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Performance Analysis of Dynamic Downlink PPP Cellular Networks Over Generalized Fading Channels With MRC Diversity

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ABSTRACT This paper proposes novel and generalized expressions to characterize the performance of modern cellular networks under realistic user mobility behavior. The η-μ distribution is employed to derive the received power probability density function, the average bit error rate for different modulation schemes, and the coverage probability assuming a Poisson point process spatial distribution of base stations in downlink. The user is assumed to experience fading with Maximum Ratio Combining (MRC) and move according to a random way-point mobility model. The proposed expressions are applicable to different widely-used fading environments, such as Rayleigh and Nakagami-m as particular cases, by an appropriate selection of the η-μ parameters. Monte Carlo simulation was used to show the validity of the proposed expressions. The generalized expressions allow the system designer to quantify the effects of user mobility on the cellular network performance, in different propagation environments, and network topologies as a function of the number of base stations and MRC branches.

INDEX TERMS η-μ fading, random way-point, maximum ratio combining, stochastic geometry, poisson point process, average bit error rate, coverage probability.

I. INTRODUCTION

The fifth generation (5G) mobile technology has received the interest of both the research institutes as well as communication companies. This importance encouraged researches on 5G to set the new generation's performance targets and work-plans for their achievment. These targets can be summarized into: high data rate, massive device connectivity, energy saving, cost reduction and reduced latency. An effective approach to satisfy the 5G high transmission rate requirement is reducing the communication distance between users and base stations (BS)s [1]. However, this distance issue becomes a more complex problem in 5G, because of the high user mobility due to the 5G large network size and decreased coverage radius [2] - [3]. Thus, the evaluation of the impact of user mobility on 5G and beyond cellular networks is an important issue.

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The impact of the user mobility on cellular networks has been studied in several papers, for instance in [4]–[6]. In [4] the authors analyzed the backhaul delay of heterogeneous networks including small cell networks and macro-cell networks. They assumed that the positions of mobile users follows an independent Poisson point process (PPP) in each time slot. In [5] the authors investigated a new small cell discovery scheme based on mobility model to improve access and energy efficiency of LTE-Advanced heterogeneous wireless networks. The power consumption of uplink and downlink of small 5G cellular networks was evaluated in [6], where the authors assumed low mobility and static users for macro cell base stations (BS) and high users mobility for small cell BS. It is well-known that users mobility is one of the fundamental causes of the time varying nature of the received signal strength, multipath, and path loss [7]. Several diversity techniques were used as fading mitigation techniques in fading environment, to improve the link performance exploiting multi-antenna systems [8], [9]. Among these are: Maximal Ratio Combining (MRC), Selection Combining (SC), Switch and Stay Combining (SSC), Equal Gain Combining (EGC), and other hybrid combining techniques [8]. Moreover, several models such as Rayleigh, Nakagami, and $\eta - \mu$ distribution were developed to describe the statistical behavior of the fading in various propagation environments [9]. Among them, the $\eta - \mu$ distribution is a generalized distribution that plays an essential role in modeling fading radio channels. It is used to describe short-range (or small scale) signal envelope, in multipath fading channels when the in-phase and quadrature power components are different. This distribution has two parameters η and μ where the parameter μ is related to the number of multipath clusters in the environment, whereas the parameter η is related to the ratio of the powers between the multipath waves in the in-phase and quadrature components [10]. It is important to assert that the $\eta - \mu$ distribution can generate other well-known distributions, adopted in the wireless communication literature, such as Rayleigh, Nakagami-m. In particular, the Rayleigh distribution can be obtained by setting $\eta = 1$ and $\mu = 0.5$, whereas, Nakagami-m can be obtained by setting $\eta = 1$ and $\mu = m$, [9]. Another important aspect of the $\eta - \mu$ distribution is that it is considered to best fit experimental data and thus, it can be fully characterized in terms of measurable physical fading variables [9], [11]. To illustrate the role of the $\eta - \mu$ distribution as a generalized form for the evaluation of wireless networks performance in fading environment, we consider the most used performance parameters: the signal-to-interference-plus-noise ratio (SINR), coverage probability, and bit error rate (BER) for the different modulation schemes.

A. RELATED WORK

Stochastic geometry has been employed to study the effects of the network topology on the behavior and performance of wireless networks, such as Wi-Fi and cellular-networks [12].

Most of the wireless-networks studies considered static or highly-constrained mobility conditions. Thus, the average received power was assumed to be deterministic and only short-term variations were modeled as random variable. Therefore, these studies ignored the user random mobility that requires modeling the transmitter-receiver relative distance as a random variable [13]–[16]. In [14] the authors derived the probability density function (p.d.f.) of the received power from a mobile transmitter at unknown location in a circle centered on the receiver. They demonstrated that the p.d.f. of the received power to have a Pareto distribution. In [15] the authors showed that in static networks, the received power by an antenna, in a reverberation chamber, follows an exponential distribution. The p.d.f. of the received power in a static ad-hoc network with log-normal shadowing and distance-dependent path loss is derived in [16]. A number of research works on the performance of wireless communication systems over η-μ fading channel in static scenario have been also presented in [17], [18]. In [17] the authors derived the expressions of the symbol error probability (SEP) of the L-branch MRC in the presence of generalized η-μ fading channels. In [18] an exact-form expression for the average symbol error probability (ASEP) of various digital modulation schemes with MRC diversity over L-independent branch have been derived.

Coverage probability has been studied in [19]–[22]. In [19], an exact closed-form expression for the Outage Probability (Pout) in η-μ fading channels was derived. Closed-form expressions were also derived for the Pout MRC in η-μ fading channels with antenna correlation and co-channel interference in [20]. In [21], the authors derived the outage probability in a scenario at which the signal of interest experienced η-μ or κ-μ fading. In [22], an approximation of the outage probability in a system employing MRC diversity technique and η-μ fading channel was derived. However, in dynamic networks, the nodes mobility, distance, and multipath fading lead to a more general statistical behavior. In fact, the received power assumption of short-term variations becomes invalid [23], and the development of new models to characterize the signal received power, coverage probability (Pcov), and BER in the dynamic networks scenarios, such as in 5G networks, becomes essential.

Several mobility models were introduced in the mobile communication literature, among these are Random Walk model (RW), and Random Way-Point (RWP) [24]–[26]. In RW, the simplest one, a mobile user walks in continuous independent steps with a random velocity and angle [24] and [25]. A more realistic and popular mobility model is obtained by adding pause intervals in the RW thus obtaining the so called RWP model, as represented in [25]. This model has been widely adopted to study the behavior of 1D, 2D, and 3D wireless-network topologies [27]. In this model, a mobile user moves along a zig-zag path of straight line segments. At each $\Delta t(sec)$, the mobile user may pause for a random period of time or choose to move, at random, in a new direction. Thus, the RWP mobility model leads to non-uniform asymptotic spatial node distributions, which is useful in the communication system performance analysis [28].

B. STUDY CONTRIBUTION

To the best of our knowledge, no prior work in literature has derived an analytical framework for studying dynamic cellular-networks in the more generalized η-μ fading channel. All the dynamic scenarios introduced in literature considered Rayleigh [28] and Nakagmai-m [29], which are derived as special cases in our framework. To be more specific, the main contribution of this study can be summarized as follows:

- Generalized expressions for the p.d.f. of the received power over $\eta - \mu$ fading distribution with RWP mobility and different topologies are derived. The expressions are obtained in terms of the well-known incomplete gamma function [30], which is available in most popular computing software.
- Expressions for the average bit error probability (ABER), with different modulation schemes, as well as

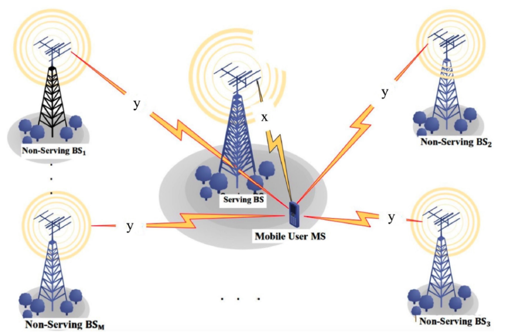

FIGURE 1. **The System Model.**

Pcov in next generation dynamic cellular network, are derived.

- The expressions are generalized to the case of L branch i.i.d. channels to allow the characterization of MRC techniques.
- Show that typical distributions used in literature are special cases of our general expressions.
- Monte Carlo simulation is used to validate our proposed model.

The remainder of this paper is as follows: After this Introduction, Section II shows the system model whereas, the channel model is derived in section III, and the performnce of our proposed model is studied in section IV. Finally, numerical results and conclusions are presented in section V, and section VI, respectively.

II. SYSTEM MODEL

We consider the dynamic PPP downlink cellular-network shown in Fig.1 in which the locations of BSs are distributed as a homogeneous Poisson point process (HPPP) with density λ. A typical user is assumed to be randomly located, according to an independent stationary point process in a Voronoi cell, and has connection with the closest BS [31]. In addition, we assume that all BSs transmit at constant power and each BS, serving one mobile station (MS), use the same radio resource. For convenience, we consider that all BSs are distributed randomly within a circle of radius R_c, large enough to make border effects negligible. Within this scenario, a mobile user MS is assumed to be moving according to the RWP.

III. CHANNEL MODEL

A. CHANNEL MODEL BETWEEN SERVING BS AND PROBE MS

In the proposed scenario, we consider that the signal transmitted by the BS to the probe MS is faded by $\eta-\mu$ fading channel. We assume independent, identically distributed (i.i.d.) L diversity branches. Thus, the resulting p.d.f. of the received amplitude s after the MRC can be expressed as in [17],

$$f_S(s) = \frac{4\sqrt{\pi}\mu^{L\mu+1/2}h^{L\mu}s^{2L\mu}}{\Gamma(L\mu)H^{L\mu-1/2}\Omega^{L\mu+1/2}} \times \exp\left(\frac{-2\mu h s^2}{\Omega}\right) I_{L\mu-1/2}\left(\frac{2\mu H s^2}{\Omega}\right) \quad (1)$$

where $\Gamma(z) = \int_0^\infty t^{z-1}\exp(-t)dt$ is the gamma function, $I_v(.)$ is the modified Bessel function of the first kind and arbitrary order v [30], h and H are functions of η and vary from one scenario to another. More specifically, here we consider two scenarios: in scenario one, $h = \frac{2+\eta^{-1}+\eta}{4}$ and $H = \frac{\eta^{-1}-\eta}{4}$, whereas, in scenario two, $h = 1/(1-\eta^2)$ and $H = \eta/(1-\eta^2)$. In addition, in scenario one, $\eta > 0$ denotes the ratio between the powers of the in-phase and quadrature scattered waves in each multipath cluster, whereas, in scenario two, it denotes the correlation between the powers of the in-phase and quadrature scattered waves in each multipath cluster. In both scenarios, the parameter $\mu > 0$ denotes the number of multipath clusters, and Ω is the average received signal power [32]. By defining the received power $x = s^2$, the corresponding p.d.f. is given by

$$f_X(x) = \frac{2\sqrt{\pi}\mu^{L\mu+1/2}h^{L\mu}x^{L\mu-1/2}}{\Gamma(L\mu)H^{L\mu-1/2}\Omega^{L\mu+1/2}} \times \exp\left(\frac{-2\mu h x}{\Omega}\right) I_{L\mu-1/2}\left(\frac{2\mu H x}{\Omega}\right). \quad (2)$$

The average received power Ω in (1) and (2) follows the classical exponential path-loss model and depends on the relative distance r between the transmitter and the receiver [33].

$$\Omega = \mathrm{P}_0 r^{-\alpha}, \quad (3)$$

where P_0 is the received power at the reference distance of 1 meter, and α is the path-loss exponent that depends on the propagation environment. To obtain a realistic mobility scenario, we assume $0 \leq r \leq R_0$, with R_0 the maximum distance of the cell edge. In static networks the distance r, and hence Ω, is kept constant and the fading statistics is given by (1) or (2). In dynamic networks, the distance r is a random variable, namely R, whose statistics depends on the mobility model. Therefore, (2), has to be interpreted as the conditional p.d.f. of the received power, as shown in (4),

$$f_{X|R}(x|r) = \frac{2\sqrt{\pi}\mu^{L\mu+1/2}h^{L\mu}x^{L\mu-1/2}}{\Gamma(L\mu)H^{L\mu-1/2}(\mathrm{P}_0 r^{-\alpha})^{L\mu+1/2}} \times \exp\left(\frac{-2\mu h x}{\mathrm{P}_0 r^{-\alpha}}\right) I_{L\mu-1/2}\left(\frac{2\mu H x}{\mathrm{P}_0 r^{-\alpha}}\right). \quad (4)$$

Since the RWP mobility model leads to non-uniform asymptotic spatial node distributions, in which the distance distribution between transmitter and receiver can be approximated as a polynomial, the p.d.f. of the distance r can be expressed by the general form defined in [34],

$$f_R(r) = \sum_{i=1}^{n} \frac{B_i r^{\beta_i}}{R_0^{\beta_i+1}}, \quad (5)$$

for $0 \leq r \leq R_0$, and zero otherwise, where parameters n, B_i, and β_i depends on the dimension considered in the topology and are summarized in [[28], table.3] for diferent dimensions. For example, in the 1D, $n = 2$, $B_i = [6, -6]$, and $\beta_i = [1, 2]$, in 2D, $n = 3$, $B_i = (1/73).[324, -420, 96]$, and in the 3D $\beta_i = [1, 3, 5]$ and $n = 3$, $B_i = (1/72).[735, -1190, 445]$, and $\beta_i = [2, 4, 6]$. Now the unconditional p.d.f. of the received power is expressed as:

$$f_X(x) = \int_0^{R_0} f_{X|R}(x|r) f_R(r) dr \,, \tag{6}$$

making use of [30],

$$I_{L\mu-1/2}\left(\frac{2\mu Hx}{\mathrm{P}_0 r^{-\alpha}}\right) = \sum_{k=0}^{\infty} \frac{1}{k!\Gamma(L\mu + k + 1/2)} \times \left(\frac{2\mu Hx}{\mathrm{P}_0 r^{-\alpha}}\right)^{L\mu+2k-1/2}, \tag{7}$$

and substituting (7) in (4), and the result (5) in (6), we obtain the solution,

$$\int_0^1 u^{\frac{1+\beta_i}{\alpha}+2L\mu+2K-1} \exp\left(-\frac{2\mu hx}{\Omega_0} u\right) du = \frac{2^{-\frac{1+\beta_i}{\alpha}-2k-2L\mu}}{\alpha} \left(\frac{hx\mu}{\Omega_0}\right)^{-\frac{1+\beta_i}{\alpha}-2k-2L\mu} \times \gamma\left(\frac{1+\beta_i}{\alpha} + 2k + 2L\mu, \frac{2hx\mu}{\Omega_0}\right), \tag{8}$$

in which $\Omega_0 = \mathrm{P}_0 R_0^{-\alpha}$ is the average received power at the edge of the coverage area, and $\gamma(.)$ is the lower incomplete gamma function [30]. Therefore, the unconditional p.d.f. and the cumulative distribution function (CDF) of the received power become,

$$f_X(x) = \sum_{i=1}^{n}\sum_{k=0}^{\infty} \frac{2B_i\sqrt{\pi}x^{-1}}{\alpha k!\Gamma(L\mu)\Gamma\left(L\mu+k+\frac{1}{2}\right)} \times \left(\frac{\Omega_0}{2\mu xh}\right)^{\frac{1+\beta}{\alpha}} \left(\frac{H}{h}\right)^{2k} \left(\frac{1}{4h}\right)^{L\mu} \times \gamma\left(\frac{1+\beta_i}{\alpha} + 2(k+L\mu), \frac{2h\mu x}{\Omega_0}\right), \tag{9}$$

and

$$F_X(x) = \sum_{i=1}^{n}\sum_{k=0}^{\infty} 2\sqrt{\pi}B_i \left(\frac{\Omega_0}{2\mu h}\right)^{\frac{1+\beta_i}{\alpha}} \left(\frac{H}{h}\right)^{2k} \left(\frac{1}{4h}\right)^{L\mu} \times \frac{C_1(x) - C_2(x)}{(1+\beta_i)k!\Gamma(L\mu)\Gamma\left(L\mu+k+\frac{1}{2}\right)}, \tag{10}$$

with

$$C_1(x) = \left(\frac{2h\mu}{\Omega_0}\right)^{\frac{1+\beta_i}{\alpha}} \gamma\left(2(k+L\mu), \frac{2h\mu x}{\Omega_0}\right), \tag{11}$$

and

$$C_2(x) = x^{-\frac{1+\beta_i}{\alpha}} \gamma\left(\frac{1+\beta_i}{\alpha} + 2k + 2L\mu, \frac{2h\mu x}{\Omega_0}\right). \tag{12}$$

Although expressions (9) and (10) are given in an infinite series form, they converge rapidly and steadily for the desired accuracy after few terms ($k = 3$), as shown in the numerical results.

B. THE DISTRIBUTIONS AT THE LIMIT VALUES OF THE $\eta - \mu$ PARAMETERS

1) THE p.d.f. OF THE RECEIVED POWER FOR $H \longrightarrow 0$

In this subsection, particular expressions for (9) and (10) are obtained for $\eta \longrightarrow 1$ in scenario one and $\eta \longrightarrow 0$ in scenario two in which $h = 1$, and $H = 0$. Using the approximated Bessel function [9]

$$I_{v-1}(z) \approx \left(\frac{z}{2}\right)^{v-1} / \Gamma(v) \,, \tag{13}$$

and substituting it in (4), the conditional p.d.f. of the received power becomes,

$$f_{X|R}(x|r) = \frac{2\sqrt{\pi}\mu^{2L\mu}x^{2L\mu-1}r^{2\alpha L\mu}}{\Gamma(L\mu)\Gamma(L\mu+0.5)\mathrm{P}_0{}^{2L\mu}} exp\left(-\frac{2\mu hxr^{\alpha}}{\mathrm{P}_0}\right). \tag{14}$$

Following the same procedure used to derive (9) and (10), and making use of the following identity $2^{2v-0.5}\Gamma(v)\Gamma(v+0.5) = \sqrt{2\pi}\Gamma(2v)$ [9], the unconditional p.d.f. and CDF of received power become,

$$f_X(x) = \sum_{i=1}^{n} \frac{B_i}{\alpha} \times \frac{1}{x\Gamma(2L\mu)} \times \left(\frac{\Omega_0}{2\mu x}\right)^{\frac{1+\beta_i}{\alpha}} \times \gamma\left(\frac{1+\beta_i+2L\alpha\mu}{\alpha}, \frac{2h\mu x}{\Omega_0}\right), \tag{15}$$

and

$$F_X(x) = \sum_{i=1}^{n} B_i \times \frac{1}{(1+\beta_i)\Gamma(2L\mu)} \times \left(\frac{\Omega_0}{2\mu}\right)^{\frac{1+\beta_i}{\alpha}} \times (C_3(x) - C_4(x)), \tag{16}$$

repectively, with

$$C_3(x) = \left(\frac{2h\mu}{\Omega_0}\right)^{\frac{1+\beta_i}{\alpha}} \gamma\left(2L\mu, \frac{2h\mu x}{\Omega_0}\right), \tag{17}$$

and

$$C_4(x) = x^{-\frac{1+\beta_i}{\alpha}} \gamma\left(\frac{1+\beta_i+2L\alpha\mu}{\alpha}, \frac{2h\mu x}{\Omega_0}\right). \tag{18}$$

Note that the Nakagami-m and Rayleigh distributions can be obtained as particular cases by setting $\mu = m$ and $\mu = 0.5$ in (15), respectively, leading to the same results derived in [28] and [29].

2) THE p.d.f. OF THE RECEIVED POWER FOR $H \longrightarrow \infty$

In this case $\eta \longrightarrow 0$ or $\eta \longrightarrow \infty$ in scenario one, and $\eta \longrightarrow 1$ in scenario two. Using the approximated Bessel function in [9], $I_v(z) \approx \frac{\exp(z)}{\sqrt{2\pi z}}$, we obtain:

$$f_{X|R}(x|r) = \mu^{L\mu}\left(\frac{h}{H}\right)^{L\mu} \frac{x^{L\mu-1}r^{\alpha L\mu}}{\mathrm{P}_0^{L\mu}\Gamma(L\mu)} \times \exp\left(-\frac{2\mu x}{\mathrm{P}_0}(h-H)r^{\alpha}\right). \tag{19}$$

For $\frac{h}{H}=1$ and $h-H=0.5$, (19) reduces to:

$$f_{X|R}(x|r)=\mu^{L\mu}\left(\frac{h}{H}\right)^{L\mu}\frac{x^{L\mu-1}r^{\alpha L\mu}}{\mathrm{P}_0^{L\mu}\Gamma(L\mu)}\times\exp\left(-\frac{2\mu x}{\mathrm{P}_0}(h-H)r^{\alpha}\right). \quad (20)$$

The unconditional p.d.f. of the received power is given by:

$$f_X(x)=\sum_{i=1}^{n}\frac{B_i}{\alpha}\left(\frac{\mu x}{\Omega_0}\right)^{(-\frac{1+\beta_i}{\alpha})}\frac{\Gamma\left(\frac{1+\beta_i}{\alpha}+L\mu\right)}{x\Gamma(L\mu)}. \quad (21)$$

C. CHANNEL MODEL BETWEEN NON-SERVING BSs AND PROBE MS

In this subsection, we deal with the interference distribution. In cellular networks, distance variations caused by moving of MS generate fluctuations of the channel gains. Such fluctuations can be treated as another type of fading besides multi-path effects [35]. Accordingly, we consider the distance distribution between non-serving BS and probe MS in RWP as expressed in [35]

$$f_{R_1}(r_1)=\frac{1}{R_m^2}\left(\frac{-4r_1^3}{R_m^2}+4r_1\right)r_1\in[0,R_m], \quad (22)$$

where R_m is defined as the maximum distance between non-serving BSs and probe MS. Since there is no closed-form p.d.f. of the total interference, only the interference from the nearest interfering MS to the receiver, which provides a good approximation, is considered in [12]. The interference power from a generic interfering MS at random distance R_1 is given by

$$Y_1=\mathrm{P}_0R_1^{-\alpha}. \quad (23)$$

The probability that no BSs are present within a distance r_{I}, provided there are M BSs, can be expressed as:

$$\begin{aligned}\mathbb{P}[R_1\le r_1|M]&=1-(1-F_{R_1}(r_1))^M\\&=1-\left(1-\left(\frac{2r_1^2}{R_m^2}-\frac{r_1^4}{R_m^4}\right)\right)^M. \quad (24)\end{aligned}$$

Since M has a poisson distribution with mean $\lambda\pi R_m^2$ due to the HPPP spatial distribution, the p.d.f. of the distance R_I of the closest interferer is

$$\begin{aligned}f_{R_{\mathrm{I}}}(r_{\mathrm{I}})&=\frac{\mathrm{d}\mathbb{E}_M[\mathbb{P}(R_1\le r_{\mathrm{I}}|M)]}{\mathrm{d}r_{\mathrm{I}}}\\&=\lambda\pi\left(4r_{\mathrm{I}}-\frac{4r_{\mathrm{I}}^3}{R_m^2}\right)\exp\left(-\lambda\pi\left(2r_{\mathrm{I}}^2-\frac{r_{\mathrm{I}}^4}{R_m^2}\right)\right)\\&\quad\times r_{\mathrm{I}}\in[0,R_m]. \quad (25)\end{aligned}$$

Using (23) and (25), the p.d.f. of the random variable (RV) Y denoting the received power from the closest interferer becomes

$$f_Y(y)=\frac{4\pi\lambda}{\alpha}\left(y^{-\frac{2}{\alpha}-1}\mathrm{P}_0-\frac{y^{-\frac{4}{\alpha}-1}\mathrm{P}_0^{\frac{4}{\alpha}+1}}{R_m^2}\right)\times\exp\left(-\lambda\pi\left(2y^{-\frac{2}{\alpha}}\mathrm{P}_0^{\frac{2}{\alpha}}-\frac{y^{-\frac{4}{\alpha}}\mathrm{P}_0^{\frac{4}{\alpha}}}{R_m^2}\right)\right). \quad (26)$$

For $y\in[R_m^{\frac{-1}{\alpha}},\infty)$. For infinite network size ($R_m\to\infty$), the CDF of the RV Y becomes

$$\Pi_Y(y)=\exp\left(-2\lambda\pi\mathrm{P}_0^{2/\alpha}y^{-\frac{2}{\alpha}}\right). \quad (27)$$

IV. PERFORMANCE EVALUATION

A. COVERAGE PROBABILITY

The coverage probability Pcov is one of the important design metrics in wireless network. It is defined as the probability that a user, moving within its cell, experiences a signal-to-interference plus noise ratio (SINR) larger than an assigned threshold. In this section, the coverage performance is developed for the following cases:

1) COVERAGE PROBABILITY WITHOUT INTERFERENCE

The coverage probability can be evaluated using the CDF $F_X(x)$ of the received power as follows:

$$\begin{aligned}\mathrm{P}_{\mathrm{cov}}^{(\mathrm{N})}&=\mathbb{P}(\mathrm{SNR}\ge\Theta)\\&=1-\mathbb{P}\left(\frac{x}{\sigma^2}\le\Theta\right)\\&=1-F_X(\Theta\sigma^2), \quad (28)\end{aligned}$$

where Θ is the assigned threshold signal-to-noise ratio (SNR), and σ^2 is the thermal noise power. By substituting (10) in (28) we obtain:

$$\mathrm{P}_{\mathrm{cov}}^{(\mathrm{N})}=1-\sum_{i=1}^{n}\sum_{k=0}^{\infty}2\sqrt{\pi}B_i\left(\frac{\Omega_0}{2\mu h}\right)^{\frac{1+\beta_i}{\alpha}}\left(\frac{H}{h}\right)^{2k}\left(\frac{1}{4h}\right)^{L\mu}\times\frac{C_1\left(\Theta\sigma^2\right)-C_2\left(\Theta\sigma^2\right)}{(1+\beta_i)k!\Gamma(L\mu)\Gamma\left(L\mu+k+\frac{1}{2}\right)}. \quad (29)$$

2) COVERAGE PROBABILITY IN THE PRESENCE OF INTERFERENCE UNDER POWER CONTROL CONSTRAINS

In this subsection, a working scenario with a classic power control strategy is considered. The power control aims at keeping the constant useful received signal power P, [36], in presence of interference. In this case the coverage probability becomes:

$$\begin{aligned}\mathrm{P}_{\mathrm{cov}}^{(\mathrm{C})}&=\mathbb{P}[\mathrm{SINR}\ge\Theta]\\&=\mathbb{P}\left[\frac{\mathrm{P}}{y+\sigma^2}\ge\Theta\right]\\&=\mathbb{P}\left[y\le\frac{\mathrm{P}}{\Theta}-\sigma^2\right]=F_Y\left(\frac{\mathrm{P}}{\Theta}-\sigma^2\right), \quad (30)\end{aligned}$$

with Θ the target SINR and $F_Y(y)$ is the CDF of RV of Y. Replacing y in (27) with $\frac{\mathrm{P}}{\Theta}-\sigma^2$, then the $\mathrm{P}_{\mathrm{cov}}^{(C)}$ for infinite network ($R_m \rightarrow \infty$) can be obtained

$$\mathrm{P}_{\mathrm{cov}}^{(C)} = \exp\left(-2\lambda\pi \mathrm{P}_0^{2/\alpha}\left(\frac{\mathrm{P}}{\Theta}-\sigma^2\right)^{-\frac{2}{\alpha}}\right). \quad (31)$$

3) COVERAGE PROBABILITY IN THE PRESENCE OF INTERFERENCE WITHOUT POWER CONTROL

When no power control is used, both the useful and interfering signals are random. In this case the coverage probability becomes:

$$\begin{aligned}\mathrm{P}_{\mathrm{cov}}^{\mathrm{I}} &= \mathbb{P}[\mathrm{SINR} \geq \Theta] \\ &= \mathbb{P}\left[\frac{X}{Y+\sigma^2} \geq \Theta\right] \\ &= 1-\mathbb{E}_Y\left[F_X\left(\Theta\left(Y+\sigma^2\right)\right)\right], \end{aligned} \quad (32)$$

where $\mathbb{E}_Y[.]$ denotes statistical expectation with respect to the random variable Y in which

$$\mathbb{E}_Y\left[F_X\left(\Theta\left(Y+\sigma^2\right)\right)\right] = \int_0^\infty F_X\left(\left(\Theta\left(y+\sigma^2\right)\right)\right) f_Y(y)\, dy. \quad (33)$$

Replacing x, in (10), with $\Theta\left(y+\sigma^2\right)$, and using the following incomplete gamma function expression,

$$\gamma(v,x) = x^v \int_0^1 z^{v-1} \exp(-xz)\, dz \quad (34)$$

we obtain

$$\begin{aligned} C_1\left(\Theta\left(y+\sigma^2\right)\right) &= \left(\frac{2h\mu}{\Omega_0}\right)^{\frac{1+\beta_i}{\alpha}} \left(\frac{2h\mu\Theta}{\Omega_0}\right)^{2k+2L\mu} \\ &\times \left(y+\sigma^2\right)^{2k+2L\mu} \times \int_0^1 z^{2k+2L\mu-1} \\ &\times \exp\left(-\left(\frac{2h\mu\Theta}{\Omega_0}\left(y+\sigma^2\right)z\right)\right) dz, \end{aligned} \quad (35)$$

and

$$\begin{aligned} C_2\left(\Theta\left(y+\sigma^2\right)\right) &= \left(\Theta(y+\sigma^2)\right)^{-\frac{1+\beta_i}{\alpha}} \\ &\times \gamma\left(\frac{1+\beta_i}{\alpha}+2k+2L\mu, \frac{2h\mu\left(\Theta(y+\sigma^2)\right)}{\Omega_0}\right). \end{aligned} \quad (36)$$

Moreover, using the binomial expansion for the term of $\left(y+\sigma^2\right)^{2k+2L\mu}$

$$\left(y+\sigma^2\right)^{2k+2L\mu} = \sum_{j=0}^{2k+2L\mu}\binom{2k+2L\mu}{j} y^j \left(\sigma^2\right)^{2k+2L\mu-j}, \quad (37)$$

and expressing the exponential, in (27), in Taylor series:

$$\exp\left(-2\lambda\pi \mathrm{P}_0^{\frac{2}{\alpha}} y^{-\frac{2}{\alpha}}\right) = \sum_{m=0}^{\infty} \frac{\left(-2p\lambda\pi \mathrm{P}_0^{\frac{2}{\alpha}}\right)^m y^{\frac{-2m}{\alpha}}}{m!}, \quad (38)$$

(32) becomes:

$$\begin{aligned} \mathrm{P}_{\mathrm{cov}}^{\mathrm{I}} &= \sum_{i=1}^{n}\sum_{k=0}^{\infty} 2\sqrt{\pi} B_i \left(\frac{\Omega_0}{2\mu h}\right)^{\frac{1+\beta}{\alpha}} \left(\frac{H}{h}\right)^{2k}\left(\frac{1}{4h}\right)^{L\mu} \\ &\times \frac{C_5(\Theta)-C_6(\Theta)}{(1+\beta_i)k!\Gamma(L\mu)\Gamma\left(L\mu+k+\frac{1}{2}\right)}, \end{aligned} \quad (39)$$

with

$$\begin{aligned} &C_5(\Theta) \\ &= \left(\frac{4\lambda\pi \mathrm{P}_0^{\frac{2}{\alpha}}}{\alpha}\right)\left(\frac{2h\mu}{\Omega_0}\right)^{\frac{1+\beta_i}{\alpha}} \sum_{m=0}^{\infty}\sum_{j=0}^{2k+2L\mu} \frac{\left(-2\lambda\pi \mathrm{P}_0^{\frac{2}{\alpha}}\right)^m}{m!} \\ &\times \binom{2k+2L\mu}{j}\left(\sigma^2\right)^{-\frac{2(1+m)}{\alpha}} \Gamma\left(j-\frac{2(1+m)}{\alpha}\right) \\ &\times \gamma\left(\frac{2(1+m)}{\alpha}+2k+2L\mu-j, \frac{2h\mu\Theta\sigma^2}{\Omega_0}\right), \end{aligned} \quad (40)$$

and

$$\begin{aligned} &C_6(\Theta) \\ &= \left(\frac{4\lambda\pi \mathrm{P}_0^{\frac{2}{\alpha}}}{\alpha}\right)\Theta^{-\frac{1+\beta_i}{\alpha}} \sum_{m=0}^{\infty}\sum_{j=0}^{2k+2L\mu} \frac{\left(-2\lambda\pi \mathrm{P}_0^{\frac{2}{\alpha}}\right)^m}{m!} \\ &\times \binom{2k+2L\mu}{j}\left(\sigma^2\right)^{-\frac{1+\beta_i}{\alpha}-\frac{2(1+m)}{\alpha}} \Gamma\left(j-\frac{2(1+m)}{\alpha}\right) \\ &\times \gamma\left(\frac{1+\beta_i}{\alpha}+\frac{2(1+m)}{\alpha}+2k+2L\mu-j, \frac{2h\mu\Theta\sigma^2}{\Omega_0}\right). \end{aligned} \quad (41)$$

B. AVERAGE BIT ERROR RATE (ABER)

In this section we investigate the performance of several digital modulation schemes under the effect of the η-μ fading condition and MRC diversity technique. The average bit error rate can be expressed, as [37]

$$\mathrm{ABER} = \int_0^\infty \frac{\Gamma(b,ax)}{2\gamma(b)} f_X(x)\, dx, \quad (42)$$

or

$$\mathrm{ABER} = \frac{a^b}{2\Gamma(b)} \int_0^\infty x^{b-1} \exp^{-ax} F_X(x)\, dx, \quad (43)$$

where $\Gamma(.,.)$ is the upper incomplete gamma function [30], $\Gamma(.)$ is the gamma function [30], and parameters a, b are constants that depends on the specific of modulation/detection scheme, [37], as shown in Table 1. By substituting (10) in (43), the ABER becomes:

$$\begin{aligned} \mathrm{ABER} &= \sum_{i=1}^{n}\sum_{k=0}^{\infty} 2\sqrt{\pi} B_i \left(\frac{\Omega_0}{2\mu h}\right)^{\frac{1+\beta_i}{\alpha}} \left(\frac{H}{h}\right)^{2k}\left(\frac{1}{4h}\right)^{L\mu} \\ &\times \frac{C_5(\Omega_0)-C_6(\Omega_0)}{(1+\beta_i)k!\Gamma(L\mu)\Gamma\left(L\mu+k+\frac{1}{2}\right)}, \end{aligned} \quad (44)$$

TABLE 1. Simulation parameters.

Parameters	value
Scenario	Urban Area
Average cell radius R	500 m
System Bandwidth	10 MHz
Carrier Frequency	2 GHz
Path loss exponent β	2-4
Received power at the reference distance of 1 m (P_0)	-9 dBm
Density of Base station (λ)	0.05 BSs/km^2
Thermal Noise σ^2	-10 dBm
Target Thresold SINR Θ	-10 dB
Mobility Model	3D-RWP

where

$$C_5(\Omega_0) = \frac{a^b\Gamma(b+2k+2L\mu)}{2\Gamma(b)}\left(\frac{2h\mu}{\Omega_0}\right)^{\frac{1+\beta_i}{\alpha}-b} \times \frac{D_1(\Omega_0)}{(2k+2L\mu)\left(1+\frac{\Omega_0 a}{2h\mu}\right)^{b+2k+2L\mu}} \quad (45)$$

and

$$C_6(\Omega_0) = \frac{a^b\Gamma(b+2k+2L\mu)}{2\Gamma(b)}\left(\frac{\Omega_0}{2h\mu}\right)^{b-\frac{1+\beta_i}{\alpha}} \times \frac{D_2(\Omega_0)}{\left(\frac{1+\beta_i}{\alpha}+2k+2L\mu\right)\left(1+\frac{\Omega_0 a}{2h\mu}\right)^{b+2k+2L\mu}} \quad (46)$$

where

$$D_1(\Omega_0) = F \times \left(1, b+2k+2L\mu; 1+2k+2L\mu; \frac{1}{1+\frac{\Omega_0 a}{2h\mu}}\right), \quad (47)$$

and

$$D_2 = F \times \left(1, b+2k+2L\mu; 1+\frac{1+\beta_i}{\alpha}+2k+2L\mu; G(\Omega_0)\right), \quad (48)$$

with $G(\Omega_0) = \frac{1}{1+\frac{\Omega_0}{2h\mu}}$, and $F(.,.;.;.)$ being the Gaussian hypergeometric function, [30].

V. NUMERICAL RESULTS

In this section, we provide analytical results to investigate the effect of mobility, diversity, and propagation parameters on the received power p.d.f. The average bit error rate, and coverage probability for the 3D-RWP mobility model in PPP downlink cellular network are also presented. The main simulation parameters are given in Table 2 if not otherwise specified.

To validate the proposed generalized model, the comparison between the theoritical results with simulation results is presented in Fig. 2-Fig. 5. In Fig. 2, it can be noted that a good matching results are obtained for the p.d.f. of received power with simultation result. Furthermore, analytical results have been obtained in expressions (39) and (44) are compared with

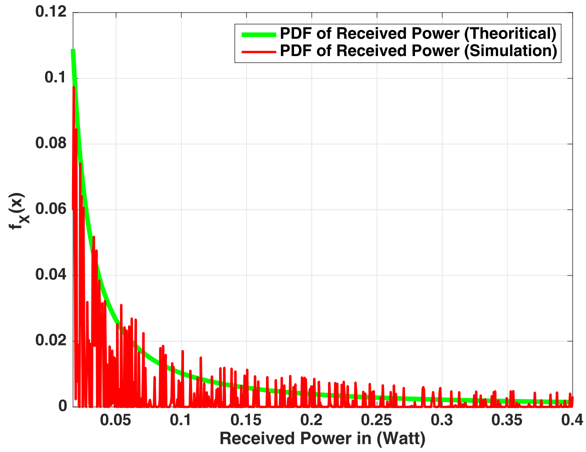

FIGURE 2. The Probability density function of the received power in 1D-RWP mobility model: $\alpha = 4$, $\eta = 1$, and $\mu = 0.5$. (Scenario One).

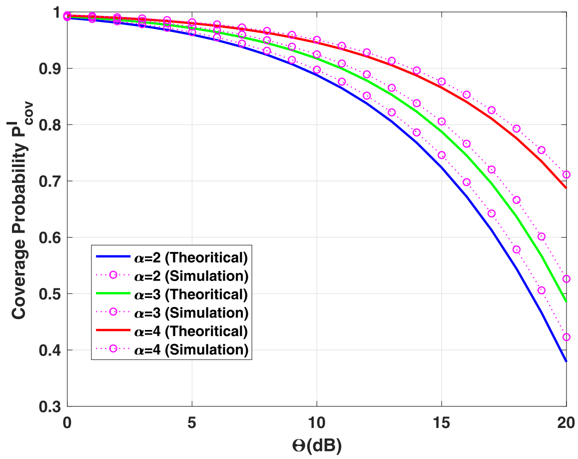

FIGURE 3. The effect of path loss on the coverage probability P^I_{cov}: $\eta = 0.5$, $\mu = 0.75$, $L = 2$, (Scenario One).

Monte Carlo simulations, where 100,000 randomly generated scenario were considered. Fig. 3 plots the coverage probability of the received power given by (39) versus the target SINR Θ for different propagation environments characterized by path-loss exponents $\alpha = 2$, 3, and 4. It can be observed that, there is a good matching between the numerical (solid lines) and Monte Carlo simulation results (dash-dot lines). In addition, it can be noted that, better coverage performance is achieved as the path loss exponent increases; this is due to the masking effect of path-loss on far interferences.

Fig. 4 shows the effect of the density of BSs and the number of MRC branches on the coverage probability as a function of the target SINR Θ. A good match between the analytical and simulation results can be appreciated. In addition, it can be observed that increasing the density of BS λ decreases the coverage probability. This is due to the fact that large λ increases the number of nearby interfering BSs. Fig. 5 shows the effect of number of MRC branches and the path-loss exponent on the ABER given by (44) for orthogonal non-coherent BFSK modulation scheme. A good matching is obtained between analytical (solid lines) and simulation results (dash-dot lines). In addition, it can be observed that the

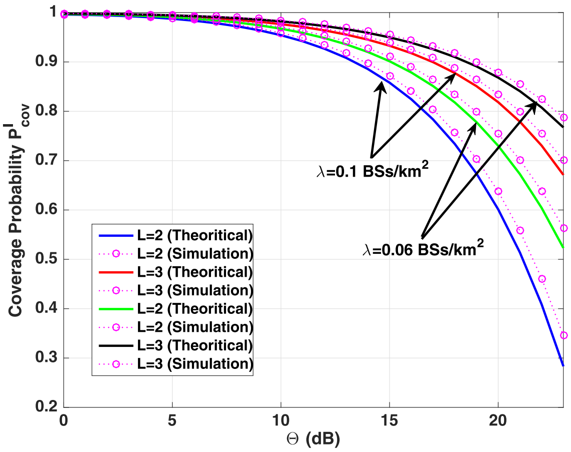

FIGURE 4. The effect of the number of MRC branches and the density of BSs on the coverage probability P^l_{cov}: $\eta = 1$, $\mu = 0.5$, and $\alpha = 4$ (Scenario One).

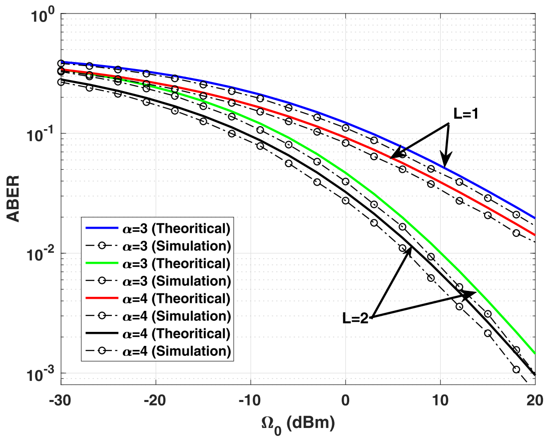

FIGURE 5. The average bit error rate BER for Orthogonal Non-Coherent BFSK scheme: $\eta = 1$, and $\mu = 0.5$ (Scenario One).

ABER increases as both path-loss exponent and the number of MRC branches decrease. This result can help the system designer to quantify the effect of transmit power, path-loss, and the number of MRC branches on the error performance of a mobile user.

VI. CONCLUSIONS

In this paper, we have derived novel expressions for the p.d.f. of the received power, average bit error rate, and coverage probability accounting for the mobility model in $\eta - \mu$ environment with MRC diversity. The effects of user mobility, propagation, path loss, and the number of MRC branches have been studied. Closed-form expressions for both the p.d.f. and CDF of the received power for some known distributions have been derived as special cases. Finally, the validation of our expressions has been done using Monte Carlo simulation and comparing with the results derived in [28] and [29].

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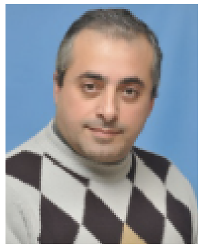

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