer and Telecommunications Engineering (ECTI DAMT & NCON)*, 168–172. https://doi.org/10.1109/ECTIDAMTNCON48261.2020.9090762
14. Salem, A. A., El-Rabaie, S., & Shokair, M. (2021). Survey on ultra-dense networks (UDNs) and applied stochastic geometry. *Wireless Personal Communications, 119*, 2345–2404. https://doi.org/10.1007/s11277-021-08334-1
15. Sharma, N., & Kumar, K. (2021). Resource allocation trends for ultra-dense networks in 5G and beyond networks: A classification and comprehensive survey. *Physical Communication, 48*, 101415. https://doi.org/10.1016/j.phycom.2021.101415
16. Guerrero-Méndez, O., et al. (2016). Performance evaluation of an OFDMA and CDMA overlaid system. *2016 IEEE MTT-S Latin America Microwave Conference (LAMC)*, 1–4. https://doi.org/10.1109/LAMC.2016.7851292
17. Castañeda-Camacho, J., Mino-Aguilar, G., Cortez-0, L., Gutiérrez-Arias, J. E. M., Guerrero-Castellanos, J. F., & Muñóz-Hernández, G. (2015). Monte Carlo simulation applied to measurement of the impact of the smart antenna technology in digital cellular systems. *Ingeniería Investigación y Tecnología (México, 16*(2), 207–212. https://doi.org/10.1016/j.riit.2015.03.005
18. Castañeda-Camacho, J., & Lara-Rodríguez, L. (2010). Ordered hunt schemes for overlaid CDMA cellular systems. *Ingeniería Investigación y Tecnología (México), 11*(3), 349–365. https://doi.org/10.22201/fi.25940732e.2010.11n3.030