

On the Fundamental Characteristics of Ultra-Dense Small Cell Networks

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ABSTRACT

In order to cope with the forecasted $1000\times$ increase in wireless capacity demands by 2030, network operators will aggressively densify their network infrastructure to reuse the spectrum as much as possible. However, it is important to realize that these new ultra-dense small cell networks are fundamentally different from the traditional macrocell or sparse small cell networks, and thus UDNs cannot be deployed and operated in the same way as in the last 25 years. In this article, we systematically investigate and visualize the performance impacts of several fundamental characteristics of UDNs that mobile operators should consider when deploying UDNs. Moreover, we also provide new deployment and management guidelines to address the main challenges brought by UDNs in the future.

INTRODUCTION

Based on recent market predictions, mobile data traffic will keep growing at an astonishing compound annual growth rate of 47 percent toward 2030, beyond the so-called $1000\times$ wireless capacity demand [1]. In response to this traffic explosion, a number of technical studies have shown that a $1000\times$ capacity gain can only be expected from solutions that involve the deployment of a massive number of cells, to either reuse the current spectrum (sub-6 GHz solutions) or gain access to new frequency bands (centimeter-wave and millimeter-wave solutions), and the mobile industry has started to walk down this path [2, 3].

Throughout the second decade of 2000 up to now, network densification has energized the Third Generation Partnership Project (3GPP) fourth-generation (4G) Long Term Evolution (LTE) networks, with the full integration of small cell technology in their specifications, and the commercial deployment of small cell products [4]. Indoor small cells have conquered the residential market as a coverage solution. Indeed, a total of over 14 million small cells were deployed worldwide by February 2016, of which over 12 million were residential. The non-residential small cells business has also recently taken off, as both a coverage and a capacity solution; enterprise and outdoor small cell shipments were expected to grow by 270 and 150 percent, respectively, in 2017 [4].

ORTHOGONAL DEPLOYMENTS OF UDNs IN SUB-6 GHz SPECTRUM

The current fifth-generation (5G) network standardization efforts and its stringent coverage and capacity requirements, set to provide an unlimited

user experience, also suggest that small cells will remain the main driving force of cellular technology in the years to come, with the overall small cell market expected to generate revenues of US\$6.7 billion by 2020 [4]. In more detail:

- In the first deployment phase of 5G, the orthogonal deployment¹ of ultra-dense (UD) small cell networks (SCNs), a.k.a. ultra-dense networks (UDNs), at sub-6 GHz frequencies is envisaged as the workhorse for capacity enhancement for most operators, mostly due to the large gains attainable via spatial reuse and the simplified interference and mobility management resulting from its low interaction with the macrocell network [5]. These sub-6 GHz small cell deployments are expected to achieve peak data rates of 1 Gb/s, and ubiquitous coverage with more than 100 Mb/s wherever needed.
- In a later second phase of 5G, the deployment of UDNs at centimeter-wave, millimeter-wave, or even terahertz [6] frequencies is expected to provide larger peak data rates of 10 Gb/s in megacities, where fiber, digital subscriber line (DSL), and wireless-based backhaul will be a widely available commodity [3].

OUR CONTRIBUTIONS AND ARTICLE STRUCTURE

In this article, we focus on the spatial reuse gain of UDNs at sub-6 GHz frequencies, as their rollouts are expected to be earlier than millimeter-wave ones.²

Compared to the conventional sparse/dense cellular networks, it is obvious that UDNs directly lead to:

- A much shorter distance between a base station (BS) and its served user equipment (UE)
 - A much smaller ratio of BSs to UEs
- Following those two direct consequences, in this article, we present five characteristics that make UDNs fundamentally different from current sparse and dense networks, and draw attention to those deployment aspects that operators will need to reconsider when deploying these UDNs.

The rest of this article is structured as follows. In the following section, a typical UDN use case together with its system model for network performance analysis are described. Following that, the network performance visualization technique introduced in this article is presented. Then the five fundamental differences that UDNs bring about are presented, and their performance impacts are visualized. In the final section, conclusions are drawn.

¹ Orthogonal deployment means that small cells and macrocells are operating on a different frequency spectrum, that is, 3GPP Small Cell Scenario #2a [2].

² We leave millimeter-wave communications analyses for further study as the topic stands on its own, and requires a completely new analysis [7]. More specifically, millimeter-wave communications present several new features that should be treated differently from sub-6 GHz ones, such as short-range coverage, low inter-cell interference, blockage effects, and high Doppler shift, among others [7].

USE CASE AND SYSTEM MODEL

Megacities like New York, London, and Shanghai are characterized by macrocell deployments with a 500 m inter-site distance or less, where each macrocell site is usually divided into 3 macrocell sectors with directional antennas, and each macrocell sector hosts a given number of small cell BSs. Based on the above description, and assuming today's 500 m inter-site distance together with 4 small cells per macrocell sector [8], we provide an illustration of a typical 4G LTE SCN scenario in Fig. 1, which has a small cell density of around 50 cells/km².

In this figure:

- Each macrocell site is illustrated with thick black lines and is equally divided into three macrocell sectors with their directional antennas shown as orange arrows.
- Each small cell BS is illustrated as a thick green circle.
- A wrap-around approach, depicted as a third macrocell tier, is considered to avoid the underestimation of interference in the outer-rim region [8].

In this article, we consider a similar system model with macrocell sites deployed in a hexagonal grid to guide the random deployment of small cells with a density of λ BSs/km². In particular, we study three different small cell BS densities:

- A typical 4G LTE SCN with 4 small cells per macrocell sector, resulting in a λ around 50 BSs/km²
- A typical 5G dense SCN with 20 small cells per macrocell sector (5-fold increase over the 4G SCN), resulting in a λ around 250 BSs/km²
- A typical UDN with 200 small cells per macrocell sector (50-fold increase over the 4G SCN), resulting in a λ around 2500 BSs/km²

Moreover, we assume that active UEs are uniformly distributed in the considered network scenario with a density of ρ UEs/km². Here, we only consider active UEs in the network because non-active UEs do not trigger data transmissions, and they are thus ignored in our study. According to [2], a typical density of active UEs in 5G is around $\rho = 300$ UEs/km².

We also consider a practical small cell BS, which implements idle mode capabilities (IMCs), and thus can mute its wireless transmissions if there is no UE connected to it. This reduces unnecessary inter-cell interference and energy consumption [9]. The set of active small cell BSs is determined by the user association strategy (UAS). In this article, we assume a practical UAS as in [2], where each UE is connected to the small cell BS having the minimum path loss, which is equivalent to a maximum received signal strength policy when all cells in the scenario have the same transmit power.

As recommended in [8], we also assume practical line of sight (LoS) and non-LoS (NLoS) transmissions, and treat them as probabilistic events. Both the LoS/NLoS path loss functions and the LoS probability function are defined based on a three-dimensional (3D) distance r , that is,

$$r = \sqrt{d^2 + L^2},$$

where d and L denote the horizontal distance and the antenna difference between a transmitter and

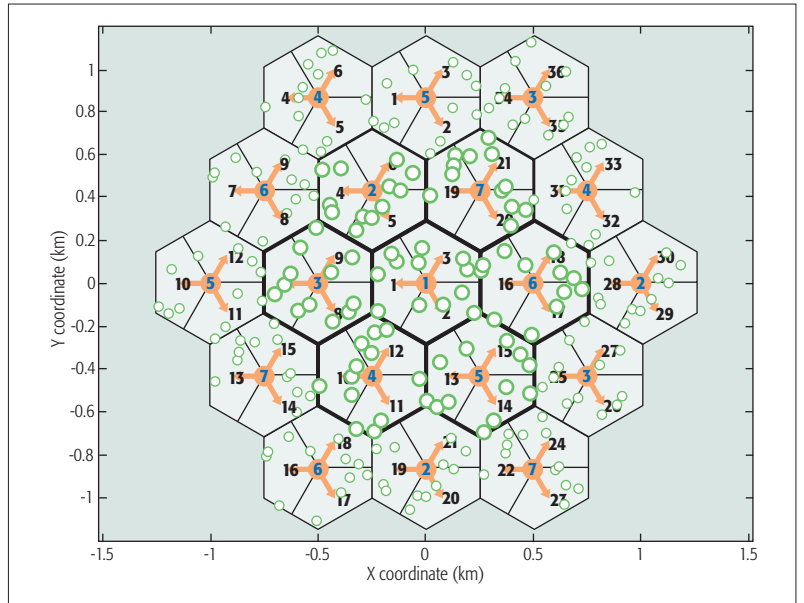


FIGURE 1. Illustration of a typical 4G LTE SCN scenario.

a receiver, respectively. Note that the LoS probability decreases as r increases [8].

Finally, we consider that each small cell BS and UE is equipped with an isotropic antenna, and that the multi-path fading between a transmitter and a receiver is modeled as an independent and identically distributed (i.i.d.) Rayleigh random variable. Additive white Gaussian noise (AWGN) is considered at the receiver side.

NETWORK PERFORMANCE VISUALIZATION

In this article, instead of showing complex mathematical charts, we propose an intuitive network performance visualization technique to simulate and illustrate the performance of UDNs, and open our results to a wider audience.

First, we randomly generate several network deployments following the 3GPP approach of the hexagonal grid presented above. As discussed, the BS densities of a typical 4G LTE network, a typical 5G dense SCN, and a typical UDN are around 50, 250, and 2500 BSs/km², respectively. In Fig. 2a, we plot the BS positions used in our network performance visualization, which are represented by dots and uniformly distributed over an area of 1.5 km × 1.5 km. Note that the hexagonal grid in Fig. 2a is of the same size as that in Fig. 1. This 3GPP hexagonal grid is used here to guide the random deployment of small cell BSs in the network.

Second, based on the explicit modeling of the signal, the interference, and the noise powers presented above, we place a probe UE at a random position in the network, and then measure its signal-to-interference-plus-noise ratio (SINR) coverage probability via 10,000 simulation experiments. Such SINR coverage probability is defined as the probability that the probe UE's SINR is larger than a threshold γ , that is, $\Pr[\text{SINR} > \gamma]$ [10]. We repeat this probing process until the whole network is scanned at an adequate geographical resolution. Note that we set the SINR threshold γ to 1 (i.e., 0 dB), which reflects a minimum working SINR threshold for practical receivers.

Third, since the SINR coverage probability ranges between 0 and 1, we show the network performance using heat maps, with red and blue

Parameter definition	Parameter value
The BS Tx power	24 dBm (on a 10 MHz bandwidth)
The maximum UE Tx power	23 dBm (on a 10 MHz bandwidth)
The AWGN power at BSs	-91 dBm (on a 10 MHz bandwidth)
The AWGN power at UEs	-95 dBm (on a 10 MHz bandwidth)
The BS-to-UE LoS path loss	$103.8 + 20.9\log_{10}r$ [dB] (r in km)
The BS-to-UE NLoS path loss	$145.4 + 37.5\log_{10}r$ [dB] (r in km)
The BS-to-BS LoS path loss	$101.9 + 40\log_{10}r$ [dB] (r in km)
The BS-to-BS NLoS path loss	$169.36 + 40\log_{10}r$ [dB] (r in km)
The UE-to-UE LoS path loss	$98.45 + 20\log_{10}r$ [dB] (r in km)
The UE-to-UE NLoS path loss	$175.78 + 40\log_{10}r$ [dB] (r in km)
The BS-to-UE LoS probability	$\begin{cases} 1 - 5\exp\left(\frac{-0.156}{r}\right) & 0 < r \leq 0.0677 \text{ km} \\ 5\exp\left(\frac{-r}{0.03}\right), & r > 0.0677 \text{ km} \end{cases}$
The BS-to-BS LoS probability	$\begin{cases} 1 - 5\exp\left(\frac{-0.156}{r}\right) & 0 < r \leq 0.0677 \text{ km} \\ 5\exp\left(\frac{-r}{0.03}\right), & r > 0.0677 \text{ km} \end{cases}$
The UE-to-UE LoS probability	$\begin{cases} 1, & 0 < r \leq 0.05 \text{ km} \\ 0, & r > 0.05 \text{ km} \end{cases}$

TABLE 1. Parameter values recommended by 3GPP [8].

indicating a high SINR coverage probability and a low one, respectively. With such SINR heat maps, the significant performance impacts of the fundamental characteristics of UDNs can be translated into striking visual plots, showing the performance transition as the network densifies.

It should be noted that a large body of theoretical work has used the stochastic geometry theory to study network performance in terms of average coverage probability [10–12]. Such performance metric averages the SINR coverage probability in the spatial domain and gives a single performance measure on a macroscopic level. In our network performance visualization, the average color of a heat map generated for a given scenario represents such average coverage probabilities.

Moreover, the proposed network visualization technique provides microscopic information on network performance, including the variance of the SINR coverage probability, the locations of coverage holes, and so on, which is useful in academic studies and for business proposals with clients. For example, the proposed technique is able to provide answers visually, when an operator wants to know the performance impact of adding several specific BSs to its current network.

TWO FUNDAMENTAL ASPECTS OF UDNs RELATED TO BS-TO-UE DISTANCE

Before 2015, the common understanding on UDNs was that the density of BSs would not affect the SINR coverage probability performance

in interference-limited fully loaded wireless networks, and thus the network capacity in bits per second per Hertz per square kilometer would scale linearly with the network densification due to the linear increase of spectrum reuse [10].

Figure 2b exemplifies this conclusion with a path loss exponent of 3.75, showing the performance trend of three networks with different BS densities according to [10]. Visually speaking, the sizes of the reddish areas (high SINR coverage probabilities) and the bluer areas (low SINR coverage probabilities) are approximately the same as the network densifies, indicating an invariant SINR performance with the BS density.

However, it is important to note that this conclusion was obtained with considerable simplifications on the propagation environment and BS/UE deployment, such as a single-slope path loss model, which should be placed under scrutiny when evaluating UDNs, since they are fundamentally different from sparse ones in various aspects. In this section, we study several fundamental aspects of UDNs, both resulting from the much shorter distance between a BS and its served UEs.

CAPPED CARRIER SIGNAL POWER

In the performance analysis of conventional sparse or dense cellular networks, the antenna height difference between BSs and UEs is denoted by L , and is usually ignored due to the dominance of the horizontal distance. However, with a much shorter distance between a BS and its served UEs in a UDN, this antenna height difference becomes non-negligible. More specifically, the existence of a non-zero antenna height difference between BSs and UEs gives rise to a *non-zero cap on the minimum distance* between a BS and its served UEs, and thus a *cap on the received signal power strength*. Thus, and although each inter-cell interference power strength is subject to the same cap, the aggregate inter-cell interference power will overwhelm the signal power in a UDN due to the sheer number of strong interferers.

To visualize this fundamental aspect, in Fig. 2c, we plot the SINR heat map of SCNs with the following assumption:

- The 3GPP antenna configuration with $L = 8.5$ m, as recommended in [8], in which the BS and the UE antenna heights are assumed to be 10 m and 1.5 m, respectively

Observations: From Fig. 2c, we can observe that:

- The non-zero BS-to-UE antenna height difference has a negligible performance impact when the BS density is not ultra-dense (i.e., when λ is around 50 BSs/km² and 250 BSs/km²), since the SINR maps are basically the same as those in Fig. 2b.
- Compared with Fig. 2b, the SINR heat map becomes much bluer for the considered UDN (i.e., when λ is around 2500 BSs/km²), indicating a significant performance degradation. This is due to the cap on the received signal power strength caused by the non-zero BS-to-UE antenna height difference in UDNs.

Concluding Remark: Considering the significant performance impact of the BS-to-UE antenna height difference, we suggest deploying small cell BSs in UDNs as close as possible to human

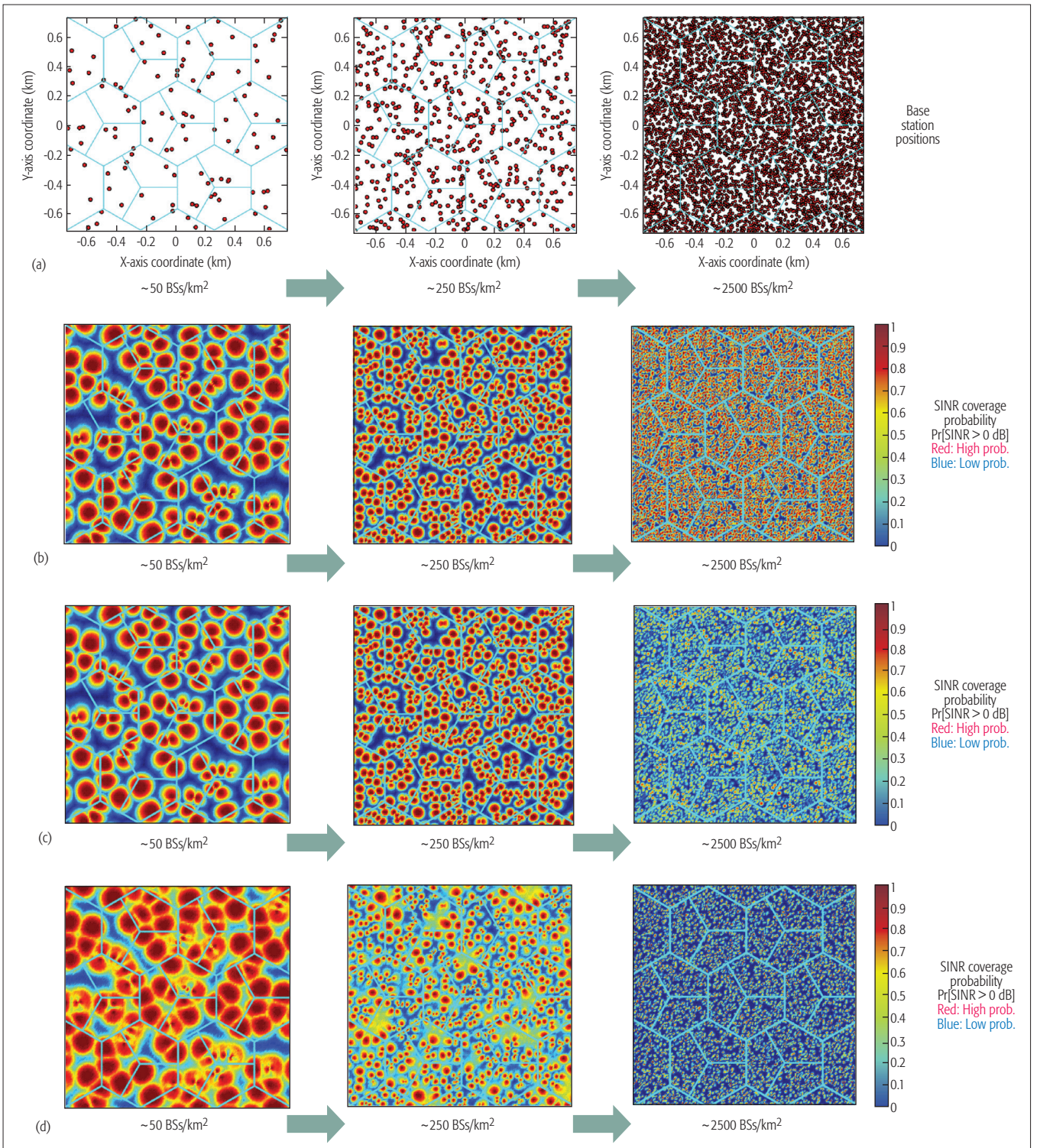


FIGURE 2. SINR heat maps considering a much shorter distance between a UE and its serving BS in UDNs: a) random BS deployments, shown as dots, for network visualization. The BS densities of a typical 4G LTE network, a typical 5G dense SCN, and a typical UDN are around 50, 250, 2500 BSs/km², respectively; b) our understanding on the performance trend of UDNs before 2015 with a single-slope path loss function (NLoS only). The sizes of the reddish areas (high SINR coverage probabilities) and the blueish areas (low SINR coverage probabilities) are approximately the same as the network densities, indicating an invariant SINR performance in UDNs; c) the performance trend of UDNs due to the non-zero BS-to-UE antenna height difference of 8.5m [8]. Compared to Fig. 2b, the SINR heat map becomes blueish as λ increases to around 2500 BSs/km², showing a significant performance degradation because of the cap on the received signal power strength caused by the non-zero BS-to-UE antenna height difference in UDNs. This issue can be fixed by lowering the BS antenna height to the human height around 1.5m; d) the performance trend of UDNs due to the high probabilities of LoS transmissions (with the 3GPP path loss model incorporating both LoS and NLoS transmissions [8]). Compared to Fig. 2b, the SINR heat map becomes more and more blueish as λ increases, showing a significant performance degradation because of the transition of a large number of interfering paths from NLoS to LoS in dense networks and UDNs.

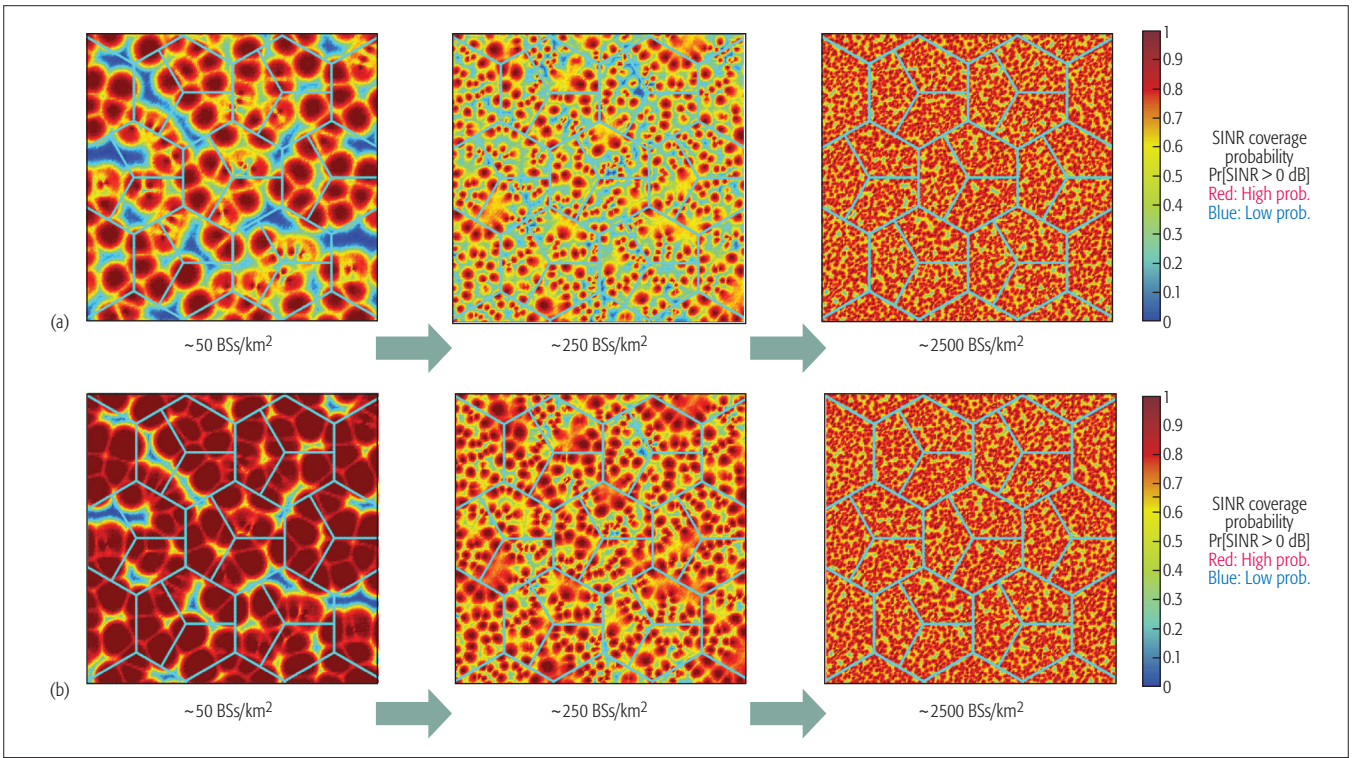


FIGURE 3. SINR heat maps considering a much larger ratio of the BS number over the UE number in UDNs: a) the performance trend of UDNs due to the oversupply of BSs with IMC compared to UEs (the UE density is $\rho = 300$ UEs/km²). Compared to Fig. 2d, the SINR heat map becomes very reddish when λ increases to around 2500 BSs/km², showing a significant performance improvement in UDNs thanks to the BS IMC. Such performance improvement is not obvious when λ is around 50 BSs/km² since almost all BSs are active, with or without the BS IMC; b) the performance trend of UDNs due to the PF scheduler working on a small number of UEs per active BS (the UE density is $\rho = 300$ UEs/km²). Compared to Fig. 3a, the SINR heat map becomes reddish when λ is lower than 250 BSs/km², showing a performance improvement due to multi-UE diversity, that is, each BS can select a UE from a plurality of UEs to serve with good channel quality. Such performance gain is negligible when λ increases to around 2500 BSs/km² due to the diminishing multi-UE diversity in UDNs.

height. However, this requires a revolutionized approach to BS architecture and deployment to avoid tampering, vandalism, and other unwanted effects [12].

In the following sections, we only consider a futuristic scenario with a zero antenna height difference between BSs and UEs (i.e., $L = 0$ m) so that the performance of UDNs is not unnecessarily penalized by this aspect, as shown in Fig. 2c.

STRONGER INTERFERENCE POWER

A much shorter distance between a BS and its served UEs in a UDN implies high probabilities of LoS transmissions. Generally speaking, LoS transmissions are more helpful to enhance the received signal strength than NLoS transmissions. However, after a certain level of densification, not only the signal power, but also the inter-cell interference power will significantly grow due to the emergence of LoS paths. Thus, the transition of a large number of interfering paths from NLoS to LoS will overwhelm the signal power in a UDN [11].

To visualize this fundamental aspect, in Fig. 2d, we plot the SINR heat map of SCNs with the following assumptions:

- The 3GPP antenna configuration with $L = 0$ m, as recommended above
- The 3GPP probabilistic LoS/NLoS path loss model exhibited in Table 1

Observations: From Fig. 2d, we can see that:

- Compared to Fig. 2b, the SINR heat map becomes redder for the 4G SCN (i.e., when λ is around 50 BSs/km²), because the received signal strength is enhanced by LoS transmissions, while most inter-cell interference remains NLoS.
- Compared to Fig. 2b, the SINR heat map becomes bluer when λ is equal to or larger than 250 BSs/km², thus showing a significant performance degradation due to the transition of a large number of interfering paths from NLoS to LoS in UDNs.

Concluding Remark: Considering the significant performance impact of the transition of a large number of interfering paths from NLoS to LoS, we propose that operators should carefully plan the deployment of small cell BSs from 4G to 5G, and adopt new solutions to mitigate the acceleration of the growth of the inter-cell interference, as discussed in the following section.

In the following sections, we focus on the 3GPP probabilistic LoS/NLoS path loss model exhibited in Table 1. This propagation model is realistic, and such NLoS-to-LoS transition cannot be avoided in the foreseeable future.

TWO FUNDAMENTAL ASPECTS OF UDNs RELATED TO SMALL UE NUMBER PER BS

In this section, we study two other fundamental aspects of UDNs caused by the much larger ratio of the BS number over the UE number.

Earlier in the article we discuss how, with a surplus of BSs, a BS can mute its transmissions when there is no active UE connected to it, which is referred to as the BS IMC [2]. As a result, the active UE SINR performance benefits from a BS diversity gain, that is, each UE has a plurality of BSs from which to select its server and tight control of unnecessary inter-cell interference, as idle BSs are put to sleep thanks to the IMC and do not generate any interference. The surplus of BSs together with the IMC can be seen as a powerful tool that can help to mitigate the fast-growing interference problems presented above.

To visualize this fundamental aspect, in Fig. 3, we plot the SINR heat map of SCNs with the following assumptions:

- The 3GPP antenna configuration with $L = 0$ m
- The 3GPP probabilistic LoS/NLoS path loss model
- A finite number of UEs ($\rho = 300$ UEs/km², a typical density of the active UEs in 5G) [2]

Observations: From Fig. 3a, we can see that:

- Compared to Fig. 2d, the SINR heat map changes little for the 4G SCN (i.e., when λ is around 50 BSs/km²), because almost all BSs are active with or without the IMC, due to the relatively small BS density compared to that of UEs.
- Compared to Fig. 2d, the SINR heat map becomes redder when λ is equal to or larger than 250 BSs/km², thus showing a significant *performance improvement* in UDNs thanks to the BS IMC. More specifically, the signal power continues increasing with the network densification, while the interference power is controlled because not all BSs are turned on.

Concluding Remark: Considering the significant performance benefit of the surplus of BSs together with the IMC, we suggest that small cell BSs in UDNs should be equipped with efficient IMCs that are able to put to sleep a given number of BSs to realize a desired UE quality of experience (QoE).

In the following sections, we consider the BS IMC because it is essential to the successful operation of UDNs.

LESS ACTIVE UEs PER ACTIVE BS

With a much larger number of BSs than UEs in UDNs, the number of active UEs in each BS also becomes smaller, and approaches the one-active-UE-per-BS limit when the BS density is very large [2]. This phenomenon incurs a diminishing multi-UE diversity gain, which refers to the gain that each BS can achieve when selecting a subset of UEs to serve with good channel qualities from a plurality of connected ones. When the one-active-UE-per-BS limit is reached, one BS is stuck with one UE and cannot perform any UE selection in its scheduler. In practice, two commonly used BS schedulers are the round-robin (RR) scheduler, which selects UEs in turn regardless of their channel state, and the proportional fair (PF) scheduler, which tends to select UEs with larger channel gains while reinforcing a certain degree of fairness among UEs [2]. However, as the number of active UEs per active BS approaches one in UDNs, there

will be very little gain that can be achieved by the advanced PF scheduler compared to the simplistic RR one [2].

To visualize this fundamental aspect, in Fig. 3b, we plot the SINR heat map of SCNs with the following assumptions:

- The 3GPP antenna configuration with $L = 0$ m
- The 3GPP probabilistic LoS/NLoS path loss model
- The BS IMC
- The PF scheduler

Note that previous results in Figs. 2 and 3a assume an RR scheduler.

Observations: From Fig. 3b, we can see that:

- Compared to Fig. 3a, the SINR heat map becomes redder when the BS density is not ultra-dense, that is, λ is equal to or less than 250 BSs/km², showing a performance improvement due to the multi-UE diversity, that is, each BS can select a UE from a plurality of UEs to serve with a good channel quality.
- Compared to Fig. 3a, the SINR heat map changes little when λ is around 2500 BSs/km², thus showing a negligible performance gain since such a UDN approaches the one-active-UE-per-BS limit.

Concluding Remark: Considering the negligible gain of the more complex channel-dependent PF scheduling in UDNs, when complexity is an issue, it is recommended to adopt simpler scheduling mechanisms such as the RR scheduler to simplify the radio resource management (RRM).

In the following sections, as we are not analyzing complexity but performance, we still consider the PF scheduler. It inflicts no harm on UDNs, while it has been widely adopted in sparse networks to enhance the performance.

ONE FUNDAMENTAL ASPECT OF UDNs RELATED TO BURSTY TRAFFIC DEMANDS

As a by-product of the small number of active UEs in each active BS, the per-cell aggregate traffic demands in the downlink (DL) and the uplink (UL) become highly dynamic. Consequently, dynamic time-division duplex (TDD) emerges as a new technology for UDNs, which serves as a transition link between the conventional network and the full duplex one [13–15]. In dynamic TDD, each BS can provide a tailored configuration of DL/UL subframe resources to match the DL/UL data requests [8]. However, such flexibility comes at the expense of allowing inter-cell inter-link interference (ICILI), that is, DL transmissions of a cell may interfere with UL ones of neighboring cells (DL-to-UL interference) and vice versa (UL-to-DL interference). This performance degradation is particularly severe for the UL due to the relatively strong DL-to-UL interference, which calls for the implementation of interference cancellation (IC) and UL power boosting (ULPB) techniques [13, 14].

In more detail, the IC technique leverages the backhaul communications among BSs and the BS signal processing capability to mitigate the DL-to-UL interference coming from other BSs. Moreover, a UL power control algorithm [8] is currently adopted in the LTE networks and con-

sidered in our network performance visualization. For a typical example, such an algorithm partially compensates each UE's path loss (in dB) by 80 percent, on top of a base power of -59 dBm for a 10 MHz bandwidth. If this power exceeds the UE

power limit, it will be clipped to the maximum UE transmission power of 23 dBm, shown in Table 1. A straightforward ULPB scheme would be letting UEs transmit at their full powers to combat the DL-to-UL interference.

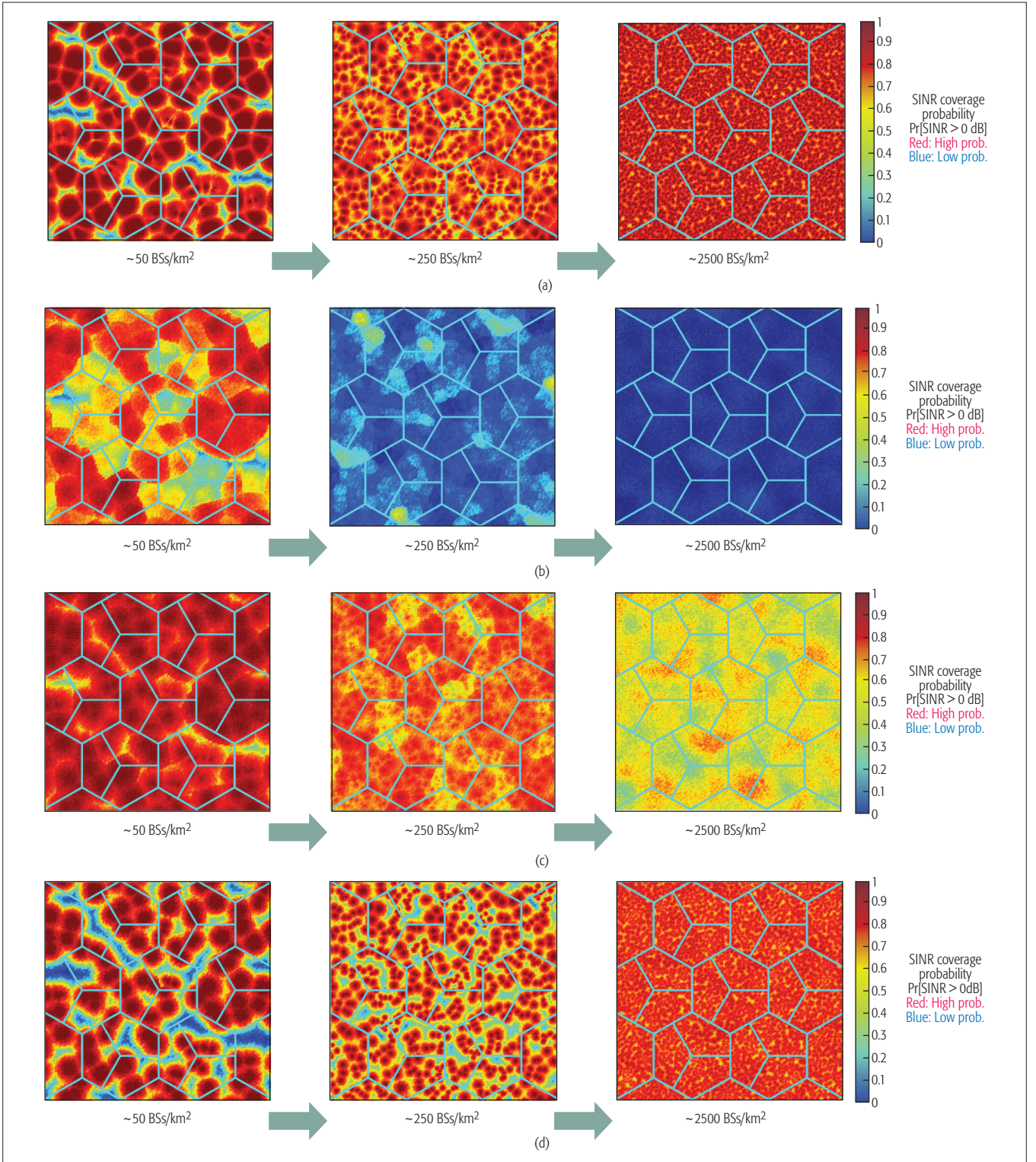


FIGURE 4. SINR heat maps considering busy traffic demands in the DL and the UL: a) the performance trend of UDNs with dynamic TDD (DL part). Compared to Fig. 3b, the DL SINR performance of dynamic TDD is shown to be robust to ICILI for all BS densities; b) the performance trend of UDNs with dynamic TDD (UL part). The UL of dynamic TDD shows total outage for UDNs; c) the performance trend of UDNs with dynamic TDD (UL part with partial IC). Compared to Fig. 4b, the UL SINR performance is greatly improved for all BS densities, thanks to the cancellation of the top three interfering signals from other BSs; d) the performance trend of UDNs with dynamic TDD (UL part with partial IC + ULPB). Compared to Fig. 4c, the UL SINR performance is further improved due to the use of full power at UEs (23 dBm). Now the UL performance is comparable to the DL one shown in Fig. 4a.

To visualize this fundamental aspect, in Fig. 4, we plot the SINR heat map of SCNs with the following assumptions:

- The 3GPP antenna configuration with $L = 0$ m
- The 3GPP probabilistic LoS/NLoS path loss model
- The BS IMC
- The PF scheduler studied previously
- The LTE dynamic TDD with each UE randomly requesting DL data and UL data with 50 percent probability in each direction

Observations: From Fig. 4, we can see that:

- In Fig. 4a, the SINR heat map of the DL UDN (i.e., when λ is around 2500 BSs/km²) is slightly redder than Fig. 3b, because some DL interference is converted to UL interference, which is generally weaker.
- In Fig. 4b, the SINR heat map of the UL shows that the UL is particularly vulnerable to the DL-to-UL interference in UDNs, especially for UDNs (i.e., when λ is around 2500 BSs/km²).
- A potential solution to mitigate the DL-to-UL interference is the partial IC technique. Here, we assume that each BS can remove the top three interfering signals from other BSs. In Fig. 4c, the SINR heat map of the UL with partial IC shows considerable improvement over that in Fig. 4b, especially for the 4G SCN and the 5G dense SCN (i.e., when λ is equal to or less than 250 BSs/km²).
- Note that no UL power boosting was considered in Figs. 4b and 4c. Here, we assume that each UE transmits at its full power, that is, 23 dBm (Table 1) [8]. In Fig. 4d, the SINR heat map of the UL with partial IC and ULPB is further improved when λ is around 2500 BSs/km² compared to Fig. 4c. However, such performance improvement is not obvious for the 4G SCN and the 5G dense SCN (i.e., when λ is equal to or less than 250 BSs/km²). This is because the ULPB technique considerably increases the UL-to-UL inter-cell interference, which makes cell edge UEs suffer.

Concluding Remark: Considering the significant performance benefit of dynamic TDD, it is recommended to enable dynamic TDD in UDNs. However, special attention needs to be paid to mitigate the strong DL-to-UL interference. The partial IC and ULPB techniques are considered here.

CONCLUSION

Using the proposed network performance visualization technique, we have investigated in a unified framework the five fundamental differences between current macrocell and sparse small cell networks and future UDNs. From our results, we conclude that in UDNs:

- The small cell BS antenna height should be lowered closer to the UE antenna height to avoid the *performance degradation* due to the capped carrier signal power.
- The small cell BS density should be carefully considered to mitigate the performance degradation due to the NLoS-to-LoS interference transition.
- The small cell BS IMC is a fundamental fea-

ture to unveil the full potential of UDNs and allow the performance improvement due to the UE selection of a good serving BS and the control of unnecessary inter-cell interference.

- The RR scheduler could be used to simplify the resource management, which is justified by its comparable performance to the PF one in UDNs.
- The dynamic TDD technology could be used to harness the high dynamics of DL/UL traffic and provide the performance improvement in the medium access control layer. However, efficient interference management is needed in the physical layer, primarily to mitigate DL-to-UL interference. As future work, we propose the following:
- The proposed network performance visualization technique can be extended to a 3D space using plane slicing. Such extension would be useful to illustrate network performance for scenarios with buildings or drones.
- As indicated previously, we have considered uniform distributions of UEs and BSs in this article. It is of great interest to investigate a hotspot deployment with non-uniform distributions of UEs and BSs, which would change the distributions of the active BSs and the UL interfering UEs, and more.
- The BS IMC is very useful to reduce the energy consumption of UDNs. However, it is important to note that a BS in idle mode may still consume a non-negligible amount of energy, thus impacting the energy efficiency of small cell networks. We plan to study the energy efficiency of realistic 5G networks using the practical power model developed in the Green-Touch project [2].

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