

Joint Uplink/Downlink Coverage and Spectral Efficiency in Heterogeneous Cellular Network

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Abstract In this paper, the joint uplink and downlink signal to interference plus noise ratio distribution have been analyzed in a two-tier heterogeneous cellular network. We assume that macro and pico base stations and user equipments are uniformly distributed in the network. User could be paired to its nearest base station or to the BS from which the average received power in the downlink is maximum. Uplink in both cases is coupled to downlink. For symmetric services both up and down links should be able to carry the information flow. Correlation between uplink and downlink coverage could be guessed even under independent Rayleigh fading. The symmetric spectral efficiency gathers both uplink and downlink capacities while forcing them to happen simultaneously. We used realistic spectral efficiencies as signaled by channel quality indicators in LTE. Fractional power control has also been included in the analysis. The results of coverage and spectral efficiency for marginal uplink, marginal downlink, and joint uplink/downlink has been obtained. The assumption of independence between both links is analyzed for the complex trade off of the parameters for network design to obtain the best symmetric efficiency.

Keywords Heterogeneous network · Poisson point process · Fractional power control · Cell range expansion

1 Introduction

The old voice-oriented cellular networks have grown to latest networks called as heterogeneous cellular networks (HCN) which consist of huge amount of small cells (micro, pico or femtocells) along with large (macro) cells. Due to different cell size targets,

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transmission power disparity across different tiers is large. Analysis of HCNs is complex although some tools as stochastic geometry came to help researchers in this task.

Several criteria can be used to associate user equipment (UE) to a macro or a pico base station (BS). In current networks, only coupled associations are used, wherein the UE is paired with the same BS for both uplink (UL) and downlink (DL) transmission. In homogeneous networks, formed by a single tier and where all BSs transmit with the same power, the association criteria as maximum average received power at the downlink is also that of maximum received power at the uplink (UL). However, uplink coverage would be higher in a heterogeneous network if the nearest BS were selected for each user. In both cases, as each UE distance from/to the BS are equal, certain correlation between the signal to interference plus noise ratio (SINR) at downlink and uplink is guessed. Two techniques are widely employed to improve performance of heterogeneous networks. The use of fractional power control (FPC) partially compensates for path loss due to distance from UE to BS. Since the association strategy has a bearing on the statistics of distance, FPC is influenced by the association criteria. The technique known as cell range expansion (CRE) is able to offload macro BS traffic by boosting the small cell DL power measure. Biasing UEs towards small cells with a coupled association improves the uplink SINR as the offloaded UEs are closer to the associated BS.

Any transmission carried out on a cellular network is formed by both uplink and downlink transmissions. Sometimes, as in video streaming, downlink traffic is extremely higher compared to reverse transmission. However, because of the symmetric traffic applications like voice, social networking or video-calls, it is vital to analyze the joint performance of downlink and uplink transmissions as both should have quality enough to support the service. In order to get more insight into heterogeneous cellular networks, it would also be quite interesting to analyze the joint uplink and downlink distribution of SINR for the two tiers along with the marginal distributions. Yang et al. [1] addressed this issue but arbitrarily assumed independence between uplink and downlink coverage. Analytical works in [2] results in weaker dependence as decoupled association between DL and UL was analyzed.

Many works in literature on Heterogenous Networks address the analysis of the SINR. However, a cellular network designer is also interested in another performance parameter of interest called as capacity, throughput, or spectral efficiency [3]. Spectral efficiency is defined as the information rate that can be transmitted over a given bandwidth in a communication system. It is a net bit rate of a communication channel, upper bounded by the well known Shannon formula $C = \log_2(1 + SINR)(bps/Hz)$. In a real system such as LTE-A, however, Shannon limit can not be reached. In that case, system avoids exceeding certain target block error rate (BLER) (e.g. 10%) by using more robust schemes when channel becomes worse while obtaining better throughput by increasing the number of bits per symbol of the scheme as channel improves.

In this work, we have analyzed the joint downlink/uplink probability for spectral efficiency of a heterogeneous network formed by pico and macro cells. The network consists of macro and pico cells forming a uniform Poisson Point Process. Poisson Point Process (PPP) is the simplest and most important point pattern [4]. Transmission powers as described by 3GPP recommendations have been assumed. Two user association criteria, to the nearest BS and to the BS with strongest signal in average in the downlink and coupled association for the uplink, have been studied. The effect of fractional power control and cell range expansion is analyzed under both strategies. The rest of this paper is organized as follows. Section 2 describes the system model including channel, user association, fractional power control and the deployment scenario. Section 3 characterizes the

measurements of interest in this work. Specifically, the joint spectral efficiency measure is defined. Section 4 presents numerical results and work insights. Finally, some conclusions are outlined.

2 System Model

A two-tier Poisson heterogeneous cellular network is considered. Figure 1 shows the system model. Tier-1 contains the macro BSs with fixed transmit power of P_1 and tier-2 is formed by pico BSs with fixed transmit power of P_2 assumed to be lower than P_1 . The locations of the base stations are modeled by independent homogeneous Poisson Point Processes (PPP) denoted by Φ_k with intensity λ_k , where k intends for macro or pico BS. Please, note, that $\Phi_{BS} = \Phi_1 \cup \Phi_2$ also forms a homogeneous PPP with intensity $\lambda_{BS} = \lambda_1 + \lambda_2$.

Users are modeled by another independent homogeneous PPP Φ_u with intensity λ_u . All the user equipments (UEs) have a transmit power P_u which might be modified by Fractional Power Control (FPC) to partially compensate path losses to the BS they are associated to.

In this paper, 3GPP channel model [5] has been used for the analysis purpose. Path losses L_k between a UE and a certain BS at tier- k located at a distance d from it can be written, with the right constants, as

$$L_k(d) = \frac{1}{K_k} d^{\alpha_k} \tag{1}$$

being K_k the path loss slope and α_k its path loss exponent. As for the uplink, symmetric path losses have been considered. Different log normal shadowing averages for macro and pico cells have been taken into account.

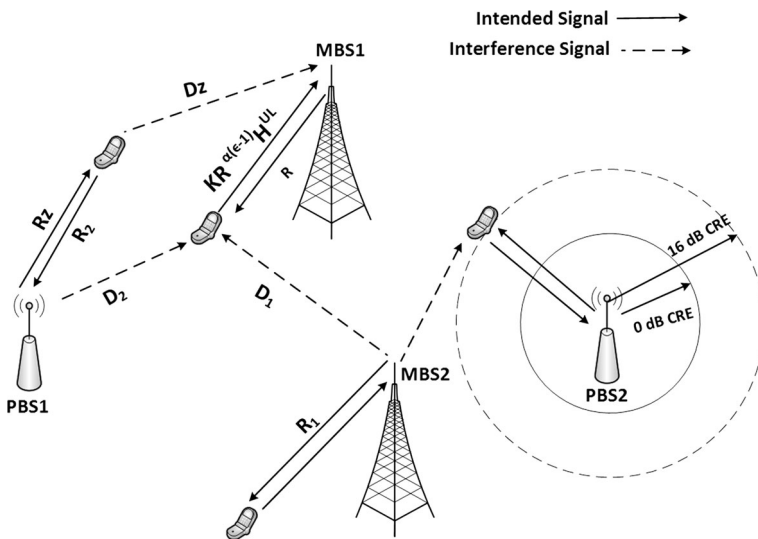


Fig. 1 System Model showing the intended and interference signals in uplink and downlink along with the CRE effect

For the channel fading, only Rayleigh distribution has been considered. The fade attenuation on any link between BS and UE is thus considered to be exponentially distributed with unit mean, i.e. $H_k^{link} \sim \text{exp}(1)$, whichever layer ($k = 1$ or $k = 2$) or link (DL or UL) is considered.

2.1 User Association and Fractional Power Control

In this paper, we have considered two serving BS selection criteria or association rules which determine the BS to which the user is associated. Distances from the associating UE z to the set of BS at k -tier Φ_k is named as $\{R_k^{z,m}\}$, being $\{R^{z,m}\}$ the distances to whole set of BSs Φ_{BS} . The tier the user is associated to is named as k^* and by m^* the specific BS. We will name as R_z to the distance from the UE z to its serving BS, $R_z = R_{k^*}^{z,m^*}$.

As a first criteria, a mobile user is connected to the nearest BS. This is equivalent to dividing the whole space R^2 into Voronoi regions. An active uplink is scheduled to that same nearest BS. Note that the associated BS is also the nearest one for the uplink.

As a second criteria, a mobile user is connected to the BS from which the UE receives the maximum average power in the downlink, possibly biased by certain cell range expansion in order to offload users from macro to pico BSs. We assumed all the pico BSs have the same CRE bias $\tau_2 = \tau$ while macro BSs are not biased $\tau_1 = 1$. Thus, at each layer, the candidate BS is the nearest BS of that layer from the UE.

In both association models, the received average power by the user from the BS it is associated to can be written as $P_z^{DL} = P_{k^*} K_{k^*} R_z^{-\alpha_{k^*}}$ while average interference power received by another UE located at a distance D_z from the same BS is $P_{k^*} K_{k^*} D_z^{-\alpha_{k^*}}$.

Association in the uplink is assumed to be coupled to that in the downlink. The FPC is thus modeled as a function of the distance toward its associated BS R_z . Using this model, the average transmitted power by a UE is a function and given by $P_z^{UL} = P_u R_z^{\epsilon \alpha_{k^*}}$ with the power control factor $\epsilon \in [0, 1]$. The average power received by a certain BS belonging to k -tier and located at a certain distance D_m from the UE can be evaluated as $P_z = P_u R_z^{\epsilon \alpha_{k^*}} K_k D_m^{-\alpha_k}$. Specifically, average power received by the BS the user is associated to can be described as $P_u K_{k^*} R_z^{(1-\epsilon)\alpha_{k^*}}$.

Figure 1 shows the macro-pico deployment scenario. The UEs are connected to their macro or pico BSs according to the association criteria as discussed above. Signal path is shown with solid arrows while interfering signals are found with dashed arrows. When considering the criteria of maximum average receive power in the downlink, the UEs might be offloaded to pico BSs by adding a bias in the average received power.

3 Joint Coverage and Symmetric Spectral Efficiency

3.1 Joint Coverage Probability

We randomly choose a BS from the PPP Φ_{BS} and a specific UE from the set of users associated to it and focus on the SINR received at that selected BS–UE pair. We took out the sub-index for the intended BS and named it as m or z for the interfering devices while understood the proper value depending on the BS layer. Thus, the distance between the chosen BS and UE is denoted as R . The set of interfering mobiles in the UL is named Z , and that of interfering BS in the DL as M .

We will begin evaluating the Signal to Interference and Noise Ratio (SINR) in the downlink. The SINR at the downlink can be written as [3]

$$SINR^{DL} = \frac{P_z K R^{\alpha} H^{DL}}{\sigma^2 + I_M} \tag{2}$$

with I_M the total power received from any BS except the intended one:

$$I_M = \sum_{m \in M} P_m K_m D_m^{-\alpha_m} H_m. \tag{3}$$

At the same BS–UE pair, the SINR at the uplink can be evaluated as [6, 7]

$$SINR^{UL} = \frac{P_u K R^{\alpha(\epsilon-1)} H^{UL}}{\sigma^2 + I_z} \tag{4}$$

where I_z is given by

$$I_z = \sum_{z \in Z} P_u R_z^{\epsilon \alpha} K D_z^{-\alpha} H_z. \tag{5}$$

being R_z the distance between the interfering UE to its associated BS and D_z that to the BS of interest. All fading channels H^{DL} , H_m , H^{UL} , and H_z are assumed to be i.i.d. exponential variables.

The aim of this work is to evaluate the joint complementary cumulative distribution function (CCDF) for both SINR at uplink and downlink:

$$F_{SINR^{DL}, SINR^{UL}}(x, y) = Prob[SINR^{DL} > x, SINR^{UL} > y] \tag{6}$$

Marginal CCDFs for UL and DL can be obtained from it by taking $x = 0$ and $y = 0$, respectively.

We define the transmission success probability (TSP) [1] as the probability of both uplink and downlink SINR being greater than certain threshold x , that is:

$$TSP(x) = F_{SINR^{DL}, SINR^{UL}}(x, x). \tag{7}$$

From previous expressions it is clear that although independence between both SINRs could be guessed if conditioned to the set of distances in the network, high correlation would exist between distance distributions. Thus, that probability cannot be assumed without discussion as the product of probabilities, i.e., $TSP(x) \neq F_{SINR^{DL}}(x)F_{SINR^{UL}}(x)$ (although some previous works did it [1]). Moreover, coupling between DL and UL creates stronger dependence not taken into account in previous bibliography [2].

3.2 Symmetric Spectral Efficiency Distribution

In order to perform Adaptive Modulation and Coding (AMC), the range of SINR is divided in to L fading regions $\mathfrak{R}_i = \{\Psi_{i-}, \Psi_i\}$, $i = 0, 1, 2, \dots, L - 1$ with $\Psi_{-1} = 0$ and $\Psi_{L-1} = \infty$. Within the fading region \mathfrak{R}_i , a certain constellation/modulation scheme with M_i bits/symbol is employed. The set of switching thresholds between constellations $\{\Psi_i\}_{i=0, \dots, L-1}$ are to be designed to accomplish certain constraints and optimizing key performance indicators in the system. The spectral efficiency for UL/DL can be thus written as a function of the SINR as:

$$\eta = \log_2(M_i), SINR \in [\Psi_{i-1}, \Psi_i]. \quad (8)$$

In any wireless service, certain minimum transmission spectral efficiency should be exceeded in order to allow a minimum rate. We are evaluating then:

$$F_{\eta^{DL}, \eta^{UL}}(x, y) = Prob[\eta^{DL} > x, \eta^{UL} > y] \quad (9)$$

Marginal CCDFs for UL and DL spectral efficiency can be obtained from it. For symmetric services, both up and down links should be able to carry enough throughput. We are then considering the random variable Symmetric Spectral Efficiency η^{sym} whose CCDF is given by:

$$F_{\eta^{sym}}(x) = Prob[\eta^{sym} > x] = Prob[\eta^{DL} > x, \eta^{UL} > x] \quad (10)$$

4 Numerical Results

We have used the 3GPP model for the simulation purpose. The simulation parameters are shown in Table 1. We will discuss the marginal uplink, downlink and joint uplink/downlink coverage and spectral efficiency results for a heterogeneous cellular network in this section.

4.1 Coverage

The joint coverage probability as given by Eq. (7) along with marginal uplink/downlink coverage probabilities have been evaluated. Results for the nearest and average BS criteria are shown in Figs. 2 and 3 respectively. Uplink results have been obtained with no

Table 1 Simulation parameters of 3GPP model

Bandwidth	10 MHz
Noise spectral density	-174 dBm/Hz
Mean log normal shadowing for macro cells	10 dB
Mean log normal shadowing for pico cells	6 dB
Macro BS density	0.24 BS/Km ²
Pico BS density	2× macro BS density
Users' density	10× macro BS density
Pathloss (dB) for macrocells	37.6×log(d(m))
Pathloss (dB) for picocells	36.7×log(d(m))
D/L macro BS transmission power	46 dBm
D/L pico BS transmission power	24 dBm
U/L users' transmission power	23 dBm
Macrocell transmit antenna gain	15 dB
Picocell transmit antenna gain	2 dB
User receive antenna gain	0 dB
Fractional power control index ϵ	0, 0.5, 1
Cell range expansion bias τ	0, 16 dB

fractional power control $\epsilon = 0$ as well as utilizing fractional power control of $\epsilon = 0.5$ and full power control ($\epsilon = 1$). It is found from these results that under the nearest BS criteria, most users are camped to pico BSs because of their higher density while when users are associated to the BS which is received with maximum average power, mostly the users are connected to macro BSs. As expected, the marginal downlink coverage using average BS criteria is better than the nearest BS criteria. For the uplink coverage, the situation is reverse as nearest criteria improves the received power at uplink.

The transmission success probability (TSP) as the probability of both uplink/downlink SINR being greater than the certain threshold x described in Eq. (7) is also shown in in Figs. 2 and 3. As both SINR should be greater than x , TSP is lower than their marginal probabilities.

Independence assumption between marginal SINRs is explored in Fig. 4. In that figure, TSP is compared to the product of marginal uplink and downlink probabilities. If both SINRs were independent, both results should fit. However, it is quite clear that TSP is not simply equal to the product of marginal uplink and downlink probabilities. Dependence is stronger under the nearest BS association criteria compared to that of maximum average received power.

Results regarding the effect of cell range expansion bias are shown in Fig. 5. Range expansion is applied as a form to offload users from macro to pico tier when users are associated to the BS strongly received. The techniques such as backhaul throughput limits or maximum number of users due to signaling are not addressed in this paper. Marginal uplink/downlink as well as joint coverage probability of uplink and downlink reduces with higher CRE. Users associated with biased pico BSs transmit with higher power because they are farther from their desired BS, producing high interference in uplink particularly at higher values of ϵ . Similarly the offloaded users from their respective macro BSs face strongest interference in the downlink [8]. This interference phenomenon can be minimized using interference management techniques such as the time domain enhanced inter-cell interference coordination (eICIC). Interference aware power control can improve UL performance.

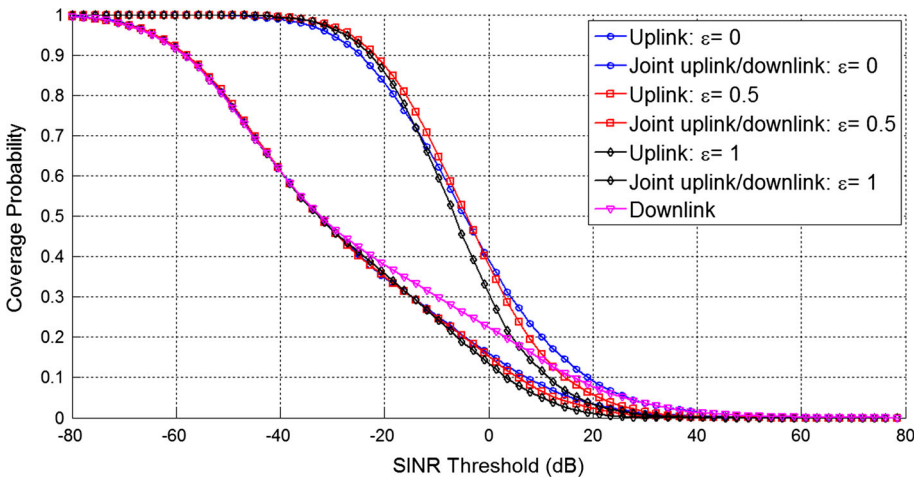


Fig. 2 Marginal uplink, marginal downlink and joint uplink and downlink coverage probabilities for association to the nearest BS

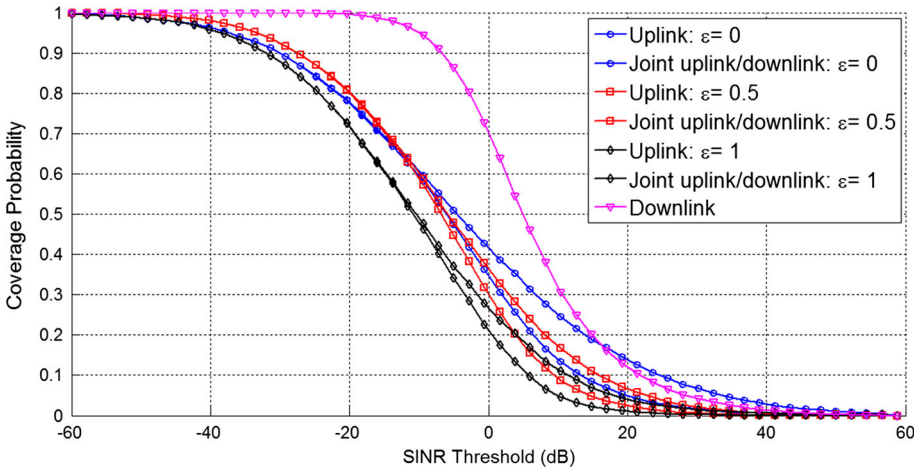


Fig. 3 Marginal uplink, marginal downlink and joint uplink and downlink coverage probabilities for average association case

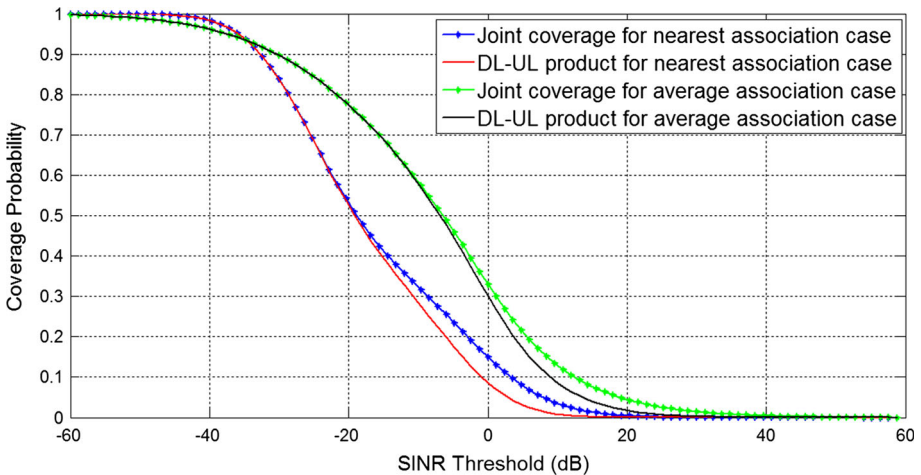


Fig. 4 Joint uplink/downlink transmission success probability for both associations compared to the probability evaluated from independence assumption

4.2 Spectral Efficiency

We have up to now discussed the CCDF of SINR for marginal uplink, marginal downlink and joint uplink/downlink which is nothing but a coverage, a measure of system performance. Now We focus on the spectral efficiency performance under adaptive modulation and coding. The set of switching thresholds considered in this work, shown in Table 2, were designed with the help of an LTE link simulator available in [9]. They maximize the spectral efficiency while the instantaneous BLER does not raise the 10% target BLER at any point of the interval. Ideal channel estimation and reporting have been assumed. For SNR values below the minimum threshold (i.e., in very poor channel conditions), there is an outage state in which there is no data transmission.

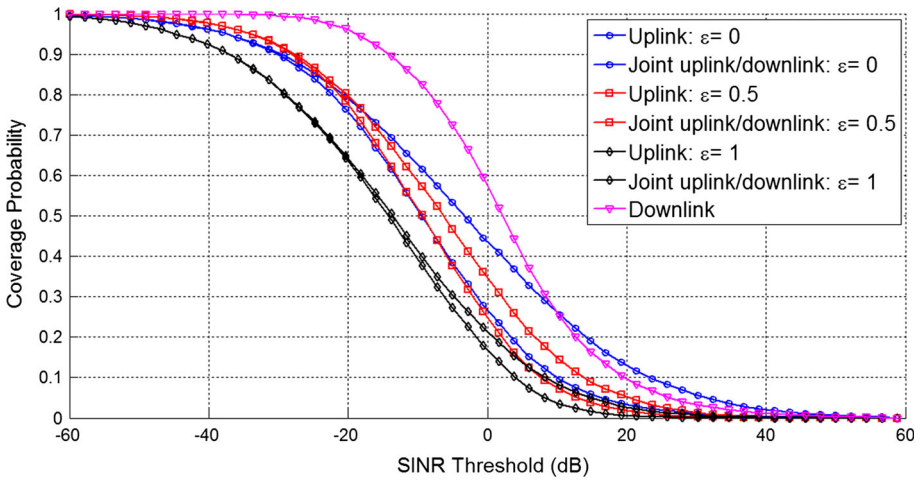


Fig. 5 Marginal uplink, marginal downlink and joint uplink and downlink coverage probabilities for average BS association criteria using 16 dB CRE bias

From the comparison of downlink marginal probabilities of spectral efficiency for both criteria (Figs. 6, 7) it is quite clear (and foreseeable) that the downlink coverage probability under maximum average DL received power association criteria is better than that of the nearest BS case. As the uplink and downlink has different transmit power so the coverage probability for the uplink and downlink is different.

Downlink, uplink and symmetrical spectral efficiency for the nearest BS association is shown in Fig. 6. In this case, uplink has better coverage than the downlink. The joint uplink/downlink coverage is forced to be lowered than uplink by the downlink due to the coupling of uplink and downlink. As we increase the fractional power control ϵ from 0 (no power control) to 1 (full power control), the uplink coverage is decreasing due to the growing interference power as no limit has been placed to transmitted power by the user. Thus, for a symmetrical transmission, not using power control improves the system performance.

Results when user is associated to the BS which is received with stronger average power in the DL are shown in Fig. 7. In this case, downlink coverage is better than that of the uplink. However, for higher values of SINR (i.e. higher spectral efficiency), the uplink with no power control $\epsilon = 0$ is better than the downlink. As the FPC parameter is increased beyond $\epsilon = 0$, the uplink spectral efficiency probability reduces even at high SINR values. The symmetric spectral efficiency is forced to reduce and is coinciding with the downlink.

In some cases the uplink quality under nearest BS criteria is slightly better than that of the average received power association criteria: for uplink the transmit power of users is the same with any association but under the nearest BS criteria, users are closer to their desired BSs. However, uplink coverage under average received power criteria is better than

Table 2 Simulation switching thresholds for adaptive modulation and coding

$\Psi_i(dB)$	-3.7	-1.6	0.0	2.3	3.8	4.8	9.0	10.5	12.4	15.4	17.2	18.9	20.7	24
$\log_2(M_i)$	0.2	0.2	0.4	0.6	1.2	1.5	1.9	2.4	2.7	3.3	3.9	4.5	5.1	5.6

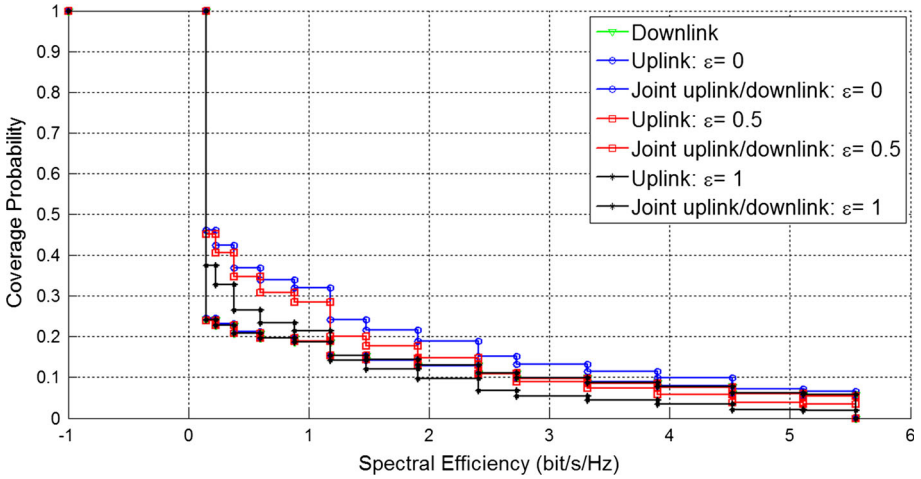


Fig. 6 Marginal uplink, marginal downlink and symmetrical spectral efficiency for association to the nearest BS

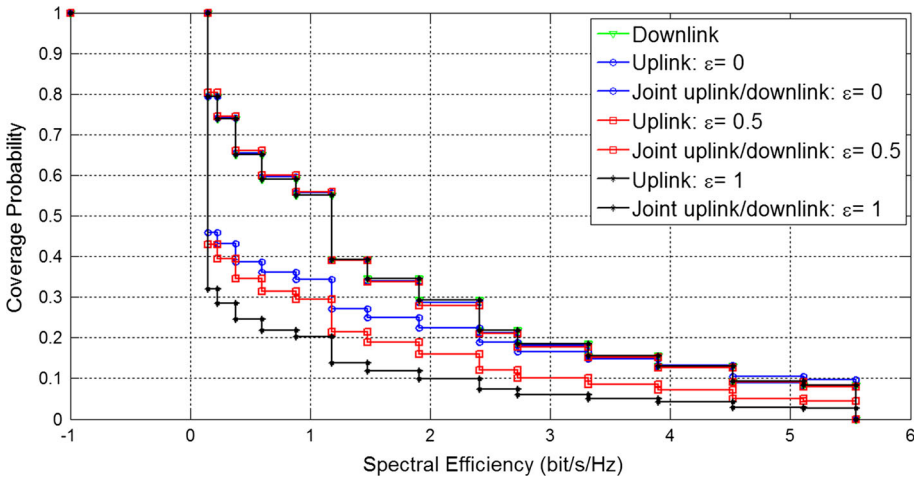


Fig. 7 Marginal uplink, marginal downlink and symmetrical spectral efficiency for association to maximum average DL power

that of the nearest BS case for $\epsilon = 0$. The reason is that users camped on macro BSs suffer overall less interference than those users camped on pico BSs. The parameter set {average criteria, no FPC} is the best to reach high symmetric spectral efficiency.

5 Conclusion

In this paper, the joint uplink/downlink SINR distribution in two-tiers heterogeneous cellular network have been analyzed by considering the power control effect in the uplink for 3GPP model. The evaluation was carried out considering the nearest BS and the

maximum downlink average power association criteria. Fractional power control and cell range expansion was taken into account. The probabilities for marginal uplink, marginal downlink and symmetrical spectral efficiencies have also been obtained using adaptive modulation with realistic thresholds from an LTE simulator. The results show a remarkable lack of independence and better symmetric spectral efficiency under average association. Moreover, associating the user to the BS received with stronger average power in the DL and avoiding the use of power control leads to the highest symmetric spectral efficiency.

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