On the Performance of Practical Ultra-Dense Networks: The Major and Minor Factors

Ming Ding[‡], *Member, IEEE*, David López-Pérez[†], *Member, IEEE*

***Abstract*—In this paper, we conduct performance evaluation for Ultra-Dense Networks (UDNs), and identify which modelling factors play major roles and minor roles. From our study, we draw the following conclusions. First, there are 3 factors/models that have a major impact on the performance of UDNs, and they should be considered when performing theoretical analyses: *i)* a multi-piece path loss model with line-of-sight (LoS) and non-line-of-sight (NLoS) transmissions; *ii)* a non-zero antenna height difference between base stations (BSs) and user equipments (UEs); *iii)* a finite BS/UE density. Second, there are 4 factors/models that have a minor impact on the performance of UDNs, i.e., changing the results quantitatively but not qualitatively, and thus their incorporation into theoretical analyses is less urgent: *i)* a general multi-path fading model based on Rician fading; *ii)* a correlated shadow fading model; *iii)* a BS density dependent transmission power; *iv)* a deterministic BS/user density. Finally, there are 3 factors/models for future study: *i)* a BS vertical antenna pattern; *ii)* multi-antenna and/or multi-BS joint transmissions; *iii)* a non-uniform distribution of BSs. Our conclusions can guide researchers to down-select the assumptions in their theoretical analyses, so as to avoid unnecessarily complicated results, while still capturing the fundamentals of UDNs in a meaningful way.**

I. Introduction

Recent market forecasts predict that the mobile data traffic volume density will keep growing towards 2030 and beyond the so-called 1000× wireless capacity demand [1]. This increase is expected to be fuelled by the growth of mobile broadband services, where high-quality videos, e.g., ultra-high definition and 4K resolution videos, are becoming an integral part of today's media contents. Moreover, new emerging services such as machine type communications (MTC) and internet of things (IoT) will contribute to the increase of massive data. This poses an ultimate challenge to the wireless industry, which must offer an exponentially increasing traffic in a profitable and energy efficient manner. To make things even more complex, the current economic situation around the globe aggravates the pressure for mobile operators and vendors to stay competitive, rendering the decision on how to increase network capacity in a cost-effective manner even more critical.

Previous practice in the wireless industry shows that the wireless network capacity has increased around one million fold from 1950 to 2000, in which an astounding 2700× gain was achieved through network densification using smaller cells [2]. In the first decade of 2000, network densification continued to serve the 3rd Generation Partnership Project (3GPP) 4th-generation (4G) Long Term Evolution (LTE) networks, and is expected to remain as one of the main forces to drive the 5th-generation (5G) networks onward [2], [3]. Indeed, *the orthogonal deployment*[1] of ultra-dense (UD) small cell networks (SCNs), or simply *ultra-dense networks (UDNs)*, within the existing macrocell network at sub-6 GHz frequencies[2], is envisaged as one of the workhorses for capacity enhancement in 5G, due to its large spatial reuse of spectrum and its easy management. The latter one arises from its low interaction with the macrocell tier, e.g., no inter-tier interference [2].

The performance analysis of UDNs, however, is challenging because *UDNs are fundamentally different from the current 4G sparse/dense networks*, and thus it is difficult to identify the essential factors that have a key impact on UDN performance. To elaborate on this, Table I provides a list of key factors/models/parameters related to the performance analysis of SCNs, along with their assumptions adopted in the 3GPP. This list is far from exhaustive, but it includes those assumptions that are essential in any SCN performance evaluation campaign in the 3GPP [5], [6]. For clarity, the assumptions in Table I are classified into two categories, i.e., network scenario (NS) and wireless system (WS).

More specifically,

- The assumptions on the NS characterise the deployments of base stations (BSs) and user equipments (UEs).
- The assumptions on the WS characterise the channel models and the transmit/receive capabilities.

Considering the 10 factors listed in Table I, a straightforward methodology to understand the fundamental differences between UDNs and sparse/dense networks would be to investigate the performance impact of those factors and their combinations one by one, thus drawing useful conclusions on which factors should define the fundamental behaviours of UDNs. Since the 3GPP assumptions on those factors were agreed upon by major companies in the wireless industry all over the world, the more of these assumptions an analysis can consider, the more practical the analysis will be.

The theoretical community has already started to explore this approach, and some of those assumptions in Table I have already been considered in various works to derive the performance of UDNs, e.g., through stochastic geometry (SG) analyses. In more detail, in SG analyses, BS positions are

[‡]Ming Ding is with Data61, CSIRO, Australia (e-mail: Ming.Ding@data61.csiro.au).

[†]David López-Pérez is with Nokia Bell Labs, Ireland (email: david.lopez-perez@nokia.com).

[1]Here, the orthogonal deployment means that small cells and macrocells are operating on different frequency spectrum, i.e., 3GPP Small Cell Scenario #2a [3].

[2]In this paper, we focus on the spatial reuse gain of UDNs at sub-6 GHz frequencies, and we do not consider millimeter wave communications, as such topic stands on its own and requires a completely new analysis [4].

Table I
A LIST OF FACTORS FOR THE PERFORMANCE ANALYSIS OF UDNS.

Factor category	Factor index	Factor and its assumption in the 3GPP [5], [6]	Assumption in our SG analysis (Sections II and III)	Assumption in our simulation
Network Scenario (NS)	NS 1	Finite BS and UE densities	✓	✓
	NS 2	Deterministic BS and UE densities	Random BS and UE numbers (Poisson-distributed)	✓ *[Focus of this paper]*
	NS 3	Non-uniform distribution of BSs with some constraints on the minimum BS-to-BS distance	Unconstrained uniform distribution of BSs	Unconstrained uniform distribution of BSs
Wireless System (WS)	WS 1	Multi-piece path loss with LoS/NLoS transmissions	✓	✓
	WS 2	3D BS-to-UE distance for path loss calculation considering BS/UE antenna heights	✓	✓
	WS 3	Generalized Rician fading	Rayleigh fading	✓ *[Focus of this paper]*
	WS 4	Correlated shadow fading	None	✓ *[Focus of this paper]*
	WS 5	BS density dependent BS transmission power	Constant BS transmission power	✓ *[Focus of this paper]*
	WS 6	BS vertical antenna pattern	None	None
	WS 7	Multi-antenna and/or multi-BS joint transmissions	None	None

typically modelled as a Homogeneous Poisson Point Process (HPPP) on the plane, and closed-form expressions of coverage probability can be found for some scenarios in single-tier cellular networks [7] and multi-tier cellular networks [8]. Using a simple modelling, the major conclusion in [7], [8] is that neither the number of cells nor the number of cell tiers changes the coverage probability in interference-limited fully-loaded wireless networks. Recently, a few noteworthy studies have been carried out to revisit the network performance analysis of UDNs under more practical assumptions [9]–[15]. These new studies include the following assumptions in Table I: *i)* a multi-piece path loss model with line-of-sight (LoS) and non-line-of-sight (NLoS) transmissions (WS 1), *ii)* a non-zero antenna height difference between BSs and UEs (WS 2), and *iii)* a finite BS/UE density (NS 1). The inclusion of these assumptions significantly changed the previous conclusion, indicating that the coverage probability performance of UDNs is *neither a convex nor a concave function* with respect to the BS density.

In light of such drastic change of conclusions, one may ask the following intriguing question: What if we further consider more assumptions in SG analyses? Will it qualitatively change the recently obtained conclusions in [9]–[15]? In this paper, we will address this fundamental question by investigating the performance impact of the 3GPP assumptions of WS 3, WS 4, WS 5 and NS 2 in Table I.

The rest of this paper is structured as follows:

- Section II describes the network scenario and the wireless system model used in our SG analysis, mostly recommended by the 3GPP.
- Section III presents our previous theoretical results in terms of the coverage probability, and discusses our main results on the performance impact of the 3GPP assumptions of NS 1, WS 1 and WS 2 in Table I.
- Section IV describes in more detail the newly considered assumptions addressed in this paper, i.e., the 3GPP assumptions of WS 3, WS 4, WS 5 and NS 2.
- Section V discloses our simulation results on the performance impact of these newly considered assumptions.
- Section VI provides some discussion on the performance impact of the remaining 3GPP assumptions of WS 6, WS 7 and NS 3, which are left as our future work.
- The conclusions are drawn in Section VII.

II. NETWORK SCENARIO AND WIRELESS SYSTEM MODEL

In this section, we present the network scenario and the wireless system model considered in this paper. Note that most of our assumptions on cellular networks are in line with the recommendations by the 3GPP [5], [6].

A. Network Scenario

We consider a cellular network with BSs deployed on a plane according to a homogeneous Poisson point process (HPPP) Φ with a density of $\lambda\,$BSs/km^2. Active UEs are also Poisson distributed in the considered network with a density of $\rho\,$UEs/km^2. We only consider active UEs in the network because non-active UEs do not trigger data transmission, and thus they are ignored in our analysis. Note that the total UE number in cellular networks should be much higher than the number of the active UEs, but at a certain time slot and on a certain frequency band, the active UEs with data traffic demands may not be too many. A typical density of the active UEs in 5G should be around $300\,$UEs/km^2 [2].

In practice, a BS should mute its transmission if there is no UE connected to it, which reduces unnecessary inter-cell interference and energy consumption [15]. Since UEs are randomly and uniformly distributed in the network, it can be assumed that the active BSs also follow an HPPP distribution $\tilde{\Phi}$ [16], the density of which is denoted by $\tilde{\lambda}\,$BSs/km^2. Note that $0 \leq \tilde{\lambda} \leq \lambda$, and a larger ρ leads to a larger $\tilde{\lambda}$. Details on the computation of $\tilde{\lambda}$ can be found in [15].

B. Wireless System Model

We denote by r the two-dimensional (2D) distance between a BS and an a UE, and by L the absolute antenna height difference between a BS and a UE. Hence, the three-dimensional (3D) distance between a BS and a UE can be expressed as

$$w = \sqrt{r^2 + L^2}, \tag{1}$$

where L is in the order of several meters for the current 4G networks. For example, according to the 3GPP assumptions for small cell networks, L equals to 8.5 m, as the BS antenna height and the UE antenna height are assumed to be 10 m and 1.5 m, respectively [17].

Following the 3GPP recommendations [5], [6], we consider practical line-of-sight (LoS) and non-line-of-sight (NLoS) transmissions, and treat them as probabilistic events. Specifically, we adopt a very general path loss model, in which the path loss $\zeta(w)$ is segmented into N pieces, i.e.,

$$\zeta(w)=\begin{cases}\zeta_1(w), & \text{when } 0\leq w\leq d_1\\ \zeta_2(w), & \text{when } d_1<w\leq d_2\\ \vdots & \vdots\\ \zeta_N(w), & \text{when } w>d_{N-1}\end{cases}, \tag{2}$$

where each piece $\zeta_n(w), n\in\{1,2,\ldots,N\}$ is modelled as

$$\zeta_n(w)=\begin{cases}\zeta_n^{\mathrm{L}}(w)=A_n^{\mathrm{L}}w^{-\alpha_n^{\mathrm{L}}}, & \text{LoS Prob: } \mathrm{Pr}_n^{\mathrm{L}}(w)\\ \zeta_n^{\mathrm{NL}}(w)=A_n^{\mathrm{NL}}w^{-\alpha_n^{\mathrm{NL}}}, & \text{NLoS Prob: } 1-\mathrm{Pr}_n^{\mathrm{L}}(w)\end{cases}, \tag{3}$$

where

- $\zeta_n^{\mathrm{L}}(w)$ and $\zeta_n^{\mathrm{NL}}(w), n\in\{1,2,\ldots,N\}$ are the n-th piece path loss functions for the LoS transmission and the NLoS transmission, respectively,
- A_n^{L} and A_n^{NL} are the path losses at a reference distance $r=1$ for the LoS and the NLoS cases, respectively,
- α_n^{L} and α_n^{NL} are the path loss exponents for the LoS and the NLoS cases, respectively.
- In practice, A_n^{L}, A_n^{NL}, α_n^{L} and α_n^{NL} are constants obtainable from field tests [5], [6].
- $\mathrm{Pr}_n^{\mathrm{L}}(w)$ is the n-th piece LoS probability function that a transmitter and a receiver separated by a distance w has a LoS path, which is assumed to be a monotonically decreasing function with regard to w. Such assumption has been confirmed by [5], [6].

For convenience, $\left\{\zeta_n^{\mathrm{L}}(w)\right\}$ and $\left\{\zeta_n^{\mathrm{NL}}(w)\right\}$ are further stacked into piece-wise functions written as

$$\zeta^{Path}(w)=\begin{cases}\zeta_1^{Path}(w), & \text{when } 0\leq w\leq d_1\\ \zeta_2^{Path}(w), & \text{when } d_1<w\leq d_2\\ \vdots & \vdots\\ \zeta_N^{Path}(w), & \text{when } w>d_{N-1}\end{cases}, \tag{4}$$

where the string variable $Path$ takes the value of "L" and "NL" for the LoS and the NLoS cases, respectively. Besides, $\left\{\mathrm{Pr}_n^{\mathrm{L}}(w)\right\}$ is also stacked into a piece-wise function as

$$\mathrm{Pr}^{\mathrm{L}}(w)=\begin{cases}\mathrm{Pr}_1^{\mathrm{L}}(w), & \text{when } 0\leq w\leq d_1\\ \mathrm{Pr}_2^{\mathrm{L}}(w), & \text{when } d_1<w\leq d_2\\ \vdots & \vdots\\ \mathrm{Pr}_N^{\mathrm{L}}(w), & \text{when } w>d_{N-1}\end{cases}. \tag{5}$$

As a special case, in the following subsections, we consider a two-piece path loss function and a LoS probability function defined by the 3GPP [5]. Specifically, we use the following path loss function,

$$\zeta(w)=\begin{cases}A^{\mathrm{L}}w^{-\alpha^{\mathrm{L}}}, & \text{LoS Prob: } \mathrm{Pr}^{\mathrm{L}}(w)\\ A^{\mathrm{NL}}w^{-\alpha^{\mathrm{NL}}}, & \text{NLoS Prob: } 1-\mathrm{Pr}^{\mathrm{L}}(w)\end{cases}, \tag{6}$$

together with the following LoS probability function,

$$\mathrm{Pr}^{\mathrm{L}}(w)=\begin{cases}1-5\exp\left(-R_1/w\right), & 0<w\leq d_1\\ 5\exp\left(-w/R_2\right), & w>d_1\end{cases}, \tag{7}$$

where $R_1=156$ m, $R_2=30$ m, and $d_1=\frac{R_1}{\ln 10}$ [5]. The combination of the path loss function in (6) and the LoS probability function in (7) can be deemed as a special case of the proposed path loss model in (2) with the following substitutions: $N=2$, $\zeta_1^{\mathrm{L}}(w)=\zeta_2^{\mathrm{L}}(w)=A^{\mathrm{L}}w^{-\alpha^{\mathrm{L}}}$, $\zeta_1^{\mathrm{NL}}(w)=\zeta_2^{\mathrm{NL}}(w)=A^{\mathrm{NL}}w^{-\alpha^{\mathrm{NL}}}$, $\mathrm{Pr}_1^{\mathrm{L}}(w)=1-5\exp\left(-R_1/w\right)$, and $\mathrm{Pr}_2^{\mathrm{L}}(w)=5\exp\left(-w/R_2\right)$. For clarity, this model is referred to as **the 3GPP Path Loss Model** hereafter.

Moreover, in this paper, we also assume a practical user association strategy (UAS), in which each UE is connected to the BS with the smallest path loss (i.e., with the largest $\zeta(r)$) to the UE [5], [6]. We also assume that each BS/UE is equipped with an isotropic antenna, and that the multi-path fading between a BS and a UE is modelled as independently identical distributed (i.i.d.) Rayleigh fading [9], [12]–[15].

III. Discussion on the State-of-The-Art Results on the Performance Analysis of UDNs

Using the theory of stochastic geometry (SG) and the presented assumptions in previous subsections, we investigated the coverage probability performance of SCNs by considering the performance of *a typical UE located at the origin o*. In such studies [13]–[15], we analysed in detail the performance impact of the 3GPP assumptions of NS 1, WS 1 and WS 2 in Table I. The concept of coverage probability and a summary of our results are presented in the following.

A. The Coverage Probability

The coverage probability is defined as the probability that the signal-to-interference-plus-noise ratio (SINR) of the typical UE is above a designated threshold γ:

$$p^{\mathrm{cov}}(\lambda,\gamma)=\mathrm{Pr}\left[\mathrm{SINR}>\gamma\right], \tag{8}$$

where the SINR is computed by

$$\mathrm{SINR}=\frac{P\zeta(r)h}{I_{\mathrm{agg}}+P_{\mathrm{N}}}, \tag{9}$$

where h is the channel gain, which is modelled as an exponentially distributed random variable (RV) with a mean of one (due to our consideration on Rayleigh fading presented before), P is the transmission power at each BS, P_{N} is the additive white Gaussian noise (AWGN) power at the typical UE, and I_{agg} is the cumulative interference given by

$$I_{\mathrm{agg}}=\sum_{i:\,b_i\in\tilde{\Phi}\setminus b_o}P\beta_i g_i, \tag{10}$$

where b_o is the BS serving the typical UE, b_i is the i-th interfering BS, β_i is the path loss from b_i to the typical UE,

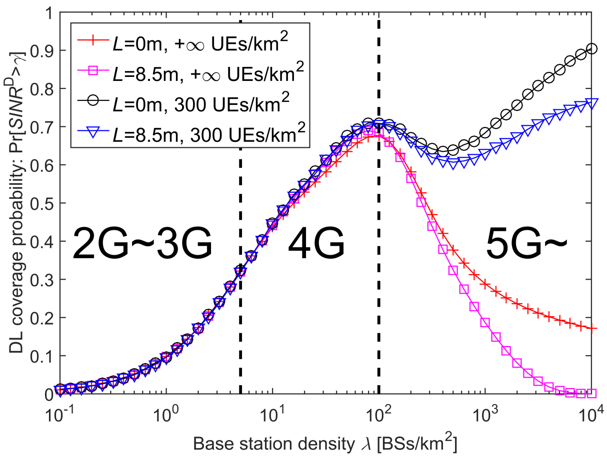

Fig. 1. Theoretical performance comparison of the coverage probability when the SINR threshold $\gamma = 0\,\text{dB}$. Note that all the results are obtained using the 3GPP Path Loss Model introduced in Subsection II-B. Moreover, the BS density regions for the 4G and 5G networks have been illustrated in the figure, considering that the maximum BS density of the 4G SCNs is in the order of $10^2\,\text{BSs/km}^2$ [2], [3].

and g_i is the multi-path fading channel gain associated with b_i. Note that when all BSs are assumed to be active, the set of all BSs Φ should be used in the expression of I_{agg} [9], [10], [12]–[14]. However, in our system model with idle mode at the small cell BSs and a finite UE density (see Subsection II-A), only the active BSs in $\tilde{\Phi} \setminus b_o$ inject effective interference into the network, where $\tilde{\Phi}$ denotes the set of the active BSs. Hence, the BSs in idle mode are not taken into account in the analysis of I_{agg} shown in (10), due to their muted transmissions.

B. Summary of Previous Findings

As a summary, to illustrate our findings in [13]–[15], we plot the SCN performance results in terms of the coverage probability in Fig. 1.

The results in Fig. 1 are analytical ones validated by simulations in [13]–[15]. Note that in Fig. 1, L denotes the absolute antenna height difference between BSs and UEs. As indicated in Subsection II-B, $L = 8.5\,\text{m}$ in the current 3GPP assumption for small cell scenarios, while $L = 0\,\text{m}$ is a futuristic assumption where BS antennas are installed at the UE height. Besides, the other parameters used to obtain the results in Fig. 1 are $\alpha^{\text{L}} = 2.09$, $\alpha^{\text{NL}} = 3.75$, $A^{\text{L}} = 10^{-10.38}$, $A^{\text{NL}} = 10^{-14.54}$, $P = 24$ dBm, $P_{\text{N}} = -95$ dBm [5].

From Fig. 1, we can draw the following observations:

- *Performance impact of WS 1*: The curve with plus markers represents the results in [13], where we consider the 3GPP multi-piece path loss function with LoS/NLoS transmissions [5] and ignore the 3GPP assumptions of WS 2 and NS 2, i.e., setting $L = 0\,\text{m}$ and deploying an infinite number of UEs. From those results, it can be seen that when the BS density is larger than a threshold around $10^2\,\text{BSs/km}^2$, the coverage probability will continuously *decrease* as the SCN becomes denser. This is because UDNs imply high probabilities of LoS transmissions between BSs and UEs, which leads to a performance *degradation* caused by a faster growth of the interference power compared with the signal power [13]. This is due to the transition of a large number of interference paths from NLoS (usually with a large path loss exponent α^{NL}) to LoS (usually with a small path loss exponent α^{L}).
- *Performance impact of WS 2*: The curve with square markers represents the results in [14], where we consider the 3GPP assumptions of multi-piece path loss function with LoS/NLoS transmissions and $L = 8.5\,\text{m}$ [5], while still keeping the assumption of an infinite number of UEs. From those results, it can be seen that the coverage probability shows a concerning trajectory toward zero when the BS density is larger than $10^3\,\text{BSs/km}^2$. This is because UDNs make the antenna height difference between BSs and UEs non-negligible, which gives rise to another performance *degradation* due to a cap on the signal power, resulted from the bounded minimum distance between a UE and its serving BS [14].
- *Performance impact of NS 2*: The curves with circle and triangle markers represents the results in [15], where we consider the 3GPP assumptions of multi-piece path loss function with LoS/NLoS transmissions and a finite UE density of $300\,\text{UEs/km}^2$ (a typical UE density in 5G [2]). Moreover, both the assumptions of $L = 0\,\text{m}$ and $L = 8.5\,\text{m}$ are investigated in Fig. 1. As we can observe, when the BS density surpasses the UE density, i.e., $300\,\text{BSs/km}^2$, thus creating a surplus of BSs, the coverage probability will continuously *increase*. Such performance behaviour of the coverage probability increasing in UDNs is referred to as *the Coverage Probability Takeoff* in [15]. The intuition behind *the Coverage Probability Takeoff* is that UDNs provide a surplus of BSs with respect to UEs, which provide a performance *improvement*, thanks to the BS diversity gain and the BS idle mode operation. In more detail, as discussed in II-A, since the UE density is finite in practical networks, a large number of BSs could switch off their transmission modules in a UDN, thus enter idle modes, if there is no active UE within their coverage areas. This helps to mitigate unnecessary inter-cell interference and reduce energy consumption.

IV. Discussion on the Incorporation of More 3GPP Assumptions into the Modeling

To investigate whether the previous conclusions still hold in more practical network scenarios, additional assumptions [5], [6] will also be considered in our analysis through simulations. The results will be discussed in Section V. Such additional practical assumptions are the 3GPP assumptions of WS 3, WS 4, WS 5 and NS 2 in Table I, which are presented in the sequel. Note that the authors of [11] have recently proposed a new approach of network performance analysis based on HPPP intensity matching, which facilitates the theoretical study of some of these additional 3GPP assumptions.

A. A general multi-path fading model based on Rician fading (WS 3 in Table I)

In SG analyses, the multi-path fading is usually modelled as Rayleigh fading for simplicity. However, in the 3GPP, a more practical model based on generalised Rician fading is widely adopted [6]. Hence, we consider the practical multi-path Rician fading model defined in the 3GPP [6], where the K factor in dB scale (the ratio between the power in the direct path and the power in the other scattered paths) is modelled as $K[\mathrm{dB}] = 13 - 0.03w$, where w is defined in (1).

B. A correlated shadow fading model (WS 4 in Table I)

In SG analyses, the shadow fading is usually not considered or simply modelled as independently identical distributed (i.i.d.) RVs. However, in the 3GPP, a more practical correlated shadow fading is often used [5], [6], [18]. Hence, we consider the practical correlated shadow fading model defined in 3GPP [5], where the shadow fading in dB is modelled as zero-mean Gaussian a random variable, e.g., with a standard deviation of 10 dB [5]. The correlation coefficient between the shadow fading values associated with two different BSs is denoted by τ, where $\tau = 0.5$ in [5].

C. A BS density dependent BS transmission power (WS 5 in Table I)

In SG analyses, the BS transmission power is usually assumed to be a constant. However, in the 3GPP, it is generally agreed that the BS transmission power should decrease as the SCN densifies because the per-cell coverage area shrinks [5]. Hence, we embrace the practical self-organising BS transmission power framework presented in [2], in which P varies with the BS density λ. Specifically, the transmit power of each BS is configured such that it provides a signal-to-noise-ratio (SNR) of $\eta_0 = 15$ dB at the edge of the average coverage area for a UE with NLoS transmissions. The distance from a cell-edge UE to its serving BS with an average coverage area is calculated by $r_0 = \sqrt{\frac{1}{\lambda\pi}}$, which is the radius of an equivalent disk-shaped coverage area with an area size of $\frac{1}{\lambda}$. Therefore, the worst-case path loss is given by $A^{\mathrm{NL}} r_0^{-\alpha^{\mathrm{NL}}}$ and the required transmission power to enable a η_0 dB SNR in this case can be computed as [2]

$$P(\lambda) = \frac{10^{\frac{\eta_0}{10}} P_{\mathrm{N}}}{A^{\mathrm{NL}} r_0^{-\alpha^{\mathrm{NL}}}}. \quad (11)$$

In Fig. 2, we plot the BS density dependent transmission power in dBm to illustrate this realistic power configuration when $\eta_0 = 15$ dB. Note that our modelling of P is practical, covering the cases of macrocells and picocells recommended in the LTE networks. More specifically, the typical BS densities of LTE macrocells and picocells are respectively several BSs/km^2 and around 50 BSs/km^2 [17], respectively. As a result, the typical P of macrocell BSs and picocells BSs are respectively assumed to be 46 dBm and 24 dBm in the 3GPP standards [17], which match well with our modelling.

D. A deterministic BS/UE density (NS 2 in Table I)

In SG analyses, the BS/UE number is usually modelled as a Poisson distributed random variable (RV). However, in the 3GPP, a deterministic BS/UE number is commonly used for a given BS/UE density [5]. Hence, we use deterministic densities λ BSs/km^2 and ρ UEs/km^2 to characterize the BS and UE deployments, respectively, instead of modelling their numbers as Poisson distributed RVs.

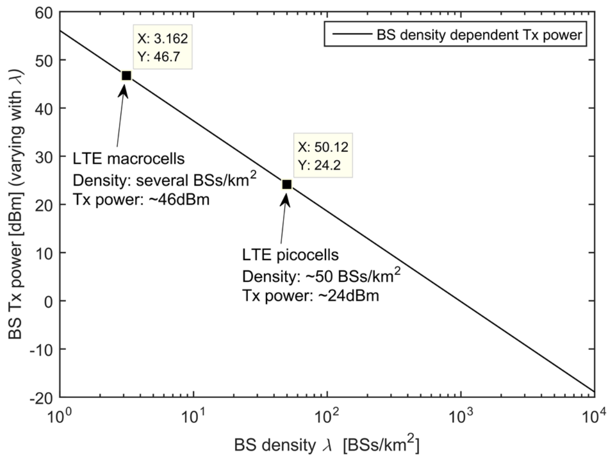

Fig. 2. The BS density dependent transmission power in dBm.

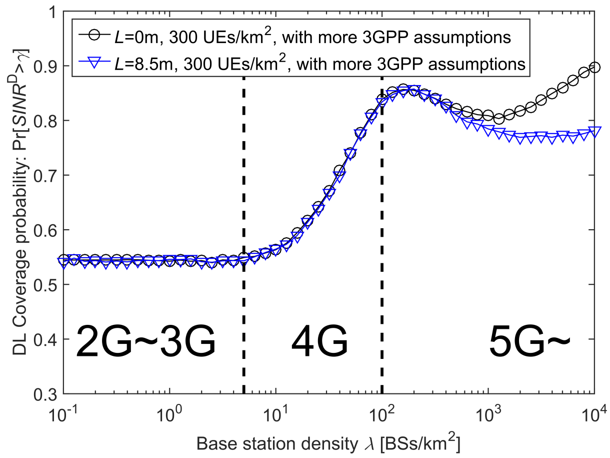

Fig. 3. Simulated performance comparison of the coverage probability with more 3GPP assumptions when the SINR threshold $\gamma = 0$ dB.

V. Main Results on the Performance Impact of the Additional 3GPP Assumptions

On top of the 3GPP assumptions discussed in Subsection III-B, in this section, we consider the 4 additional 3GPP assumptions described in Section IV, and study their performance impacts on UDNs. More specifically, using the same parameter values for Fig. 1, we conduct simulations to investigate the coverage probability performance of SCNs while also considering the 3GPP assumptions of WS 3, WS 4, WS 5 and NS 2 in Table I. The results are plotted in Fig. 3.

Comparing Fig. 1 with Fig. 3, we can draw the following observations:

- Those 4 additional 3GPP assumptions introduced in Section IV do not change the fundamental behaviours of UDNs shown in Fig. 1, i.e.,
  - the performance *degradation* due to the transition of a large number of interfering links from NLoS to

LoS, when $\lambda \in [10^2, 10^3]$ BSs/km^2,
  - the further performance *degradation*, due to the cap on the signal power caused by the non-zero antenna height difference between BSs and UEs, when $L = 8.5\,\text{m}$ and λ is larger than 10^3 BSs/km^2, and
  - the performance *improvement* when λ is larger than ρ, thus creating a surplus of BSs and thus allowing for idle mode operation to mitigate unnecessary inter-cell interference.
- The performance behaviour of sparse networks ($\lambda \in [10^{-1}, 10^0]$ BSs/km^2) is different in Fig. 3 compared with that in Fig. 1. This is mainly due to the larger BS transmission power used in Fig. 3 for sparse networks, as displayed in Fig. 2, which is helpful to remove coverage holes in the noise-limited region. Based on our knowledge of the successful operation of the existing 2G/3G systems, the results in Fig. 3 make more sense than those in Fig. 1, since the macrocell BS transmission power in the 2G/3G systems is indeed much larger than 24 dBm, which is the case for Fig. 1. Nevertheless, such BS density dependent transmission power has a minor impact on UDNs, because BSs in UDNs usually work in a interference-limited region, and thus the BS transmission power in the signal power and that in the aggregated interference power cancel out each other. This is obvious from the SINR expression in (9).

VI. Future Work

The performance impact of the remaining 3 assumptions in Table I, i.e., the 3GPP assumptions of WS 6, WS 7 and NS 3, are left to our future work, but presented in the following:

- *A 3D antenna pattern:* In SG analyses, the vertical antenna pattern at each BS is usually ignored for simplicity. However, in the 3GPP performance evaluations, it is of good practice to consider 3D antenna patterns, where the main beam is mechanically and/or electrically tilted downwards to improve the signal power as well as to reduce the inter-cell interference [5], [6].
- *A Multi-antenna and/or multi-BS joint transmission framework:* In SG analyses, each BS/UE is usually equipped with one omni-directional antenna for simplicity. However, in the 3GPP performance evaluations, it is usual to consider multi-antenna transmissions [5], even with an enhancement of multi-BS cooperation [19]–[21].
- *A non-uniform distribution of BSs with some constraints on the minimum BS-to-BS distance:* In SG analyses, BSs are usually assumed to be uniformly deployed in the interested network area. However, in the 3GPP performance evaluations, small cell clusters are often considered, and it is forbidden to place any two BSs too close to each other [5]. Such assumption is in line with the realistic network planning to avoid strong inter-cell interference. It is interesting to note that several recent studies are looking at this aspect from difference angles [22]–[24]. In particular, a deterministic hexagonal grid network model [7] might be useful for the analysis. More specifically, we can construct an idealistic BS deployment on a perfect hexagonal lattice, and then we can perform a network analysis on such BS deployment to extract an upper-bound of the SINR performance. Note that the BS deployment on a hexagonal lattice leads to an upper-bound performance because BSs are evenly distributed in the network scenario, and thus very strong interference due to close proximity is precluded in the analysis [7]. Illustration of such hexagonal grid network is provided in Fig. 4.

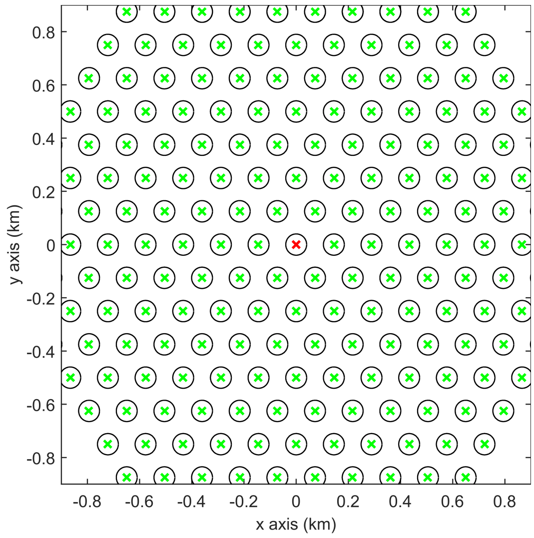

Fig. 4. Illustration of the ideal BS deployment in a hexagonal grid network.

Finally, it is very important to point out that even if an analysis can treat all the assumptions in Table I, a non-negligible gap may still exist between the analytical results and the performance results in reality, because of the following non-tractable factors [5]:

- non-full-buffer traffic
- non-linear channel measurement errors
- imperfect channel state information (CSI)
- hybrid automatic repeat request (HARQ) processes
- UE misreading of control signalling
- discrete modulation and coding schemes
- UE mobility and handover procedures, and so on.

Hence, in the context of the performance analysis for UDNs, a high priority should be given to identifying the performance trends qualitatively, rather than improving the numerical results quantitatively.

VII. Conclusion

In this paper, we have conducted a performance evaluation of UDNs, and identified which modelling factors really matter in theoretical analyses. From our study, we have identified that **3 factors/models have a major impact on the performance of UDNs**, and they should be considered when performing theoretical analyses:

- a multi-piece path loss model with LoS/NLoS transmissions;
- a non-zero antenna height difference between BSs and UEs;

- a finite BS/UE density.

In contrast, we have found that the following **4 factors/models have a minor impact on the performance of UDNs**, i.e., change the results quantitatively but not qualitatively, and thus their incorporation into theoretical analyses is less urgent:

- a general multi-path fading model based on Rician fading;
- a correlated shadow fading model;
- a BS density dependent transmission power;
- a deterministic BS/user density.

Finally, there are **3 factors/models for future study**:

- a BS vertical antenna pattern;
- multi-antenna and/or multi-BS joint transmissions;
- a non-uniform distribution of BSs.

Our conclusions can guide researchers to down-select the assumptions in their theoretical analyses, so as to avoid unnecessarily complicated results, while still capturing the fundamentals of UDNs in a meaningful way.

REFERENCES

[1] CISCO, "Cisco visual networking index: Global mobile data traffic forecast update (2015-2020)," Feb. 2016.

[2] D. López-Pérez, M. Ding, H. Claussen, and A. Jafari, "Towards 1 Gbps/UE in cellular systems: Understanding ultra-dense small cell deployments," *IEEE Communications Surveys Tutorials*, vol. 17, no. 4, pp. 2078–2101, Jun. 2015.

[3] 3GPP, "TR 36.872: Small cell enhancements for E-UTRA and E-UTRAN - Physical layer aspects," Dec. 2013.

[4] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: Potentials and challenges," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.

[5] 3GPP, "TR 36.828: Further enhancements to LTE Time Division Duplex for Downlink-Uplink interference management and traffic adaptation," Jun. 2012.

[6] Spatial Channel Model AHG, "Subsection 3.5.3, Spatial Channel Model Text Description V6.0," Apr. 2003.

[7] J. Andrews, F. Baccelli, and R. Ganti, "A tractable approach to coverage and rate in cellular networks," *IEEE Transactions on Communications*, vol. 59, no. 11, pp. 3122–3134, Nov. 2011.

[8] H. S. Dhillon, R. K. Ganti, F. Baccelli, and J. G. Andrews, "Modeling and analysis of K-tier downlink heterogeneous cellular networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 3, pp. 550–560, Apr. 2012.

[9] X. Zhang and J. Andrews, "Downlink cellular network analysis with multi-slope path loss models," *IEEE Transactions on Communications*, vol. 63, no. 5, pp. 1881–1894, May 2015.

[10] T. Bai and R. Heath, "Coverage and rate analysis for millimeter-wave cellular networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 2, pp. 1100–1114, Feb. 2015.

[11] M. D. Renzo, W. Lu, and P. Guan, "The intensity matching approach: A tractable stochastic geometry approximation to system-level analysis of cellular networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 5963–5983, Sep. 2016.

[12] M. Ding, D. López-Pérez, G. Mao, P. Wang, and Z. Lin, "Will the area spectral efficiency monotonically grow as small cells go dense?" *IEEE GLOBECOM 2015*, pp. 1–7, Dec. 2015.

[13] M. Ding, P. Wang, D. López-Pérez, G. Mao, and Z. Lin, "Performance impact of LoS and NLoS transmissions in dense cellular networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 3, pp. 2365–2380, Mar. 2016.

[14] M. Ding and D. Lopez Perez, "Please Lower Small Cell Antenna Heights in 5G," *arXiv:1611.01869 [cs.IT], to appear in IEEE Globecom 2016*, Nov. 2016.

[15] M. Ding, D. Lopez Perez, G. Mao, and Z. Lin, "Study on the idle mode capability with LoS and NLoS transmissions," *IEEE Globecom 2016*, pp. 1–6, Dec. 2016.

[16] S. Lee and K. Huang, "Coverage and economy of cellular networks with many base stations," *IEEE Communications Letters*, vol. 16, no. 7, pp. 1038–1040, Jul. 2012.

[17] 3GPP, "TR 36.814: Further advancements for E-UTRA physical layer aspects," Mar. 2010.

[18] M. Ding, M. Zhang, D. López-Pérez, and H. Claussen, "Correlated shadow fading for cellular network system-level simulations with wrap-around," *2015 IEEE International Conference on Communications (ICC)*, pp. 2245–2250, Jun. 2015.

[19] M. Ding, M. Zhang, H. Luo, and W. Chen, "Leakage-based robust beamforming for multi-antenna broadcast system with per-antenna power constraints and quantized cdi," *IEEE Transactions on Signal Processing*, vol. 61, no. 21, pp. 5181–5192, Nov. 2013.

[20] M. Ding, J. Zou, Z. Yang, H. Luo, and W. Chen, "Sequential and incremental precoder design for joint transmission network mimo systems with imperfect backhaul," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 6, pp. 2490–2503, Jul. 2012.

[21] M. Ding and H. Luo, *Multi-point Cooperative Communication Systems: Theory and Applications*. Springer, 2013.

[22] A. Al-Hourani, R. J. Evans, and K. Sithamparanathan, "Nearest neighbour distance distribution in hard-core point processes," *arXiv:1606.03695 [cs.IT]*, Jun. 2016.

[23] C. Choi, J. O. Woo, and J. G. Andrews, "Modeling a spatially correlated cellular network with strong repulsion," *arXiv:1701.02261 [cs.IT]*, Jan. 2017.

[24] M. Ding, D. López-Pérez, G. Mao, and Z. Lin, "Microscopic analysis of the uplink interference in FDMA small cell networks," *IEEE Trans. on Wireless Communications*, vol. 15, no. 6, pp. 4277–4291, Jun. 2016.