IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 10, 2020, accepted April 27, 2020, date of publication May 7, 2020, date of current version June 9, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2993199

On LOS Contribution to Ultra-Dense Network

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This work was supported in part by an Engineering and Physical Sciences Research Council Doctoral Training Partnership (EPSRC DTP) Award under Grant 2327091, and in part by the Toshiba Research Europe Ltd.

ABSTRACT Ultra-dense networks (UDNs) are widely considered as an effective solution to greatly improve coverage by shortening the communication distance between user equipments (UEs) and base stations (BSs). The reality of UDN is that line-of-sight (LOS) communication becomes more likely to occur but this desirable result also complicates the performance analysis of random UDNs and puts an obstacle on the design and optimization of UDNs. The aim of this paper is to derive analytical results that take into account the phenomenon of having mixed LOS and non line-of-sight (NLOS) links in UDNs. In particular, the use of an arbitrary shaped thinning process to model the LOS wireless links allowed us to investigate a wide set of scenarios for what concerns the desired and interfering power levels. Our contribution is an accurate approximation in closed form for the success content delivery probability (SCDP) that decouples the contribution from LOS and NLOS links. Simulation results corroborate the accuracy of the proposed approximation.

INDEX TERMS Line-of-sight, ultra dense network, stochastic geometry, success content delivery probability.

I. INTRODUCTION

Future-generation mobile wireless networks are foreseen to cope with an enormous number of content requests generated at the network edge [1]. Massive deployment of short-range, low-power small-cell base stations (SBSs) has been regarded as a promising way to unlock network performance and meet the stringent key performance indicators (KPIs), e.g., [2]–[4]. When this network densification is adopted, LOS links are more likely to occur, and more power is associated to the transmission of the content as both desired and interfering power.

Traditionally, small-scale channel fading is usually assumed to follow Rayleigh distribution. This model best describes the phenomenon of having multi-path signals bouncing off buildings and obstacles before reaching the destination, without a direct LOS path. However, this model is less accurate when it comes to UDN setup in which LOS paths tend to exist. When an LOS link is experienced, then a dominant component of the multi-path signal will affect the channel power fading experienced by the UE and so does the performance metric. According to the 3GPP, the probability of having an LOS link depends on specific cities' architectures [5].

While it is well understood that LOS channel paths improve performance, it is unfortunately extremely difficult to account for their contributions to the network performance [6]. In [7], the authors considered an exponential series approximation to model the non-central Chi-squared distribution which derives from LOS Rician faded channels. However, the approximation only holds for Rician faded channel power of the desired signal and Rayleigh faded signals from the interferers, and it fails to account for the interferers which also have LOS links. Furthermore, [8] employed a distance-dependent probabilistic rule to distinguish between LOS and NLOS communication channels, and a more suitable approximation of the interference term was proposed by approximating the resulting non-homogeneous Poisson point processes (PPPs) from the application of the distance-dependent LOS model with an homogeneous counterpart. The limitation of this result is nevertheless that the approximation is complex and unable to be used to gain insight for network optimization. Moreover, joint transmission (JT) or any form of cooperative transmission from SBSs which has become an essential feature for UDNs [9] was not considered. Technically speaking, the mathematical challenge to account

The associate editor coordinating the review of this manuscript and approving it for publication was Adnan Kavak.

for Rician LOS channel paths is to handle the Bessel function of the first kind in the channel power distribution [10]. There is a pressing need to analytically quantify network metrics such as success content delivery probability (SCDP) for UDNs with a mixture of LOS and NLOS links that could help optimize network parameters such as content caching probability, SBS spatial density, and etc. [11], which motivates our work.

In this paper, our objective is to consider a more realistic scenario where both the desirable links and interference links can come from LOS and NLOS paths randomly. We focus on analyzing the SCDP performance of the UDN using JT in this scenario. Our contribution is an approximation for the SCDP for the mixed LOS/NLOS scenarios by separating the contributions of a full NLOS network and that from an LOS network. The proposed approximation can be interpreted as a correction factor for previous results which only account for Rayleigh distributed small-scale channel fading. By means of close form derivations, the access to some key network parameters is uncovered and the relations among those variables that mostly affect the LOS components are revealed. Our model permits the use of any arbitrary LOS probability function, and the supporting simulated results show the tightness of the proposed approximation over a wide set of LOS probability functions.

The remainder of this paper is organized as follows. Section II introduces our UDN model with JT under the framework of stochastic geometry. Our approximation of the SCDP is provided in Section III. Section IV then provides our numerical results. Finally, we conclude the paper in Section V.

II. STOCHASTIC UDN MODEL

A. NETWORK MODEL

Let us consider a heterogeneous network (HetNet) in which a layer of densely populated SBSs is placed on top of a tier of macro base stations (MBSs) serving the UEs in the downlink. The spatial deployment of SBS follows a homogeneous PPP ϕ^S of intensity function λ^S while the MBS tier stands as a homogeneous PPP ϕ^M of intensity function λ^M. These pieces of equipment are supposed to respond to the requests of the UEs, spatially modeled as an independent homogeneous PPP ϕ^U with intensity function λ^U. The concept of a typical user has been employed to average the performance of the whole network by considering a single user placed at the origin of the two dimensional Euclidean network space.

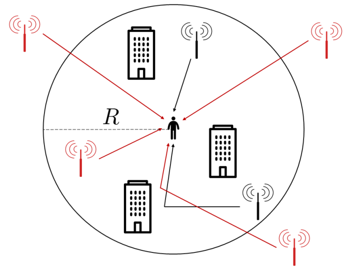

FIGURE 1. Visual representation of the network model, with interfering power indicated in red and desired power from the cooperating set K_f in black.

Time is split into frames, within which UEs generate their content request. The contents are assumed to have unit length and be drawn from a wordbook of size F files. Each file has a popularity $\hat{p}_f$ computed as a zipf-like distributed variable with skewness factor ζ. Without loss of generality, we consider the set of popularity coefficients $\{\hat{p}_1, \hat{p}_2, \ldots, \hat{p}_F\}$ in decreasing order. SBSs serve as caching nodes to deliver contents to the UEs with shorter distances. Each SBS has a limited cache size $M \ll F$ and each content has a caching probability p_f in such a way that the constraint $\sum_{f=1}^{F} p_f = M$ is respected. Eqs. (1) and (2), as shown at the bottom of this page.

B. CONTENT REQUEST AND DELIVERY

Each content request is first passed to the SBSs over a two dimensional Euclidean ball $\mathcal{B}(0, R)$, centered at the origin of the network space of radius R. If a hit-cache is experienced, the content can be directly transmitted from the SBSs at the

$$\gamma_f^S = \frac{\left|\sum_{k\in\phi_f^{S,nL}\cap\mathcal{B}(0,R)} h_k r_k^{-\alpha/2} + \sum_{k\in\phi_f^{S,L}\cap\mathcal{B}(0,R)} h'_k r_k^{-\alpha/2}\right|^2}{\sum\limits_{i\in\phi_{-f}^{S,nL}\cap\mathcal{B}(0,R)} |h_i|^2\, r_i^{-\alpha} + \sum\limits_{i\in\phi_{-f}^{S,L}\cap\mathcal{B}(0,R)} \left|h'_i\right|^2 r_i^{-\alpha} + \sum\limits_{i\in\phi^{S,nL}\cap\mathcal{B}(R,\infty)} |h_i|^2\, r_i^{-\alpha} + \sum\limits_{i\in\phi^{S,L}\cap\mathcal{B}(R,\infty)} \left|h'_i\right|^2 r_i^{-\alpha} + \sum\limits_{i\in\phi^{M,nL}} |h_i|^2 r_i^{-\alpha} + \sum\limits_{i\in\phi^{M,L}} \left|h'_i\right|^2 r_i^{-\alpha} + W} \tag{1}$$

$$\gamma^M = \begin{cases} \dfrac{|h_k|^2\, r_k^{-\alpha}}{\sum\limits_{i\in\phi^{S,nL}} |h_i|^2\, r_i^{-\alpha} + \sum\limits_{i\in\phi^{S,L}} \left|h'_i\right|^2\, r_i^{-\alpha} + \sum\limits_{i\in\phi^{M,nL}\setminus\mathcal{B}(\bar{r},\infty)} |h_i|^2\, r_i^{-\alpha} + \sum\limits_{i\in\phi^{M,L}\setminus\mathcal{B}(\bar{r},\infty)} \left|h'_i\right|^2\, r_i^{-\alpha} + W}, & \text{if NLOS} \quad (2a) \\[2ex] \dfrac{\left|h'_k\right|^2\, r_k^{-\alpha}}{\sum\limits_{i\in\phi^{S,nL}} |h_i|^2\, r_i^{-\alpha} + \sum\limits_{i\in\phi^{S,L}} \left|h'_i\right|^2\, r_i^{-\alpha} + \sum\limits_{i\in\phi^{M,nL}\setminus\mathcal{B}(\bar{r},\infty)} |h_i|^2\, r_i^{-\alpha} + \sum\limits_{i\in\phi^{M,L}\setminus\mathcal{B}(\bar{r},\infty)} \left|h'_i\right|^2\, r_i^{-\alpha} + W}, & \text{if LOS} \quad (2b) \end{cases}$$

network edge. In case multiple hit-caches are experienced, this means several SBSs have the content to serve the request and a non-coherent JT scheme over those SBSs is performed to transmit the same required content over the same portion of bandwidth [12], [13]. It is reasonable to impose a practical limit on the maximum number of cooperating SBS nodes for JT, say $K_f^{\max}$ for transmission of content f. When the request experiences a missed-cache, the closest MBS is responsible to deliver the content. In this case, for simplicity, we consider the MBS to be able to meet all the possible content requests, with no extra costs in terms of latency and power consumption.

The total bandwidth is set to be B [MHz] and the performance for each content delivery is quantified by a target bit-rate ρ which is the same for all users and all contents. According to the number of simultaneous distinct content requests forwarded to a single MBS or a set of SBSs, i.e., user-load, the whole bandwidth B is equally split into smaller bands to serve the requests, following a frequency-division multiple-access (FDMA) scheme. The available power at the SBS and MBS is, respectively, given by $P^S = 26$ [dBm] and $P^M = 46$ [dBm] while the thermal noise power stands at $W = -174$ [dBm]. To perform the content transmission of a generic f-th content over the same portion of bandwidth, the available bandwidth for the transmission is split by the user-load $\Xi_f^S = \max\{\xi_1, \ldots, \xi_{K_f}\}$, where ξ_k stands as the user-load experienced by the k-th SBS from the set of $K_f \leq K_f^{\max}$ cooperating nodes. Similarly, Ξ_f^M indicates the user-load of the closest MBS. At the typical user, the averaged target SCDP over the whole wordbook is given by

$$\mathrm{SCDP} = \sum_{f=1}^{F} \hat{p}_f \left(a_f \underbrace{\Pr\left(\gamma_f^S > \bar{\rho}_f^S\right)}_{\Gamma_f^S} + (1-a_f) \underbrace{\Pr\left(\gamma^M > \bar{\rho}_f^M\right)}_{\Gamma_f^M} \right), \tag{3}$$

where $a_f = (1 - e^{-\lambda^S p_f \pi R^2})$ is the probability there is at least one SBS that has cached the required content within $\mathcal{B}(0, R)$, with Γ_f^S and Γ_f^M respectively standing as the SCDP when a hit-cache or a missed-cache are experienced, and finally with $\bar{\rho}_f^S = 2^{\frac{\rho}{B}\Xi_f^S} - 1$ and $\bar{\rho}_f^M = 2^{\frac{\rho}{B}\Xi_f^M} - 1$ which stand as the signal-to-interference plus noise ratio (SINR) thresholds. Indicating the NLOS and LOS channel fading respectively as nL and L, and using *in* and *out* to refer to the nodes within and outside the Euclidean ball $\mathcal{B}(0, R)$, we can write the SINR from the cooperating SBS nodes as

$$\gamma_f^S = \frac{D_f^S}{\left(\begin{array}{l} I_f^{S,in,nL} + I_f^{S,in,L} + I^{S,out,nL} \\ + I^{S,out,L} + I^{M,nL} + I^{M,L} + W \end{array} \right)}, \tag{4}$$

and the SINR from the closest MBS as

$$\gamma^M = \frac{D^M}{I^{S,nL} + I^{S,L} + I^{M,nL} + I^{M,L} + W}. \tag{5}$$

The extended versions are reported in (1), (2a) and (2b), where the coefficients h and h' indicate, respectively, the Rayleigh and Rician fading channel coefficients which follow a circularly symmetric zero-mean unit-variance Gaussian distribution $h \sim \mathcal{CN}(0, 1)$ and a non zero-mean non unit-variance Gaussian distribution h'. In (2a) and (2b), the $\bar{r}$ indicates the distance of the closest MBS from the typical user and the interfering pattern is determined by those SBSs that have at least one mobile users within their content searching area and by all the MBSs in the circular sector $\mathcal{B}(\bar{r}, \infty)$. In (1), the interfering pattern is determined by the union of the set of SBS edge nodes with at least one user within their content searching area, the set of those edge nodes that experience a missed-cache within $\mathcal{B}(0, R)$ and from the MBS tier as if they are all active. Apparently, when a number of cooperating edge nodes exceeds $K_f^{\max}$, the two interfering regions are determined by $\bar{r} \leq R$, with $\bar{r}$ denoting the distance of the farthest cooperating SBS edge node.

The set of nodes $\phi_{-f}^{S,[L,nL]}$ in (1) refers respectively to those SBSs with a LOS and NLOS link where the f-th content has not been cached and that are associated to at least one UE. For Rician fading, the mean and variance of the channel modelling Gaussian process depend on the k-factor, which is the ratio of the signal power of the dominant component over the scattered power. In particular, the mean and variance of the generating Gaussian random variables of h' are, respectively, $\mu_h = (k/(k+1))^{1/2}$ and $\sigma_h = (2(k+1))^{-1/2}$. The large-scale power fading is modeled by $r^{-\alpha} = P^{[S,M]} \max(d_0, r^{-\alpha})$, with the reference distance chosen as $d_0 = 1$ [m], α as the standard single-slope path-loss exponent and $P^{[S,M]}$ which stands as the transmitting power for SBS and MBS, respectively. For ease of subsequent analysis, we refer to $K_f^{S,L}$ and $K_f^{S,nL}$, respectively, as the random number of cooperating nodes whose channel links experience LOS and NLOS small-scale channel fading, namely, the snapshots of the two PPPs $\phi_f^{S,L} \cap \mathcal{B}(0, R)$ and $\phi_f^{S,nL} \cap \mathcal{B}(0, R)$, after having applied the LOS thinning function to the processes.

C. THE LOS THINNING FUNCTION

A space dependent thinning transformation is applied to ϕ^S and ϕ^M, in order to model the spatial displacement of LOS communications. Given a realization of the PPP, a probabilistic rule $p(r) \in [0, 1]$ is applied to each atom of the process. The modeling non-homogeneous PPP for LOS communications $\phi^{S,L}$ has therefore an intensity function $p(r)\lambda^S$, with r which stands as the user link-distance. Clearly, the intensity function of NLOS content transmission is $(1 - p(r))\lambda^S$. The independent thinning rule $p(r)$ is strictly correlated to the surrounding environment. We therefore expect this function to dramatically change according to the city's architecture. Empirical measures to establish the shape of $p(r)$ are often limited to specific architectures and unable to generalize and adapt to dynamic environments [5]. We can make some observations over the hypothetical nature of this function, to have a tool to arbitrarily control the signal shadowing. It is necessary to point out that for the sake of our investigation, we are interested in making use of a distance-based probability density function which can be arbitrarily changed to evaluate both open and narrow spaces. The thinning rule employed in our model is

$$p(r) = e^{-\frac{(r-\mu)^2}{2\sigma^2}}, \tag{6}$$

with the scaling factor $\sqrt{2\pi\sigma^2}$ being applied to the original Gaussian-like function to allow $p(r \to 0) \to 1$.

From (6), we consider $\mu = 0$ as we account for the typical user located at the origin of a two dimensional Euclidean space and we vary the factor σ^2 to mimic the obstruction effect on our performance metric. The adopted function can easily be changed with any arbitrary LOS probability rule with no changes to be applied to our model.

III. OUR MAIN RESULTS

Here, we present our approximations for Γ_f^S and Γ_f^M. Due to the property of a sum of normal distributed random variables, the desired power term in (1) can be obtained as

$$\begin{aligned} D_f^S &= \left| \sum_{k \in K_f^{S,nL}} h_k r_k^{-\alpha/2} + \sum_{k \in K_f^{S,L}} h'_k r_k^{-\alpha/2} \right|^2 \\ &= \left|H + H'\right|^2 = \left|\bar{H}\right|^2, \end{aligned}$$

where $H \sim \mathcal{CN}(0, \sum_{k\in K_f^{S,nL}} r_k^{-\alpha})$, and $H' = X' + iY'$ with $X' \sim \mathcal{N}(\mu_h \sum_{k\in K_f^{S,L}} r_k^{-\alpha/2}, \sigma_h^2 \sum_{k\in K_f^{S,L}} r_k^{-\alpha})$ and $Y' \sim \mathcal{N}(0, \sigma_h^2 \sum_{k\in K_f^{S,L}} r_k^{-\alpha})$. Consequently, $\bar{H} = \bar{X} + i\bar{Y}$ where

$$\bar{X} \sim \mathcal{N}\Bigg(\underbrace{\mu_h \sum_{k\in K_f^{S,L}} r_k^{-\alpha/2}}_{\mu_L}, \sigma_h^2 \sum_{k\in K_f^{S,L}} r_k^{-\alpha} + \frac{1}{2}\sum_{k\in K_f^{S,nL}} r_k^{-\alpha}\Bigg),$$

$$\bar{Y} \sim \mathcal{N}\Bigg(0, \sigma_h^2 \sum_{k\in K_f^{S,L}} r_k^{-\alpha} + \frac{1}{2}\sum_{k\in K_f^{S,nL}} r_k^{-\alpha}\Bigg).$$

We can rewrite the variance of $\bar{X}$ and $\bar{Y}$ as

$$\begin{aligned} &\mathbb{V}_{[\bar{X},\bar{Y}]} \\ &= \frac{1}{2}\Bigg(\left(1 - 1 + \frac{1}{k+1}\right)\sum_{k\in K_f^{S,L}} r_k^{-\alpha} + \sum_{k\in K_f^{S,nL}} r_k^{-\alpha}\Bigg) \\ &= \frac{1}{2}\Bigg(\underbrace{\sum_{k\in K_f^{S,L}} r_k^{-\alpha} + \sum_{k\in K_f^{S,nL}} r_k^{-\alpha}}_{\sigma_P^2 = \sum_{k\in\phi_f\cap\mathcal{B}(0,R)} r_k^{-\alpha}} - \frac{k}{k+1}\underbrace{\sum_{k\in K_f^{S,L}} r_k^{-\alpha}}_{\sigma_L^2}\Bigg), \end{aligned} \tag{7}$$

where the scaling factor for σ_L^2 can be written as μ_h^2, following the definition of the mean for the Gaussian distributed modelling variable for Rician distributed channel coefficient h'. Therefore the desired power can finally be written in terms of non-complex, zero-mean Gaussian random variables as

$$\begin{aligned} D_f^S &= \left|\bar{H}\right|^2 = \left(\bar{X}^2 + \bar{Y}^2\right) = \Big(\underbrace{\sigma_P^2(X^2+Y^2)}_{D_f^{S,nL}} \\ &\underbrace{-\mu^2\sigma_L^2\left(X^2+Y^2\right) + 2\mu_L\mu\sqrt{\sigma_P^2 - \mu^2\sigma_L^2}X + \mu_L^2\mu^2}_{\Delta D_f^S | D_f^{S,nL}}\Big), \end{aligned} \tag{8}$$

in which $X \sim Y \sim \mathcal{N}(0, 1/2)$. Note in (8) that we have decoupled the term that describes the desired power from a full NLOS network $D_f^{S,nL}$ from the contribution of the LOS components indicated with $\Delta D_f^S | D_f^{S,nL}$. It can be seen that the term σ_P^2 can be interpreted as the sum of the power attenuation factors of the cooperating SBSs, with no distinction made on the experienced NLOS/LOS small-scale channel fading. In other words, this term coincides with the sum of the contributions of the power attenuation for the desired content as if the network is only composed by NLOS links.

The interfering power from the SBSs in (4) is now studied in terms of non-complex normal random variables $X \sim Y \sim \mathcal{N}(0, 1/2)$. From the derivation in Appendix and shortly reported in the following for the couples of PPPs $\phi_{-f}^{S,nL} \cap \mathcal{B}(0,R)$, $\phi_{-f}^{S,L} \cap \mathcal{B}(0,R)$ and $\phi^{S,nL} \cap \mathcal{B}(R,\infty)$, $\phi^{S,L} \cap \mathcal{B}(R,\infty)$

$$\begin{aligned} &I_f^{S,in,nL} + I_f^{S,in,L} + I^{S,out,nL} + I^{S,out,L} \\ &= \underbrace{\sum_{i\in\phi_{-f}^S\cap\mathcal{B}(0,R)} (X^2+Y^2) r_i^{-\alpha}}_{I_f^{S,in}} + \underbrace{\sum_{i\in\phi^S\cap\mathcal{B}(R,\infty)} (X^2+Y^2) r_i^{-\alpha}}_{I^{S,out}} \\ &\quad + \underbrace{\sum_{i\in\phi_{-f}^{S,L}\cap\mathcal{B}(0,R)} \left(-\frac{k}{k+1}(X^2+Y^2) + \frac{2\sqrt{k}}{k+1}X + \frac{k}{k+1}\right) r_i^{-\alpha}}_{\Delta I_f^{S,in} | I_f^{S,in}} \\ &\quad + \underbrace{\sum_{i\in\phi^{S,L}\cap\mathcal{B}(R,\infty)} \left(-\frac{k}{k+1}(X^2+Y^2) + \frac{2\sqrt{k}}{k+1}X + \frac{k}{k+1}\right) r_i^{-\alpha}}_{\Delta I^{S,out} | I^{S,out}}, \end{aligned} \tag{9}$$

where the terms $I_f^{S,in}$ and $I^{S,out}$ do not distinguish among NLOS/LOS small-scale channel fading and with $\Delta I_f^{S,in} | I_f^{S,in}$

TABLE 1. Some key model parameters.

Variable	Description
μ_h	Mean for LOS small-scale channel fading
σ_h	Standard deviation for LOS small-scale channel fading
μ_L	Sum of amplitude losses LOS components
σ_L^2	Sum of power losses LOS components
σ_P^2	Sum of power losses full NLOS network
σ	Control parameter for LOS thinning function $p(r)$

and $\Delta I^{S,out}|I^{S,out}$, respectively, standing for the conditioned terms that describe the LOS contributions. Similarly, for what concerns the interference from the MBS in (4), we can apply the same intuitions in Appendix for $\phi^{M,nL}$ and $\phi^{M,L}$ to obtain

$$I^{M,nL} + I^{M,L} = \underbrace{\sum_{i\in\phi^M} (X^2+Y^2) r_i^{-\alpha}}_{I^M} + \underbrace{\sum_{i\in\phi^{M,L}} \left(-\frac{k}{k+1}(X^2+Y^2) + \frac{2\sqrt{k}}{k+1}X + \frac{k}{k+1}\right) r_i^{-\alpha}}_{\Delta I^M|I^M}. \quad (10)$$

A. THE APPROXIMATIONS

The term γ_f^S can now be rewritten by isolating the contribution given by a full NLOS network from the contribution given by LOS communications. We therefore obtain that an approximation for γ_f^S can be attained by considering the conditioned terms to be independent from their respective conditioning factors. Thus, the SINR γ_f^S is approximated as

$$\gamma_f^S \approx \tilde{\gamma}_f^S = \frac{D_f^{S,nL} + \Delta D_f^S}{I_f^{S,in} + I^{S,out} + \Delta I_f^{S,in} + \Delta I^{S,out} + I^M + \Delta I^M + W}. \quad (11)$$

This allows us to uncondition the SCDP independently as a full NLOS network, and separately account for the LOS contribution. Note that the conditioning factor on the terms $\Delta I_f^{S,in}|I_f^{S,in}$, $\Delta I^{S,out}|I^{S,out}$ and $\Delta I^M|I^M$ refers to the Gaussian distributed random variables X, Y, and the point processes $\phi_f^{S,L} \cap \mathcal{B}(0,R)$, $\phi_f^{S,L} \cap \mathcal{B}(R,\infty)$ and $\phi^{M,L}$.

Similarly, for what concerns the desired power in the SINR γ^M in (2b), we can write, following the guidelines in Appendix.

$$D^M = |h'|^2 r^{-\alpha} = \underbrace{\left(X^2+Y^2\right) r_i^{-\alpha}}_{D^{M,nL}} + \underbrace{\left(-\frac{k}{k+1}(X^2+Y^2) + \frac{2\sqrt{k}}{k+1}X + \frac{k}{k+1}\right) r_i^{-\alpha}}_{\Delta D^M}. \quad (12)$$

Note that for (2a), no LOS contribution is experienced for the term of the desired power and the result would coincide with the $D^{M,nL}$ component in (12).

We now apply the separation of the full NLOS term to the interference perceived when the closest MBS is transmitting as previously obtained, which gives, following the result in Appendix for $\phi^{S,nL}$, $\phi^{S,L}$ and $\phi^{M,nL} \setminus \mathcal{B}(\bar{r},\infty)$, $\phi^{M,L} \setminus \mathcal{B}(\bar{r},\infty)$)

$$I^{S,L} + I^{S,nL} + I^{M,nL} + I^{M,L} = \underbrace{\sum_{i\in\phi^S} (X^2+Y^2) r_i^{-\alpha}}_{I^S} + \underbrace{\sum_{i\in\phi^M\setminus\mathcal{B}(\bar{r},\infty)} (X^2+Y^2) r_i^{-\alpha}}_{I^M} + \underbrace{\sum_{i\in\phi^{S,L}} \left(-\frac{k}{k+1}(X^2+Y^2) + \frac{2\sqrt{k}}{k+1}X + \frac{k}{k+1}\right) r_i^{-\alpha}}_{\Delta I^S|I^S} + \underbrace{\sum_{i\in\phi^{M,L}\setminus\mathcal{B}(\bar{r},\infty)} \left(-\frac{k}{k+1}(X^2+Y^2) + \frac{2\sqrt{k}}{k+1}X + \frac{k}{k+1}\right) r_i^{-\alpha}}_{\Delta I^M|I^M}, \quad (13)$$

We claim that the same approximation is valid for γ^M when the closest MBS is associated to the typical user. Then,

$$\gamma^M \approx \tilde{\gamma}^M = \frac{D^{M,nL} + \Delta D^M}{I^S + \Delta I^S + I^M + \Delta I^M + W}, \quad (14)$$

with $\Delta D^M = 0$ in case the wireless link is NLOS as in (2a). We can finally work out the approximation for SCDP with $\Gamma_f^S \approx \bar{\Gamma}_f^S$ and $\Gamma_f^M \approx \bar{\Gamma}_f^M$, respectively, as

$$\bar{\Gamma}_f^S = \underbrace{\mathbb{E}\left[\exp\left(-\frac{\bar{\rho}_f^S}{\sigma_P^2}(I_f^{S,in} + I^{S,out} + I^M + W)\right)\right]}_{\text{typical NLOS network}} \times \underbrace{\mathbb{E}\left[\exp\left(-\frac{\bar{\rho}_f^S}{\sigma_P^2}(\Delta I_f^{S,in} + \Delta I^{S,out} + \Delta I^M) + \frac{\Delta D_f^S}{\sigma_P^2}\right)\right]}_{\text{LOS contribution}}, \quad (15)$$

$$\bar{\Gamma}_f^M = \underbrace{\mathbb{E}\left[\exp\left(-\frac{\bar{\rho}_f^M}{\bar{r}^{-\alpha}}\left(I^S + I^M + W\right)\right)\right]}_{\text{typical NLOS network}} \times \underbrace{\mathbb{E}\left[\exp\left(-\frac{\bar{\rho}_f^M}{\bar{r}^{-\alpha}}\left(\Delta I^S + \Delta I^M\right) + \frac{\Delta D^M}{\bar{r}^{-\alpha}}\right)\right]}_{\text{LOS contribution}}. \quad (16)$$

At this point, a full definition of the approximate SCDP from (3) can be attained as

$$\text{SCDP} \approx \overline{\text{SCDP}} = \sum_f^F \hat{p}_f \left(a_f \bar{\Gamma}_f^S + (1-a_f)\bar{\Gamma}_f^M\right). \quad (17)$$

It can be seen that the probabilities $\bar{\Gamma}_f^S$ and $\bar{\Gamma}_f^M$ can assume values higher than one, due to the LOS contribution. If this happens, we would end up with a probability higher than one. Therefore, during future empirical simulations, we have to respect the support of the exponentially distributed random variable $[0,\infty]$ and fix the probability to one when the argument of the exponential function assumes positive values following $\bar{\Gamma}_f^S = \min(\bar{\Gamma}_f^S, 1)$ and $\bar{\Gamma}_f^M = \min(\bar{\Gamma}_f^M, 1)$.

In the following, we show that our solution is able to enhance the understanding of the effects of LOS communications. The expected value over the random variables X and Y (thus the channel small-scale fading) for the LOS contribution of the desired power of $\bar{\Gamma}_f^S$ can be obtained as

$$\mathbb{E}_{X,Y}\left[\exp\left(\frac{\Delta D_f^S}{\sigma_P^2}\right)\right] = \exp\left(\frac{2\mu_L^2\mu^2}{\mu^2\sigma_L^2+\sigma_P^2}\right)\frac{\sigma_P^2}{\sigma_P^2+\mu^2\sigma_L^2}. \quad (18)$$

For what concerns the interfering LOS contribution of $\bar{\Gamma}_f^S$, the Laplace transform and probability generating functional (pgf) can be employed. We therefore obtain

$$\mathbb{E}\left[\exp\left(-\frac{\bar{\rho}_f^S}{\sigma_P^2}\left(\Delta I_f^{S,in}+\Delta I^{S,out}+\Delta I^M\right)\right)\right] = \left.\begin{pmatrix}\mathcal{L}^{\Delta S,in}\left(s,0,R,\phi_{-f}^{S,L}\cap\mathcal{B}(0,R)\right)\\ \times\mathcal{L}^{\Delta S,out}\left(s,R,\infty,\phi^{S,L}\cap\mathcal{B}(R,\infty)\right)\\ \times\mathcal{L}^{\Delta M}\left(s,0,\infty,\phi^{M,L}\right)\end{pmatrix}\right|_{s=\frac{\bar{\rho}_f^S}{\sigma_P^2}}, \quad (19)$$

where $\mathcal{L}^{\Delta S,in}$, $\mathcal{L}^{\Delta S,out}$ and $\mathcal{L}^{\Delta M}$ can be drawn from the Laplacian over the LOS interfering contribution in (21) (see top of next page). The NLOS term in (15) can easily be retrieved as

$$\mathbb{E}\left[\exp\left(-\frac{\bar{\rho}_f^S}{\sigma_P^2}(I_f^{S,in}+I^{S,out}+I^M+W)\right)\right] = e^{-\frac{\bar{\rho}_f^S}{\sigma_P^2}W} \times \left.\begin{pmatrix}\mathcal{L}^{S,in}\left(s,0,R,\phi_{-f}^{S}\cap\mathcal{B}(0,R)\right)\\ \times\mathcal{L}^{S,out}\left(s,R,\infty,\phi^{S}\cap\mathcal{B}(R,\infty)\right)\\ \times\mathcal{L}^{M}\left(s,0,\infty,\phi^{M}\right)\end{pmatrix}\right|_{s=\frac{\bar{\rho}_f^S}{\sigma_P^2}}, \quad (20)$$

where $\mathcal{L}^{S,in}$, $\mathcal{L}^{S,out}$ and $\mathcal{L}^{M}$ are drawn from the Laplacian of the NLOS interfering terms in (22) (see top of next page). By replacing (18), (19) and (20) in (15), we have obtained the proposed approximation for $\bar{\Gamma}_f^S$. Eq (21) and (22), as shown at the bottom of this page. Similarly, the de-conditioned derivation from X and Y of the LOS contribution for the desired power in $\bar{\Gamma}_f^M$ can be computed to yield

$$\mathbb{E}_{X,Y}\left[\exp\left(\frac{\Delta D^M}{\bar{r}^{-\alpha}}\right)\right] = \exp\left(\frac{k\bar{r}^{-\alpha}(\bar{r}^{-\alpha}+1)}{k\bar{r}^{-\alpha}+k+1}\right) \times \frac{k+1}{k\bar{r}^{-\alpha}+k+1}. \quad (23)$$

In case the closest MBS does not experience an LOS link with the typical user, we would simply consider $\Delta D^M = 0$. For what concerns the LOS interfering contribution, we can apply the Laplace transform of the interference as

$$\mathbb{E}\left[\exp\left(-\frac{\bar{\rho}_f^M}{\bar{r}^{-\alpha}}(\Delta I^S+\Delta I^M)\right)\right] = \left(\mathcal{L}^{\Delta S}\left(s,0,\infty,\phi^{S,L}\right) \times \mathcal{L}^{\Delta M}\left(s,\bar{r},\infty,\phi^{M,L}\setminus\mathcal{B}(\bar{r},\infty)\right)\right)\Big|_{s=\frac{\bar{\rho}_f^M}{\bar{r}^{-\alpha}}}, \quad (24)$$

where $\mathcal{L}^{\Delta S}$ and $\mathcal{L}^{\Delta M}$ are obtained from the Laplacian in (21) with $\bar{r}$ standing as the distance of the closest serving MBS. Similarly, the interfering term of a typical NLOS network can be written as

$$\mathbb{E}\left[\exp\left(-\frac{\bar{\rho}_f^M}{\bar{r}^{-\alpha}}(I^S+I^M+W)\right)\right] = e^{-\frac{\bar{\rho}_f^M}{\bar{r}^{-\alpha}}W} \times \left(\mathcal{L}^{S}\left(s,0,\infty,\phi^{S}\right) \times \mathcal{L}^{M}\left(s,\bar{r},\infty,\phi^{M}\setminus\mathcal{B}(\bar{r},\infty)\right)\right)\Big|_{s=\frac{\bar{\rho}_f^M}{\bar{r}^{-\alpha}}}, \quad (25)$$

where $\mathcal{L}^S$ and $\mathcal{L}^M$ are obtained from (22).

By replacing (23), (24) and (25) in (16), we have derived our approximation $\bar{\Gamma}^M$. Note that in case the approximated terms in (11) and (14) were not considered, the derived SCDP in (15) and (16) would write as a non solvable integral which involves a modified Bessel function of the first kind as in [10]. Also, it is known that a closed-form solution for

$$\mathcal{L}^{\Phi,L}(s,a,b,\Phi) = \mathbb{E}\left[\exp\left(s\sum_{i\in\phi}\left(-\frac{k}{k+1}(X^2+Y^2)+\frac{2\sqrt{k}}{k+1}X+\frac{k}{k+1}\right)r_i^{-\alpha}\right)\right]$$
$$= \mathbb{E}\left[\prod_{i\in\phi}\exp\left(s\left(-\frac{k}{k+1}(X^2+Y^2)+\frac{2\sqrt{k}}{k+1}X+\frac{k}{k+1}\right)r_i^{-\alpha}\right)\right]$$
$$= \exp\left(-2\pi\lambda\left(\int_a^b\left(1-\frac{e^{\frac{ksr^{-\alpha}(sr^{-\alpha}+1)}{ksr^{-\alpha}+k+1}}(k+1)}{ksr^{-\alpha}+k+1}\right)rp(r)\,dr\right)\right) \quad (21)$$

$$\mathcal{L}^{\Phi,nL}(s,a,b,\Phi) = \mathbb{E}\left[\exp\left(s\sum_{i\in\phi}\left(X^2+Y^2\right)r_i^{-\alpha}\right)\right] = \mathbb{E}\left[\prod_{i\in\phi}\exp\left(s\left(X^2+Y^2\right)r_i^{-\alpha}\right)\right]$$
$$= \exp\left(-2\pi\lambda\int_a^b\left(1-\frac{1}{sr^{-\alpha}+1}\right)r\,dr\right) \quad (22)$$

jointly transmitted contents has not been found yet, even for the simple full NLOS network [13]–[15]. Thus, when maximizing the SCDP (or minimizing the outage probability) over some network parameters, an iterative solution is generally required to achieve a sub-optimal feasible set of decision variables. Based on our proposed approximation, existing solutions in the literature which aim to find sub-optimal network parameters can be updated by scaling the SCDP for a full NLOS network with the proposed LOS contribution as in (15) and (16).

B. NETWORK TRADE-OFF

From the approximated $\bar{\Gamma}_f^S$ and $\bar{\Gamma}_f^M$, some intuitions over the effects of LOS communications can be retrieved. Some preliminary insights can be obtained at this stage.

Conjecture 1: The limit for $k \to 0$ for the approximated SCDP in (17) results in a full NLOS network.

When we consider the limit to infinity of k, it can be seen that the mean and variance of the generating Gaussian random variables for the Rician distributed channel fading coefficient tend to $\mu_h \to 1$ and $\sigma_h^2 \to 0$. As a consequence, the channel power fading for the LOS link no longer acts like a random variable, due to the collapse of the variance.

Conjecture 2: The limit for $k \to \infty$ for the approximated SCDP in (17) conditioned on Rayleigh distributed small-scale channel power fading for the interference results in a scaling factor to be applied to the typical NLOS contribution in order to account the LOS for the desired power.

In particular, referring to **Conjecture 2**, the typical full NLOS SCDP terms in (15) and (16) have to be scaled, respectively, by

$$\lim_{k\to\infty}\left[\exp\left(\frac{2\mu_L^2\mu^2}{\mu^2\sigma_L^2+\sigma_P^2}\right)\frac{\sigma_P^2}{\sigma_P^2+\mu^2\sigma_L^2}\right] = \exp\left(\frac{2\mu_L^2}{\sigma_L^2+\sigma_P^2}\right)\frac{\sigma_P^2}{\sigma_P^2+\sigma_L^2}, \tag{26}$$

$$\lim_{k\to\infty}\left[\exp\left(\frac{k\bar{r}^{-\alpha}(\bar{r}^{-\alpha}+1)}{k\bar{r}^{-\alpha}+k+1}\right)\frac{k+1}{k\bar{r}^{-\alpha}+k+1}\right]=\frac{\exp\left(\bar{r}^{-\alpha}\right)}{\bar{r}^{-\alpha}+1}. \tag{27}$$

By means of **Conjecture 1** and **Conjecture 2**, we are able to understand the SCDP results for $k \in [0,\infty]$.

Some intuitions over the effects of LOS wireless links on the SCDP can be attained at this point. The LOS contribution from the cooperating edge nodes in (18) can be easily proved to be upper-bounded by the particular case in (26). However, the term (26) can be considered, especially under a UDN scenario, by the case that all the cooperating nodes experience LOS links. Thus, from (26), we can write

$$\exp\left(\frac{2\mu_L^2}{\sigma_L^2+\sigma_P^2}\right)\frac{\sigma_P^2}{\sigma_P^2+\sigma_L^2} \leq \frac{1}{2}\exp\left(\left(\frac{\mu_L}{\sigma_L}\right)^2\right)\Bigg|_{\sigma_P^2\to\sigma_L^2}. \tag{28}$$

It can be seen that the latest upper-bound on the LOS contribution from the set of cooperating nodes is exponentially dependent on the ratio of the received amplitude-to-power attenuation from the cooperating nodes. This quantity is therefore highly sensible on the chosen path-loss model. The result from **Conjecture 2** works as an upper-bound over the received LOS desired power. Therefore, we will employ this quantity in future sections to investigate the gap for a full NLOS network derived in **Conjecture 1**. Similar conclusions can be attained for what concerns the LOS contribution from the MBS, with the particular case for $k \to \infty$ employed as an upper-bound of the desired signal power.

C. EXTENSION TO DOUBLE-SLOPE PATH-LOSS MODEL

In this paper, we considered a single-slope path-loss model for simplicity sake. However, an extension to double or multi-slope path-loss model can be attained with minor changes applied to the previous derivations. To provide some guidelines to achieve this result, we consider a double-slope path-loss model. Consider the difference of path-loss coefficients as $\Delta\alpha = \alpha^{nL} - \alpha^L$, where α^{nL} and α^L stand respectively for the NLOS and LOS links. To introduce a double-slope path-loss in our model, it is necessary to change the scaling factor in (7) to $(r^{-\Delta\alpha} - r^{-\Delta\alpha} + \frac{1}{k+1})$ and to include this term inside the sum for the cooperating edge nodes with an LOS wireless link. As a result, we can decouple the derivation as a full NLOS and LOS contributions, as previously obtained.

IV. NUMERICAL RESULTS

In this section, numerical results are illustrated to demonstrate the validity of our SCDP approximation under various network parameters. We set $B = 40$ [MHz] for MBS and SBS, with a standard single-slope path-loss function of coefficient $\alpha = 3$, a transmitting power for SBS and MBS of, respectively, $P^S = 26$ [dBm] and $P^B = 43$ [dBm], and thermal noise power of $W = -174$ [dBm]. The wordbook and cache size are considered, respectively, as $F = 20$ and $M = 3$ with the skewness factor for contents' popularity set at $\zeta = 1$. The baseline densities for respectively the UEs, SBSs and MBSs spatial displacement are $\lambda^U = 10^{-4}$, $\lambda^S = 5 \times 10^{-4}$ and $\lambda^M = 10^{-6}$. The radius of the Euclidean ball is fixed at $R = 25$ [m], the maximum number of cooperating edge nodes is set at $K_f^{\max} = 3$ and the target bit-rate is set at $\rho = 2$ [Mbps]. The results are obtained by employing a uniform content (UC) caching strategy and we keep the same values herein reported unless specified otherwise.

A. VALIDATION AGAINST λ^S

In Fig. 2, results are provided to compare the target SCDP with the proposed approximation in (17), against the edge node density λ^S. For comparison purposes, the results for a full Rayleigh network together with **Conjecture 1** have been included to give an estimation of the existing gap between full NLOS and mixed Rayleigh/Rician networks. Results show that the proposed approximation matches with the exact result of the case of a full Rayleigh network when $k = 0$.

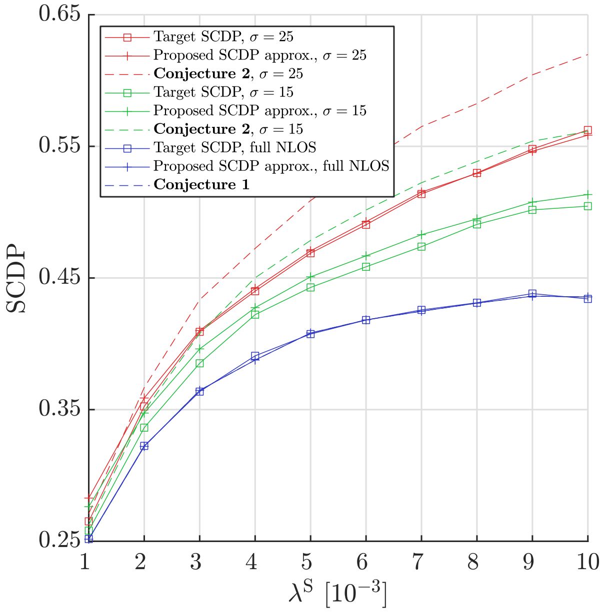

FIGURE 2. Target and approximated SCDP against λ^S.

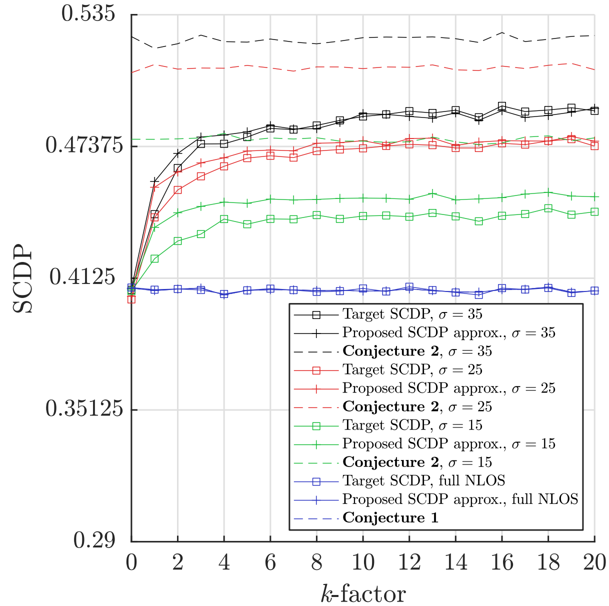

FIGURE 3. Target and approximated SCDP against Rician k-factor.

With a higher probability to encounter LOS links, results begin to see some gaps between the SCDP approximation and the exact result for $\sigma > 0$, as λ^S increases. However, the proposed approximation is largely accurate for the entire range of λ^S.

B. VALIDATION AGAINST RICIAN k-FACTOR

The power ratio between the LOS component and the shadowed multipaths plays an important role when addressing the SCDP. In Fig. 3, the target and approximated SCDP are investigated for different values of the Ricean k-factor. An initial increasing trend can be noticed as the Rician k-factor is incremented until the SCDP measure converges. As the k-factor increases the desired power benefits from the contribution from the cooperating nodes until it balances with the destructive contribution of the interferers. It can be seen from the results in **Conjecture 2** to stand on constantly higher values than the target and approximated SCDP measures. This is because the results from **Conjecture 2** are calculated for $k \to \infty$. These results work therefore as an upper limit of the measured SCDP when the interference is Rayleigh distributed, as per definition of **Conjecture 2**. The better performance obtained for higher values of σ derive from the higher percentage of experienced LOS wireless links, most of which are associated to the set of cooperating nodes. It can be seen that to better SINR conditions lower gap between the target and approximated SCDPs are obtained, revealing higher accuracy of the proposed approximation when better transmitting conditions are experienced. The experienced gap allows to have a visual feedback on the importance of considering a distance-based probabilistic rule when modeling the LOS wireless links. In this sense, the proposed approximation allows to better follow the target SCDP than other proposed methods.

C. EFFECTIVE BANDWIDTH AND USER DENSITY

In our network model, user density has a crucial impact on the available frequency bands and possibly our approximation. Our model catches the number of simultaneous content transmission by means of the terms $\bar{\rho}_f^S$ and $\bar{\rho}_f^M$ introduced in (3). Therefore, a study of how the proposed approximation performs according to the available bandwidth for each content transmission is essential. As we considered the transmission to the typical user to occur if the request is previously cached, each edge node has a maximum of M simultaneous content requests that can be simultaneously performed. In Fig. 4, we illustrate the experienced SCDP against λ^U. As expected, it can be seen that a decrease of the overall performance is experienced, as a consequence of the increasingly higher number of simultaneous content transmissions. The reduction of the available bandwidth for the single content transmission is observed to slightly increase the gap among the proposed approximation and the target SCDP.

D. MAXIMUM NUMBER OF COOPERATING NODES

Cooperation among nodes has been indicated as a promising strategy to achieve the performance standards of future mobile networks. It is important to have our proposed approximation to be as tight as possible as the maximum number of cooperating nodes increases. In general, due to the overhead necessary to synchronize JT, a maximum number of cooperating SBS edge nodes is generally fixed. In the following, we considered an increased radius for the content searching ball $\mathcal{B}(0, R)$ of $R = 35$ $[m]$ and SBS density of $\lambda^S = 10^{-3}$ such that the average number of cooperating nodes for content f stands as $\mathbb{E}\left[\left|\phi_f^S \cap (\mathcal{B}(0,R))\right|\right] = p_f \lambda^S \pi R^2 \approx 5.77$. The obtained numerical results are reported in Fig. 5. We see that our proposed approximation follows the target measure, especially at higher σ. When low values of $K^{\max}$ are considered,

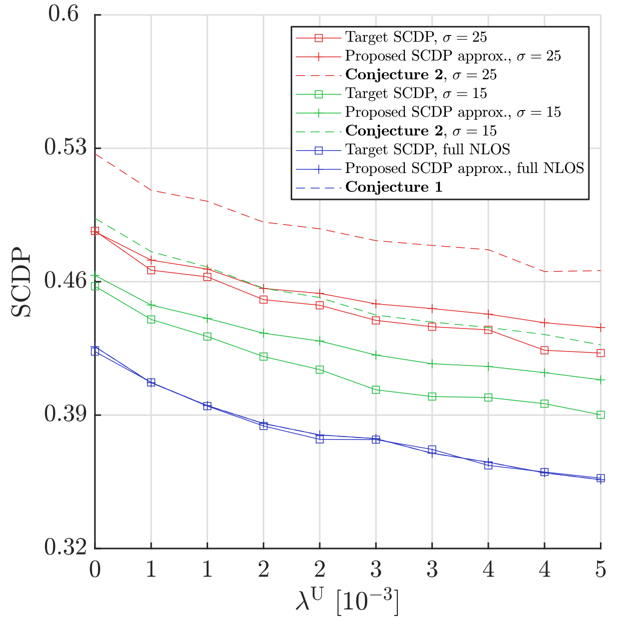

FIGURE 4. Target and approximated SCDP against λ^U.

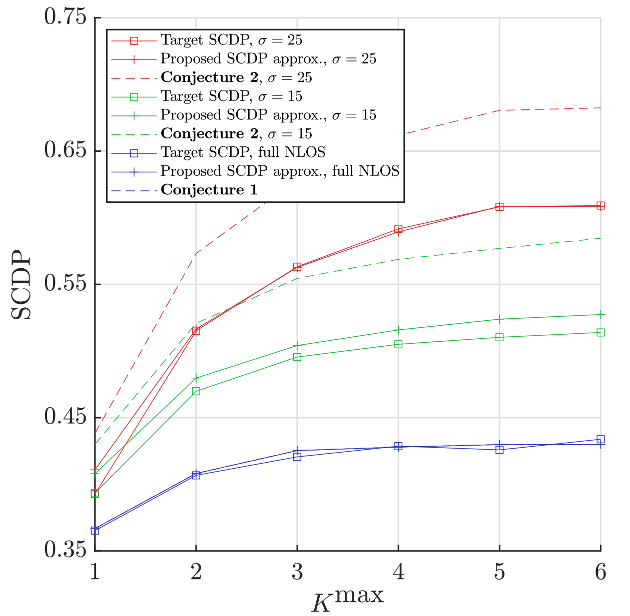

FIGURE 5. Target and approximated SCDP against maximum number of cooperating edge nodes.

it is more likely some nodes that can potentially take part to the content delivery to be not included in the cooperating set of edge nodes and, in some cases, considered as additional interferers. This reason is behind the increase of SCDP against $K^{\max}$. On top of it, the obtained measures highlights the role of σ in terms of SCDP performance and experienced gap. As $K^{\max}$ increases, the higher probability of experiencing LOS wireless links for higher σ values turned out as higher SCDP performance and lower gap with its target SCDP. Therefore, to better SINR conditions not only an higher increase of SCDP is expected, but a closer gap is experienced, highlighting the better level of accuracy of the proposed approximation for better SINR conditions. A saturation of SCDP performance at higher values of $K^{\max}$ indicates the balance between desired and interfering power and is due to the chosen average number of cooperating nodes for content f.

E. THE PROPOSED APPROXIMATION AGAINST σ

The intensity of σ gives an indication of the percentage of LOS wireless links over the elements of a snapshot of ϕ^S. Also, as an indicative point of view, the higher the σ the better are the SINR conditions as consequence of the fact that the closer SBSs experience LOS wireless links. The obtained numerical measures show that the gap between the proposed SCDP approximation and its target measure is lower as σ increases. Since at higher σ the gap is reduced, the generation of the gap has to be linked to the nature of the wireless link of the cooperating nodes, and, in particular, whether the majority of them experience LOS wireless links with their associated receiver, better levels of accuracy of our proposed approximation are seen. This analysis reveals the trade off between performance and experienced gap in our simulations, showing that, to better SCDP performance, thus better SINR values, also a better approximation can be achieved.

V. CONCLUSION

In this paper, an accurate approximation for a two-tier mixed Rayleigh/Rician small-scale channel faded UDN with non-coherent JT has been proposed. In particular, we derived a scaling factor to SCDP to account for Rayleigh channel power fading in closed form, which then permits our analysis to SCDP for the mixed fading UDN with LOS and NLOS links with any arbitrary LOS probability function and dual-slope path-LOSs model. Finally, the proposed approximation can be employed to extend existing Rayleigh limited mobile networks to a more accurate small-scale channel modeling.

Appendix

Given two PPPs defined over the same portion of space which refer to the received power from LOS and NLOS terms, ϕ^L and ϕ^{nL} respectively, we can develop the result as the summation of a term which refers to the whole received power as if no differentiation been conducted on the kind of wireless link and a second term which takes into account the contribution from the LOS term. In particular, the LOS contribution is dependent to the power of full NLOS network. Namely

$$\begin{aligned} I^{nL} + I^{L} &= \sum_{i \in \phi^{nL}} |h_i|^2 \; r_i^{-\alpha} + \sum_{i \in \phi^{L}} \left|h_i'\right|^2 \; r_i^{-\alpha} \\ &= \sum_{i \in \phi^{nL}} (X^2 + Y^2) r_i^{-\alpha} \\ &\quad + \sum_{i \in \phi^{L}} ((\sqrt{2}\sigma_h X + \mu_h)^2 + (\sqrt{2}\sigma_h Y)^2) r_i^{-\alpha} \end{aligned}$$

$$
\begin{aligned}
&= \sum_{i\in\phi^{nL}} (X^2+Y^2) r_i^{-\alpha} \\
&\quad + \sum_{i\in\phi^{L}} (2\sigma^2 X^2 + 2\sigma_h^2 Y^2 + 2\sqrt{2}\mu_h\sigma_h X + \mu_h^2) r_i^{-\alpha} \\
&= \sum_{i\in\phi^{nL}} (X^2+Y^2) r_i^{-\alpha} \\
&\quad + \sum_{i\in\phi^{L}} ((1-1+2\sigma_h^2)(X^2+Y^2) + 2\sqrt{2}\mu_h\sigma_h X + \mu_h^2) r_i^{-\alpha} \\
&\overset{a}{=} \underbrace{\sum_{i\in\phi}(X^2+Y^2) r_i^{-\alpha}}_{I} \\
&\quad + \underbrace{\sum_{i\in\phi^{L}} \left(-\frac{k}{k+1}(X^2+Y^2) + \frac{2\sqrt{k}}{k+1}X + \frac{k}{k+1} \right) r_i^{-\alpha}}_{\Delta I^L|I},
\end{aligned}
$$

where (a) comes from substituting the values of σ_h and μ_h with the k-factor and from re-arranging the terms of the two sums. The obtained derivation stands as the separated contributions from a full NLOS network I and the contribution given by its LOS components $\Delta I^L|I$.

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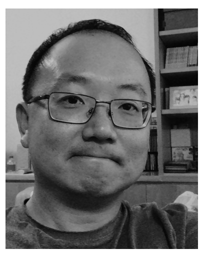

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