BASE STATION ASSOCIATION AND INTERFERENCE CHARACTERIZATION IN HETEROGENEOUS WIRELESS NETWORKS

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Abstract

Research and development in the field of cellular networks is at his highest today, and in continuous growth. Every researcher is trying every possible method to remedy one single problem: how to accommodate the ever-growing cellular network users within a limited spectrum. With the growth of heterogeneous networks, that allow the users access to high speed data connections almost everywhere, and with different transmission powers for different cell types, the frequency usage is a concerning factor.

Arguably one of the best solutions is for all the cells within a region to have a uniform frequency. This, however, leads to another concern – co-channel interference. Since every base station transmits signals at the same frequency, a receiving device might experience interference in its desired signal, from undesired stations. Also, the presence of a station with a higher transmitting power may cause problems in the surrounding stations. At times, this interference might also cause an outage, thus disrupting the service momentarily. In order to limit the impact of co-channel interference, its further scrutiny is inevitable. This includes not only the study of spatial distributions and dependencies, but also the base station association schemes, which allow stations with lower transmitting powers to be used without suffering with a large probability of outages. This project involves characterization of such co-channel interference. Probability of outage, with respect to the location of mobile device as well as with respect to the received power or distance to the associated station and interfering stations is also examined.

Acknowledgment

First and foremost, I would like to express my sincere appreciation to Mr. Sachitha Kusaladharma for his supervising this work, showing me the way to go when I was confused, always with priceless patience and dedication. This work would not have been possible without that precious help.

I would also like to thank my friends and colleagues for all the priceless moments we had together, both in school and outside of it. Thanks for all the trips, parties and long lunches. I hope we will meet again somewhere! A special mention to Ravinder Kaur, that has been a true support and friend in all this period.

Last but not least, I would like to mention my parents, Karamjit and Balwinder and my brothers Kamal and Ivjot: thank you for your love and support. Although you are far away, at every moment I feel like you are always close to me.

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1 Introduction

Wireless networks are high in demand in today's world, not only in the number of wireless devices, but also in the growing need for high speed data transfer. As a result of this, the demand for band width is rising but the spectrum is finite. In order to improve spectrum efficiency, and also due to their flexible adaptation to the surrounding environment (inner spaces, urban areas), heterogeneous wireless networks are encouraged. Heterogeneous networks have different classes of base stations serving mobile users, with different transmission power. For example, macro cells would cover large geographical areas (up to 30km), while pico-cells may have transmitting ranges as low as a few dozen meters. This allows a very good coverage in the desired area, without zones where the signal coverage is affected by some local constraints (high buldings, structures with different materials, indoor locations and other factors).

In emerging cellular network standards like LTE and LTE-advanced, the frequency reuse factor is 1, and all these networks will be utilizing the same frequency. The presence of a large number of stations sharing the same frequency and transmitting at different powers leads to a possible increase in the outages of the services experienced by the users, where stations transmitting at higher power levels interferewith users which associate with low power base stations.

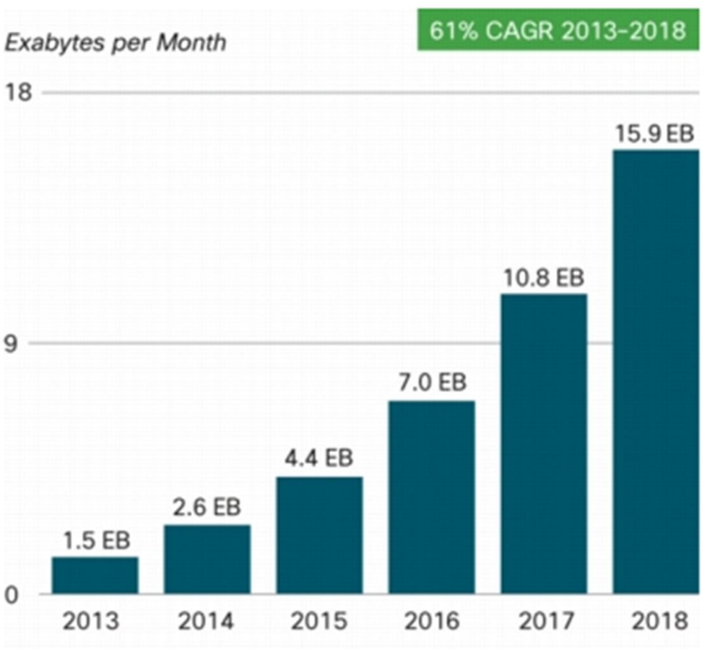

Figure 1 - Cisco prediction of monthly global data traffic [1]

With the increase in the number of users, each one demanding more and more access to data (see Figure 1 and Figure 4) the need for these flexible network structure is increasing [2]. But the risk of outages has to be taken into account due to the fact that the users that share the same frequency in a possibly high density populated location is increasing. In order to counter this fact, there are several association schemes between the user equipment and the station that can be used in order to guarantee a balanced use of the network, with low probabilities of outages.

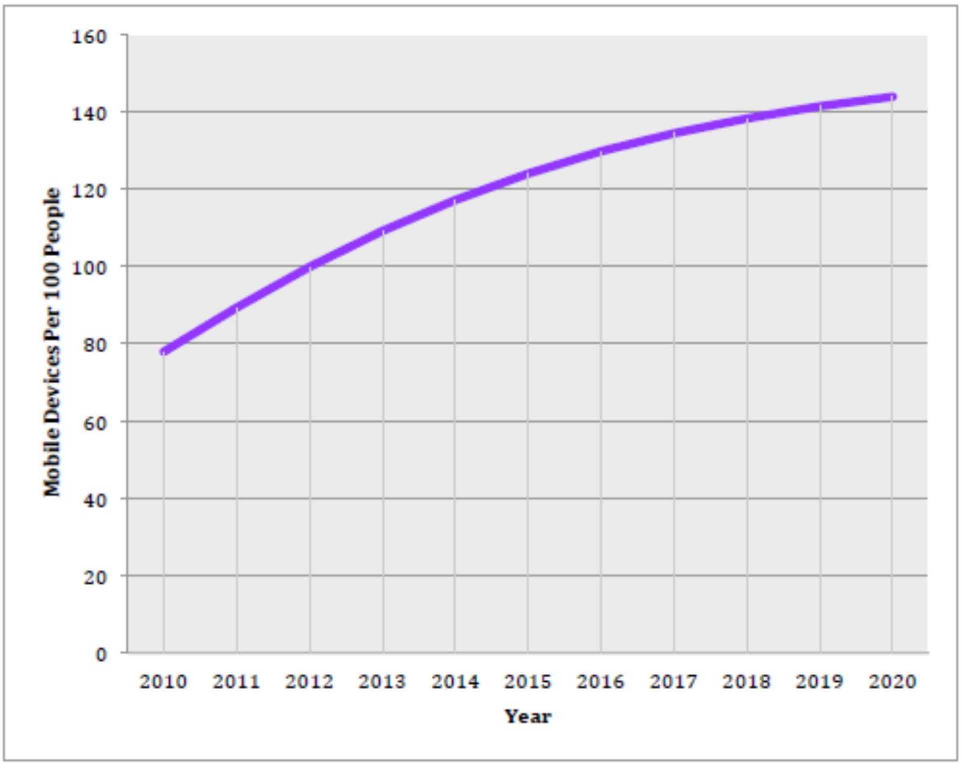

Figure 2- Mobile devices per 100 people (Frederick S. Pardee Center for International Futures)

Problem Statement

In a heterogeneous environment, the mobile user has to decide on the appropriate base station to associate to. After association, the signals from other base stations would become interference (Figure 3). This interference will degrade the user's quality of service, and has to be analyzed. The base station association algorithm would also affect the experienced interference, and has to be chosen accordingly. Furthermore, the received signal in dense areas may suffer from the presence of obstacles and multiple reflections. Some models for this fading phenomena are presented in this report, including Rayleigh and Nakagami-m fading model.

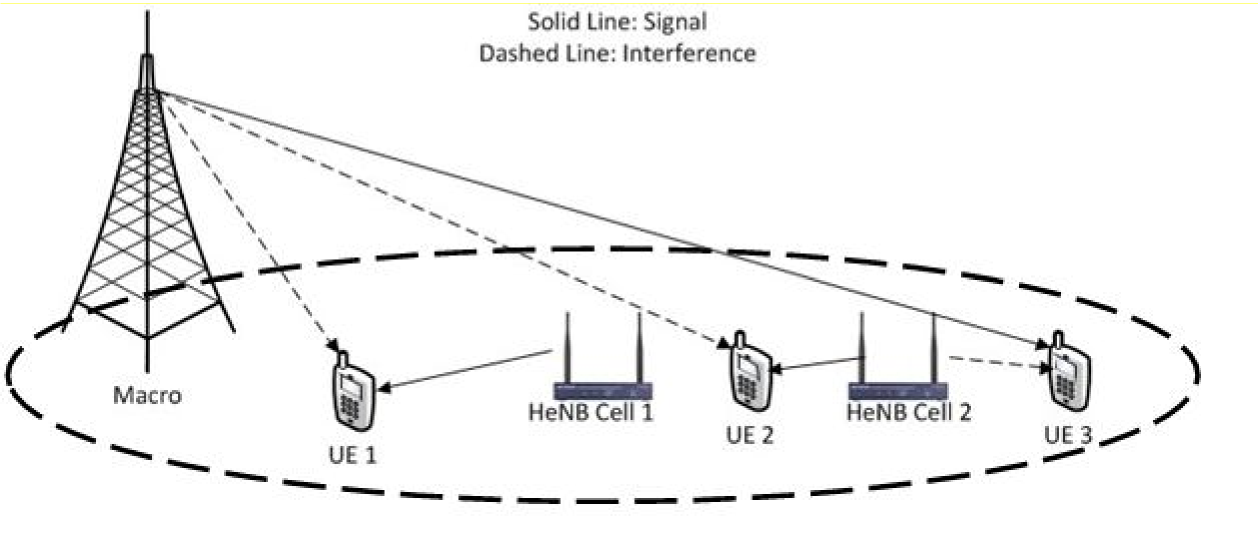

Figure 3- Interference in Heterogeneous Networks (Long Gao, 2013)

In this work, by using an extensive number of simulations for two different association schemes – closest station and maximum received power – in an heterogeneous network (see Figure 4), with the two fading models mentioned above, some discussion is presented on these results and some practical conclusions are taken.

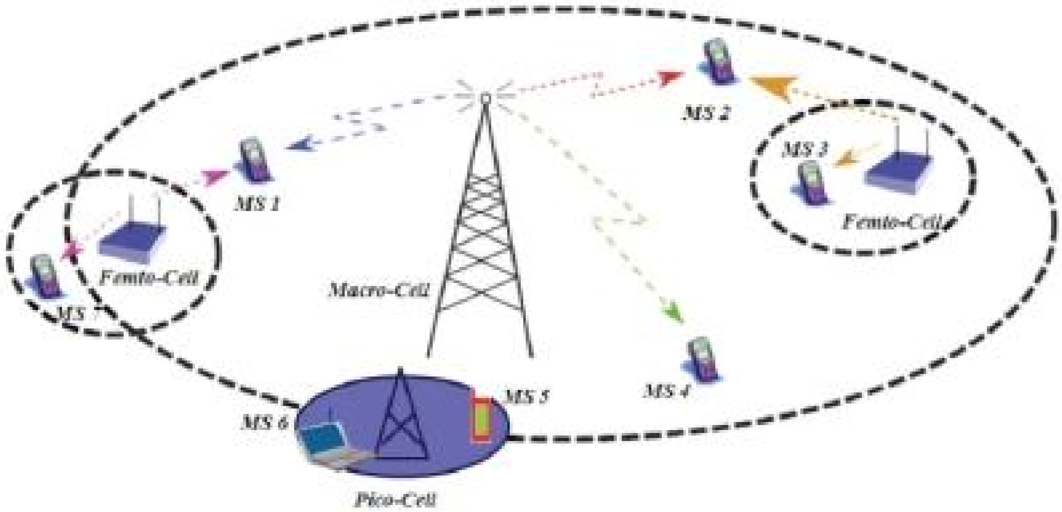

Figure 4- Heterogeneous mobile network

Report Outline

This work is organized as follows:

- Chapter I – this introductory text, with an overview of the project
- Chapter II – background theory used for the analysis of interference in different scenarios
- Chapter III – analysis of the interference in the case of the nearest station association scheme
- Chapter IV – analysis of the interference in the case of the association scheme based on the station with maximum received signal power.
- Chapter V - here it is presented a discussion of the simulation results from Chapters III and IV, with comparisons.
- Chapter VI – a conclusion is presented.

2 Background Theory

In order to study the interference in heterogeneous networks, a few theoretical tools are used. The transmitted signals experience path loss related to the propagation path. Furthermore, the transmission mean is not perfect. Multiple reflections may occur due to environment conditions, which results in Rayleigh or Nakagami-m fading in the received signal power.

In the presence of a heterogeneous network, the user can choose the base station it wants to associate to ([3], [4]). Multiple algorithms exist to balance the received signal power with the usage of multiple base stations by the different users and avoide cases where a few stations are used and thre rest is ignored. In the simulations presented in this report, the closest station and higher SNR receiver association schemes are used. Those are some of the most basic association schemes possible, but they already provide us with some comparison of performance that can be useful when designing the network. That network design is assumed in here, for all the simulations, to be a random structure following a Poisson Point Process model for the distribution of both the macro base stations and the pico-cells. This is a commonly used model for simulation of wireless networks [3].

A brief description of each of these topics is presented below, together with some assumptions used in the simulations performed.

Path loss model

Theoretical and measured propagation models indicate that average received signal power decreases logarithmically with distance, which is a normal assumption for a line of sight propagation model where the transmitted power is spread over an area that is larger and larger with the distance.

There are many models for path loss used in the literature. The simplest one is the free space path loss model, where the path loss is proportional to the square of the distance.

$$FSL \propto (\frac{4\pi d}{\lambda})^2$$

with d being the distance and λ the wavelength of the signal.

With the existence of environmental constrains, some empirical models have been developed to match the measured data, taking into account the local performance. Examples of such models include the Okumura model, the COST 213 Hata model and the COST 231 Wolfisch-Ikegami model ([4], [5]).

As an example, the COST 213 Hata model is given by (in dB)

$$PL = 46.3 + 33.9 log_{10}(f_c) - 13.82 log_{10}(h_t) - a(h_r) + (44.9 - 6.55 log_{10}(h_t)) log_{10}(d) + C_M$$

With h_t is the transmit antenna height, h_r is the receiver antenna height, f_c is the transmit signal frequency, and d is the distance between the transmitter and receiver.

The parameters$a(h_r)$ and $C_M$depend on the type of environment (urban/suburban, suburbs).

These models usually represent the best the conditions for a specific location. However, they add complexity to the simulations. Therefore, another model is introduced, the simplified path loss, which on average, is given by

$$PL(d) \propto (\frac{d}{d_0})^n$$

Where d is the distance between the transmitting station and the user and d_0 is a normalizing constant. This can be normalized by considering d_0=1, which leads to

$$PL(d) \propto d^n$$

which, in dB, can be expressed as

$$PL(d) = PL(d_0) + 10.n.log\left(\frac{d}{d_0}\right) \quad = PL(1) + 10.n.log(d)$$

This is the model used in the simulations performed.

Rayleigh and Nakagami-m fading

In order to describe the statistical varying nature of the received envelope of a signal experiencing fading, the Rayleigh distribution is commonly used. It is considered that a large number of reflections are present, and typically this is found in environments with a large number of obstacles. In that case, the phase of the received signal is modeled as random variable with uniform distribution and the envelope amplitude is scaled by a Rayleigh random variable following the probability density function (pdf):

$$p(r) = \begin{cases} \frac{r}{\sigma^2}\exp\left(\frac{-r^2}{2\sigma^2}\right), r \geq 0 \\ 0, r < 0 \end{cases}$$

A graph of this pdf is shown below in Figure 5.

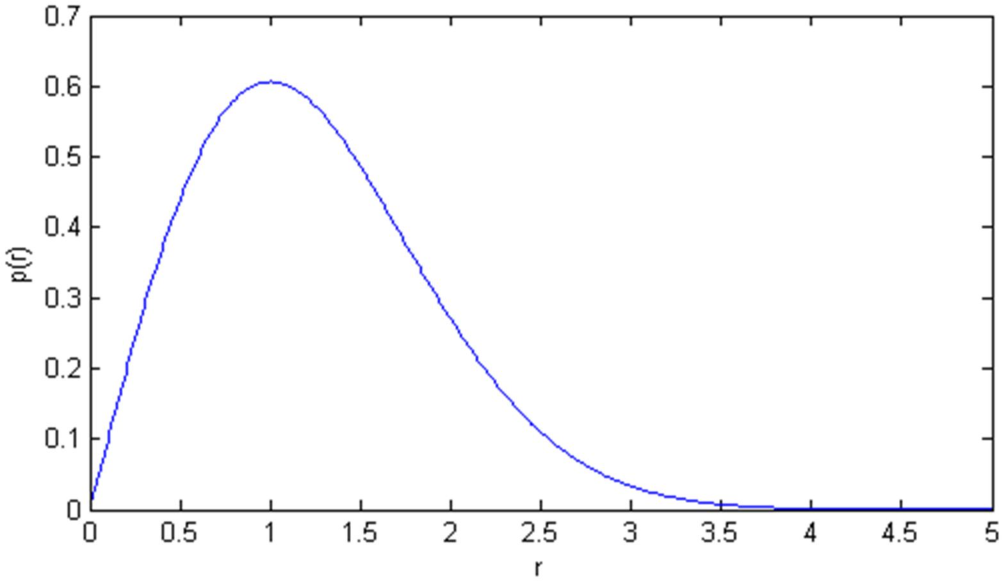

Figure 5- Rayleigh probability density function - example

It should be noted that while the Rayleigh distribution denotes the envelope amplitude, the power is specified by an exponential distribution [4]:

$$f_\gamma(r) = \frac{1}{\gamma}\exp\left(-\frac{r}{\gamma}\right), r \geq 0$$

where γ is the average received signal power.

This Rayleigh component is also called the random or scatter or diffuse component. An example of the Rayleigh fluctuations of the envelope amplitude over time is given in Figure 6. It is interesting to notice the sudden variations of amplitude of the signal envelope that can exist, which can lead to some short term outages when in the presence of multiple signals, where the interfering signals can dominate.

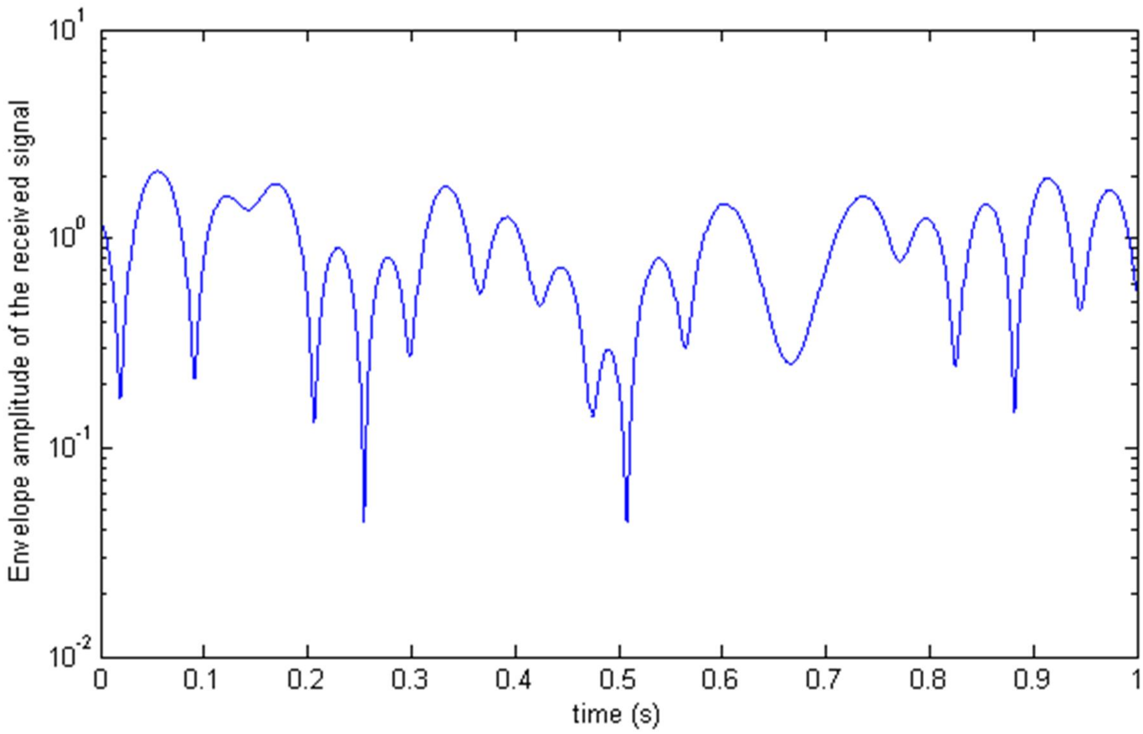

Figure 6- A typical Rayleigh fading envelope

A more general fading model that is used is the Nakagami-m model. It is convenient to use because there are situations where it matches considerably better the real data, where very fast fluctuations in signal data may occur. The magnitude of the envelope with respect to the mean amplitude follows a Nakagami-m distribution with the pdf given by:

$$p(r) = \begin{cases} \dfrac{2m^m}{\Gamma(m)\Omega^m} r^{2m-1} \exp(\dfrac{-m}{\Omega} r^2), r \geq 0 \\ 0, r < 0 \end{cases}$$

It is interesting to note that for m=1, this is the Rayleigh pdf. For m=1/2, it is the one-sided Gaussian distribution. For large values of m, the fading is less severe, and the distribution tends to an impulse as the parameter m tends to infinity.

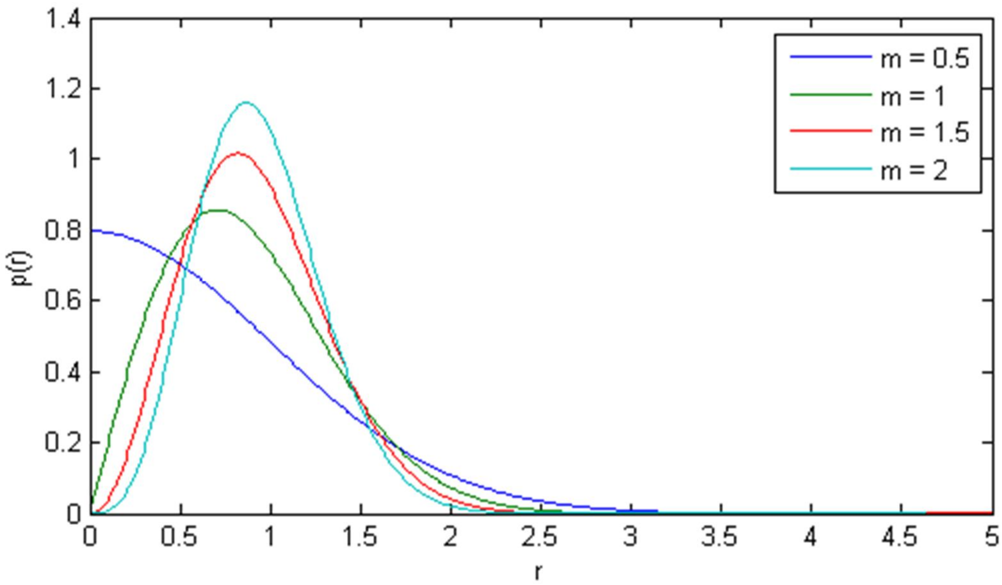

Figure 7- Nakagami-m p.d.f. as a function of r for 4 different values of m

These fading models can be applied by generating a vector that satisfies this pdf for each element, and using the multiplication of this vector with the amplitude of the original signal one computes the new received envelope. By doing that, some fluctuations will occur around the mean average amplitude.

Poisson Point Process

In order to model the spatial distribution of the interferer nodes, several models have been used in the literature [4]. The randomness associated to this spatial structure must take into account the usual fact that powerful transmitters can be spread more or less homogeneously through a vast area, with some distance between them, while lower power stations are usually in larger number and can be much close to each other. A popular model is the 2D Poisson Point Process ([5], [6], [7], [8]), where the distribution of the stations depends on the Poisson distribution with respect to the location. For a 2-dimensional homogeneous (intensity parameter is constant), the probability of having n nodes in a region B is given by

$$p(N(B) = n) = \frac{(\lambda . v(B))^n}{n!} e^{-\lambda . v(B)}$$

where the parameter λ is the intensity parameter and $v(B)$ is the area of B [4]. In the case of a nonhomogeneous Poisson Point process, the intensity parameter is dependent of the location.

In the simulations, two different layers, corresponding to two different types of cells are used, and for each cell, a Poisson Point Process (PPP) is used, with a certain parameter λ_i, corresponding to different concentrations of different cells (the base stations are assumed to be in less number than the pico-cells in general).

A typical spatial distribution of two layers of cells, with different intensity parameters and following a PPP, can be seen in Figure 8.

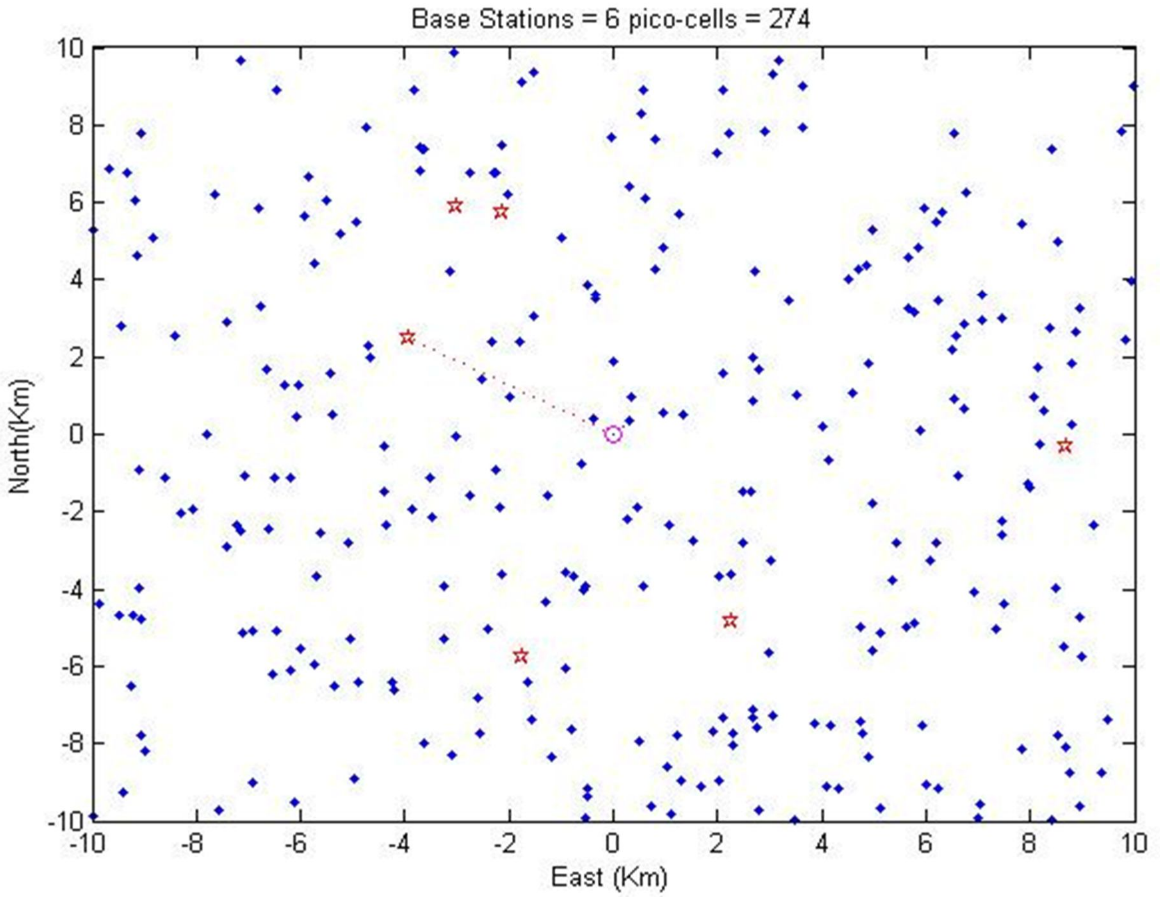

Figure 8 - A typical distribution of base stations (red stars), pico-cells (blue dots) and user location (red circle), distributed as independent Poisson Point Processes. The dotted lines show the closest base station and pico-cell with respect to the user.

When studying outages probabilities, the dependence on the network structure is surely relevant, so, in order to obtain general results, a large number of simulations with different samples of networks following a certain PPP model with given intensity parameters is needed in order not to be biased by just a few samples that may not represent a general point of view.

Interference analysis

In order to study the influence of other transmitting stations in the link user - desired station, a simple test will be used. The Signal to Interference Noise Ratio can be computed by [1]

$$SINR = \frac{G_{ii}P_i}{\sum_{j\neq i}^{N_{stations}} G_{ij}P_j + \sigma^2}$$

Where $G_{ii}$and $G_{ij}$are gains associated with the transmitters i and j. The higher $G_{ii}$the better the performance with respect to the interference, while for G_{ij}we have the opposite effect. The SINR will allow one to indicate if there can be an outage due to the interfering signals.

The probability of the occurrence of an outage is given by

$$P(SINR < T) = \\ = P(\frac{G_{ii}P_i}{\sum_{j\neq i}^{N_{stations}} G_{ij}P_j + \sigma^2} < T)$$

where T is a threshold. In the simulations, it is assumed that both $G_{ii}$and G_{ij} are equal to 1, and the interference is tested as a function of T, related to the gain between the primary transmitter and receiver. By doing this, we can relate in network design studies the SINR with the variations of G_{ii} and G_{ij}, from which T can also be deducted.

Association Schemes

As refered before, in the presence of a heterogeneous network, the user can choose the base station it wants to associate to. Having multiple options, the goal is to find a station with a high receiving power, but at the same time, that is not too far, as that can lead to the user transmitting higher power signals and running out of battery ([12], [13]). Furthermore, the presence of a station that transmits with a dominant high power in the surroundings should not force the user to choose that station in all cases, as there is a limited band width that has to be shared among different users. These are some considerations that lead then to the existence of different association schemes. In this work the focus goes to two of them, that are explained below.

Closest station association scheme

This is one of the simplest algorithms available. From all the network of stations where the user can associate to, the user chooses the closest station, while all the others become interferers.

This association scheme allows the user to transmitt low power signals to the station, but it does not necessarily imply that that particular station is the one from which the received signals have the highest power. This is important in heterogeneous networks, as a closest station can be a pico-cell, while in the surroundings there may be located a macro cell transmitting with such higher power that the user receives the highest power from there.

Higher received power association scheme

In this case the simulation will use the received signal that is, on average, the one with higher power, be it transmitted by a base station or a picocell as the one that is the link between the user and the transmitting station. As commented in the closest station association scheme, in this case we ensure that on average the user will be receiving the signal with maximum power. However, in the case of sending data to the station, the user may be using a lot more power if that station is located at a considerably larger distance.

With this association scheme there is also a risk that, in case a base station that transmits with a larger power than the neighbouring ones, the users in that area will be all connecting to that station, leading to congestion in some occasions, and low capacity networks.

Transmission Power

In the simulations the transmitting power for the base stations depends on the layer. Layer 1 consists of stations transmitting with signal power equal to 40dBmW, while Layer 2 stations transmit with signal power equal to 30dBmW.

Simulation structure

For each simulation, the following steps are performed:

- Initialization of the variables
- Definition of the changing parameter and its possible values, together with the possible values of the SINR threshold T.
- For each iteration, a random network structure following a PPP distribution for both layers is generated. In total, 1000 different networks are generated.
- For each network structure, and for each value of the varying parameter, 1000 simulations are performed
- The results are stored per different values of the parameter
- At the end, the results are plotted, typically one line in the graph per parameter, along different values of the SINR threshold T.

3 Association with the closest station

In this chapter, the results of simulation of the outages experienced by a user in a heterogeneous network, as a function of the threshold term T and when the user chooses to associate with the closest station in the network are shown. The simulations in this chapter assume the existence of two different layers of base stations in the network.

The basic expression that is rewritten here to be remembered during the whole chapter is that an outage will happen if

$$SINR = \frac{P_i}{\sum_{j \neq i}^{N_{stations}} P_j + \sigma^2} < T$$

For each set of simulations, a network of stations is generated, and the outage probability of a user is computed, depending on the varying parameters (simulation dependent), for different values of the outage threshold T.

The simulations for this association scheme are divided in 4 types:

- Simulation of the outage probability in the case where the Poisson Point Process (PPP) parameter λ_1 for the network layer 1 is constant, and the PPP parameter λ_2 for the network layer 2 changes. This will allow us to assess the changes in outage probabilities with respect to different network layer densities
- Simulation of the outage probability in the case where the only term that changes in the simulations is the path loss exponent.
- Simulation of the outage probability in the case where there is Rayleigh fading, in the case of different path exponent.
- Simulation of the outage probability in the case where there is Nakagami-m fading, in the case of different path exponent and in the case where the Nakagami-m pdf parameter m changes

Dependence on the Poisson Point Process distribution parameter

As refered in the previous chapter, a Poisson Point Process model for all the network layers is used. In this work, two different types of cells are used, and it is assumed that both of them have a spatial Poisson distribution.

In order to study the dependence on the spatial distribution parameter of the PPP, here defined as λ_1 or λ_2, depending on the layer, the following procedure is followed: λ_1 is kept constant in all the simulations, while λ_2 assumes different values for each simulation. This is done for different levels of the SINR threshold. Figure 9 shows the results of the simulations.

It is clear that there is a dependence on λ_2 for each value of the threshold T. Large values of T lead to almost 100% probability of outages. For smaller values of T, the lower λ_2 the lower the probability of an outage. This result is not surprising, as a higher density of stations may lead to increased interference. High density networks, with λ_2 larger than 0.0001, have an outage probability that is quite relevant even for T= -20dB.

The dependence of the outage probability on the spatial density of the stations in one of the layers is

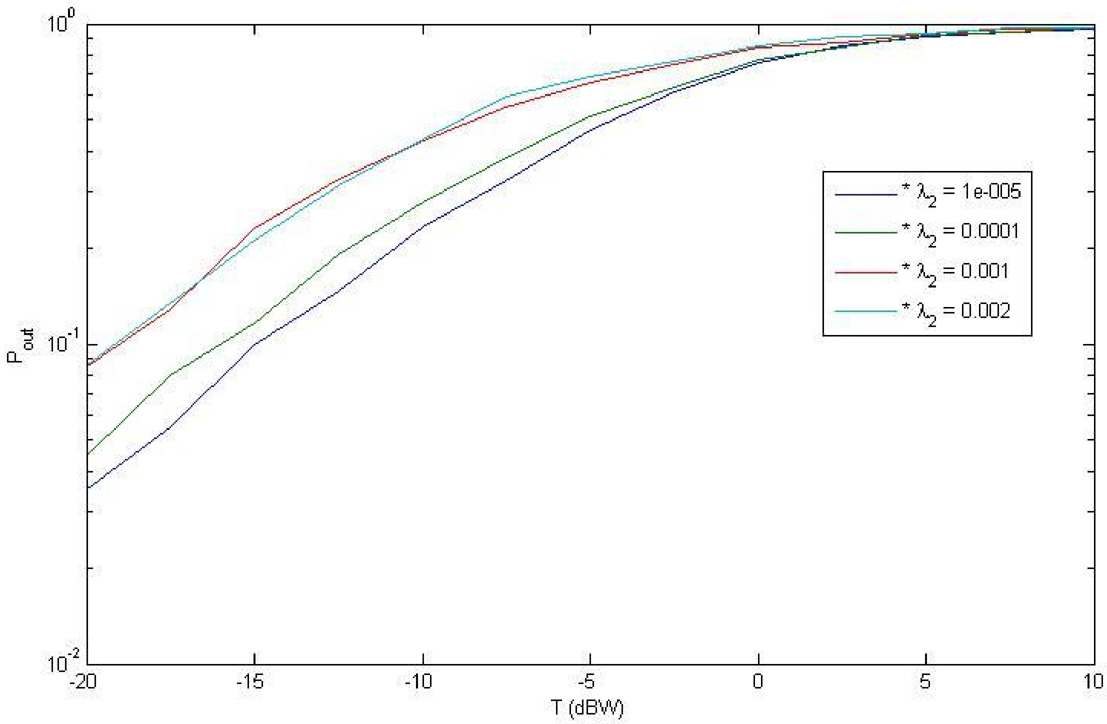

Figure 9- Simulation results for different values of λ_2, when the user associates with the closest station (Rayleigh fading present) and path loss exponent a=2.

then clear, for different values of SINR threshold.

Dependence on the path loss exponent

In distinct environments, the existence of different values of the path loss exponent, which is related to the rate at which the received power decays with the distance from the station to the user, may also affect the interference and outage probability in heterogeneous networks.

Here, once again, the results of the simulation are not surprising. The larger the path exponent, the less relevant are the stations that are more distant than the closest station. Therefore, the outage probability decreases as the path loss exponent *a* increases. The difference between the curves is notable, even for higher values of T. This leads us to think that this is an important factor to be taken into account when designing a network.

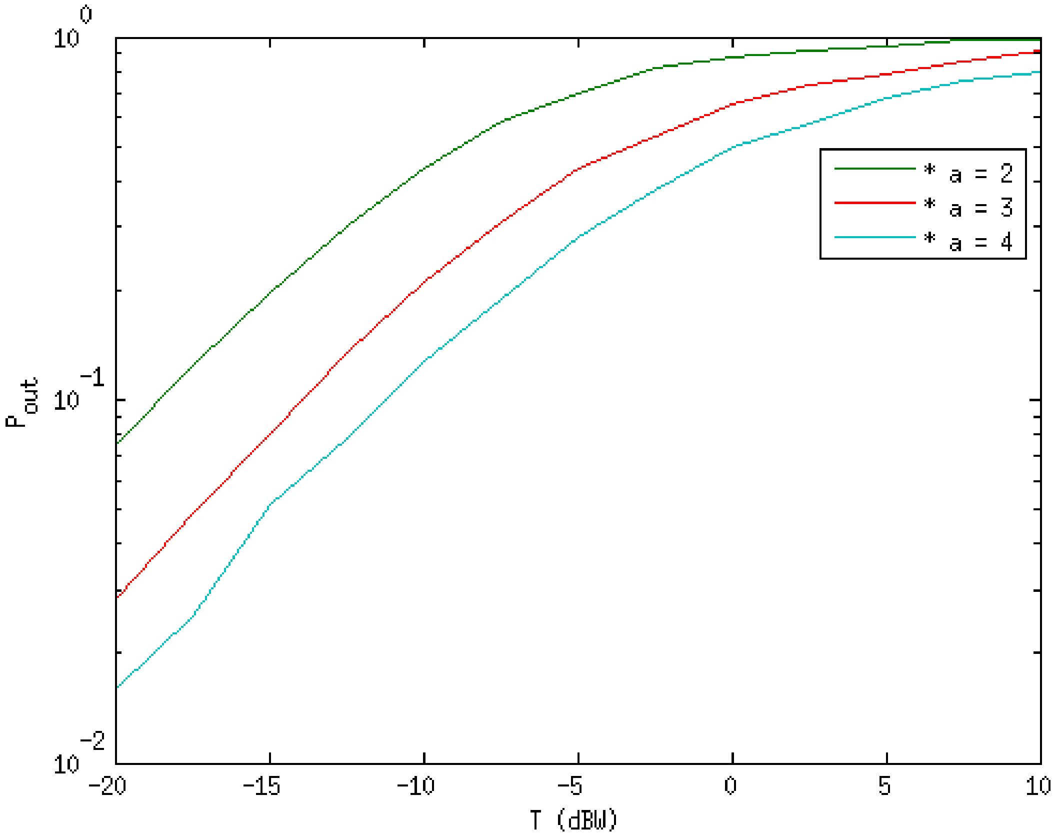

Figure 10- simulation results for the closest station association scheme with different values of the path loss exponent (Rayleigh fading present), with $\lambda_1=10^{-2}$ and $\lambda_2=10^{-3}$

Rayleigh Fading

After the simulations for different path loss exponents, here we compare the results with just simplified path loss model and simplified path loss model (SPLM) + Rayleigh fading. In this case, the received signal will have a multiplied random variable following a Rayleigh pdf, as explained in Chapter 2.

The results of the simulation are condensed in Figure 11.

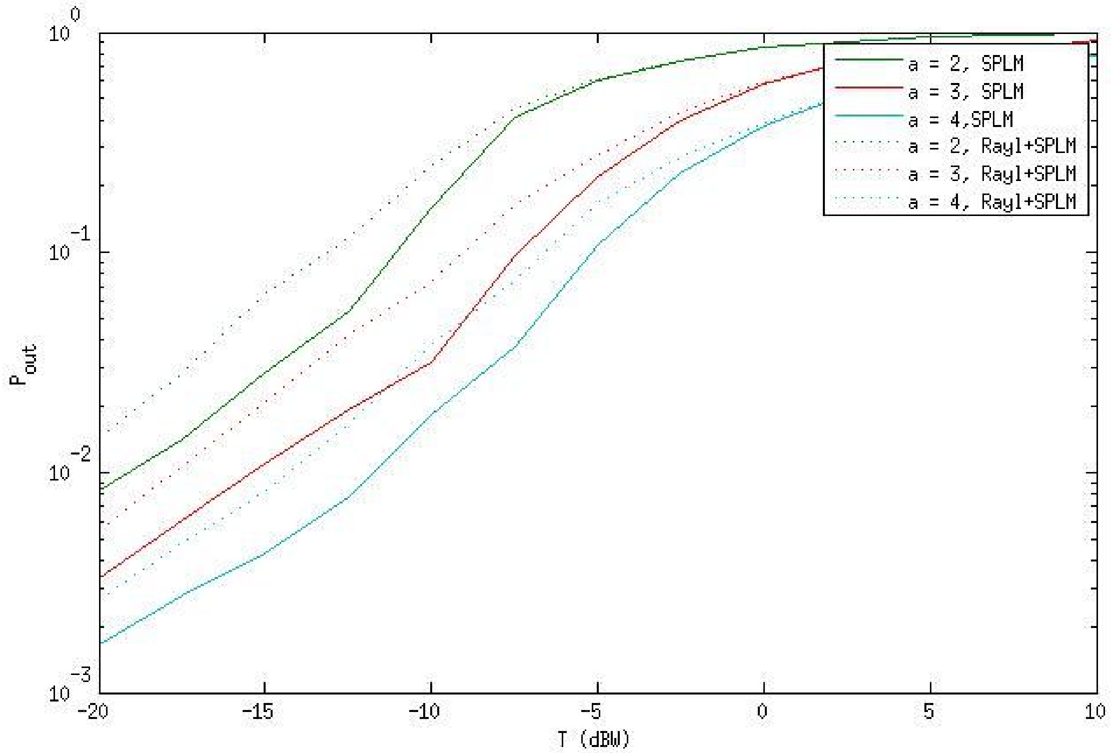

Figure 11- Simulation with the closest station association scheme, with SPLM+Rayleigh fading (dotted lines) and with just SPLM, for different path exponent, $\lambda_1=10^{-2}$ *and* $\lambda_2=10^{-3}$

What is clear is that for values of SINR below 0dB, the existence of Rayleigh fading influences the outage probability, increasing this term by a factor of up to 1,5 for lower values of T. Notice that, similarly to the results presented before, for higher values of the path exponent, the probability outage decreases even with Rayleigh fading.

Nakagami-m fading

As there are scenarios where the Rayleigh fading does not fit the experienced fading so well, it is convenient to use the Nakagami-m distribution, which is more versatile and of which the Rayleigh distribution is a particular case.

Another interesting case is when the Nakagami-m fading depends on the parameter *m*. This is relevant because in practical cases, that parameter can be used to model severe or mild fading, therefore it is interesting to simulate that. Figure 12 shows the results for different values of m when the path loss exponent is equal to 2, and for different values of the threshold T.

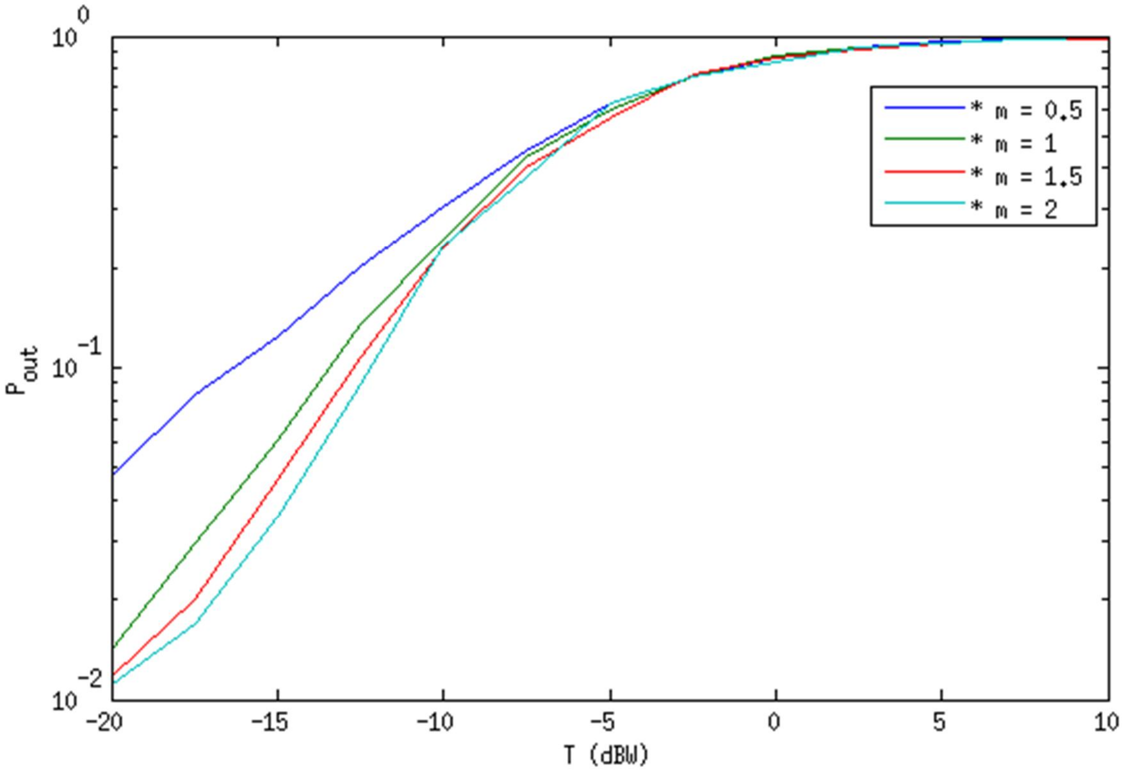

Figure 12- Simulation with the closest station association scheme, with Nakagami-m fading, for different values of m, and with the path loss exponent equal to 2, $\lambda_1=10^{-2}$ and $\lambda_2=10^{-3}$

In this case, there is clearly a strong dependence on m, for lower values of m (moderate to high fading). As refered in the theretical background, when m tends to infinity, there is a tendency to no fading. With lower values of m, the changes in amplitude of the received signals for each station are considerable, leading to more periods with outages.

This justifies the use of the Nakagami-m fading model. For different channel conditions the parameter *m* can be adjusted to better represent the amplitude envelope variations of the received signals. This is a more complete model than the Rayleigh, because it can deal with both higher and milder fading conditions.

Discussion

In the closest station association scheme, a higher density of stations lead to an increased probability of outages, which seems logical, as the concentration of possible interfers increases arround the user.

An increase in the pathloss exponent lead to a decrease in the outage probability. Intituitively, as the pathloss exponent increases, the stations that are farther away become less relevant, and that leads to less interference.

Finally, for values of the threshold T less than 0dB, the Nakagami-m and Rayleigh fading are relevant in the degradation of the availability of service. Especially in the case when m=0.5 for the Nakagami-m fading, the increase in the outage probability is noted even more than for larger values of m.

4 Association with the maximum power received station

In this chapter, the results of simulation of the outages experienced by a user in a heterogeneous network, as a function of the threshold term T and when the user chooses to associate with the station that sends the signal which is received with maximum power, are shown.

Similarly to the previous chapter, it is considered that an outage will happen if

$$SINR = \frac{P_i}{\sum_{j \neq i}^{N_{stations}} P_j + \sigma^2} < T$$

Where P_i is the received signal power from the associated station, and P_j is the received signal power from the station j. For each set of simulations, a network of stations was generated, and the outage probability of a user is computed, depending on the varying parameters (simulation dependent), for different values of the outage threshold T.

The structure of the simulations is the same as in the previous chapter. The only different is in the association scheme used.

Dependence on the Poisson Point Process distribution parameter

In this simulation, again, a Poisson Point Process model for the two network layers is used. The same procedure as in the case for the simulation with the closest station association scheme is used: λ_1 is kept constant in all the simulations, while λ_2 assumes different values for each simulation. Figure 13 shows the results of the simulations.

The strong dependence of the outage probability on the parameter λ_2 for each value of the threshold T is again confirmed. Large values of T lead to almost 100% probability of outages. For smaller values of T, the higher λ_2 the lower the probability of an outage. In this case, an higher density of stations may lead to the existence of one station that transmits with higher power that is close enough to the user to dominate all the others.

The dependence of the outage probability on the spatial density of the stations in one of the layers is then clear, for different values of SINR threshold.

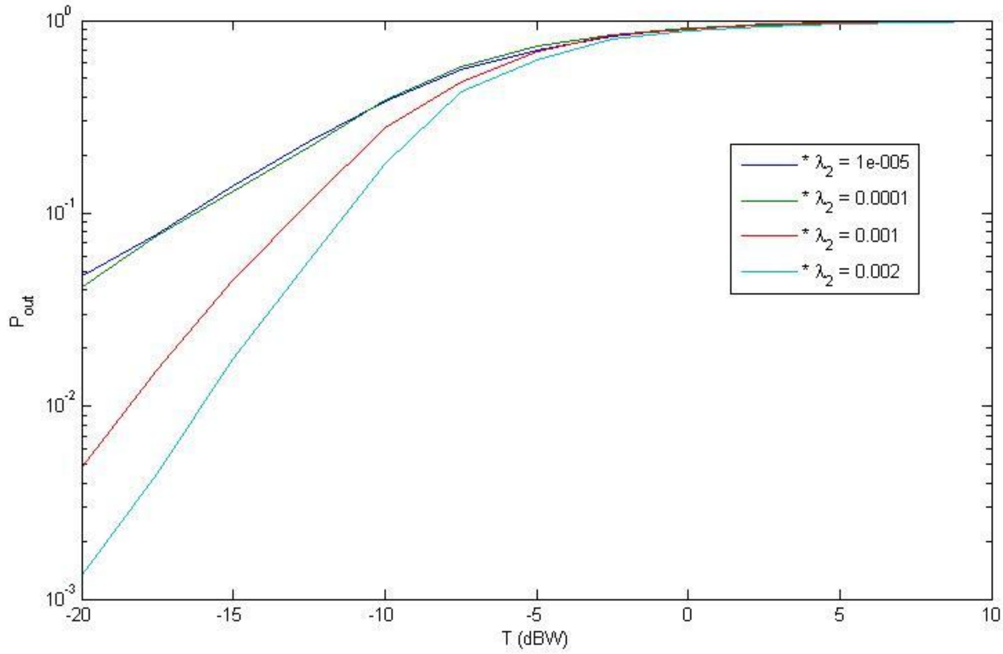

Figure 13- Simulation results for different values of λ_2, when the user associates with the station that transmits the signal which is received with maximum power (Rayleigh fading present), and pathloss exponent a=2.

Dependence on the path loss exponent

When associating to a station that transmits the signal that is received with the highest power, the importance of the path loss exponent is tested with this simulation model.

The results of the simulations are shown in Figure 14. It is clear that for threshold values under -5 dB there is an important dependence on this parameter, which becomes really strong for T<10 dB. Lower values of the path loss exponent lead to a much lower outage probability for T<10dB.

It is surprising to see how important this parameter appears to be for the outage prediction in the maximum power association scheme, with low threshold levels.

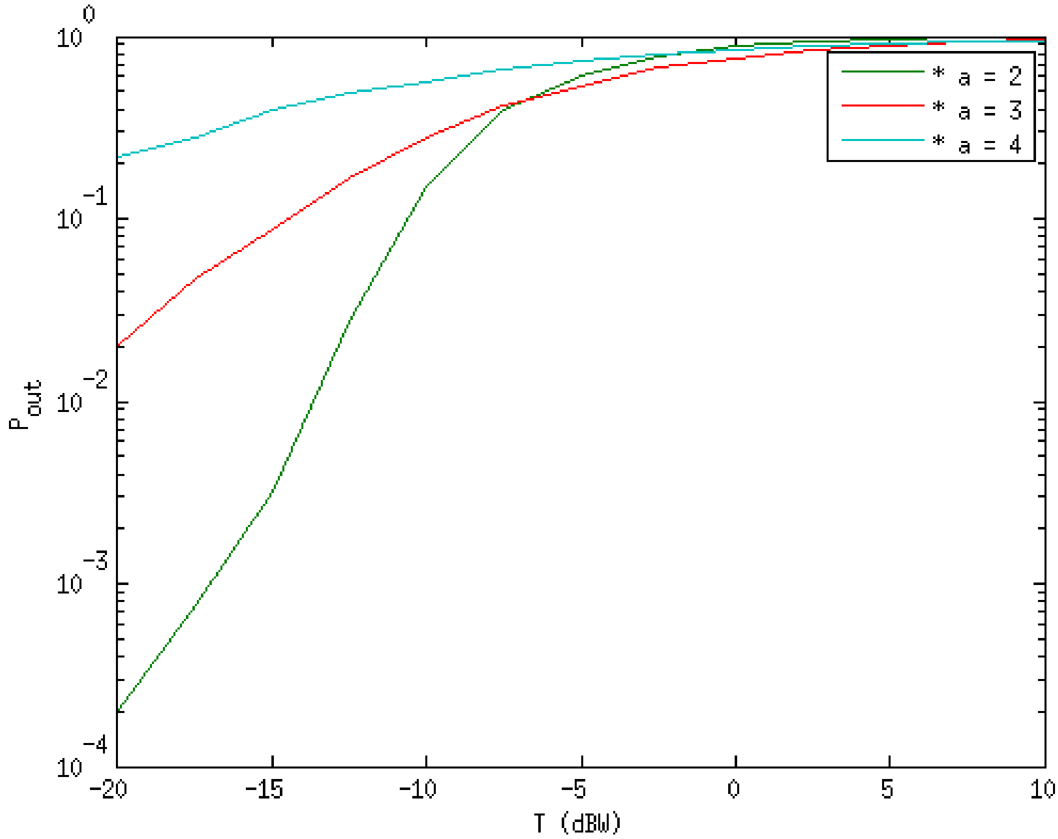

Figure 14- Simulation results for the maximum power association scheme with different values of the path loss exponent (Rayleigh fading present), $\lambda_1=10^{-2}$ and $\lambda_2=10^{-3}$

Rayleigh Fading

After the simulations for different path loss exponents, here we compare the results with the simplified path loss model and with Rayleigh fading + simplified path loss model. For comparison, in the simulation the outage probability was computed for the cases of presence and absence of Rayleigh fading. The results of the simulation are shown in Figure 15.

In this case, for values of SINR below -10dB, the existence of Rayleigh fading influences the outage probability, increasing this term by a factor of up to 1.5 for T = 20dB.

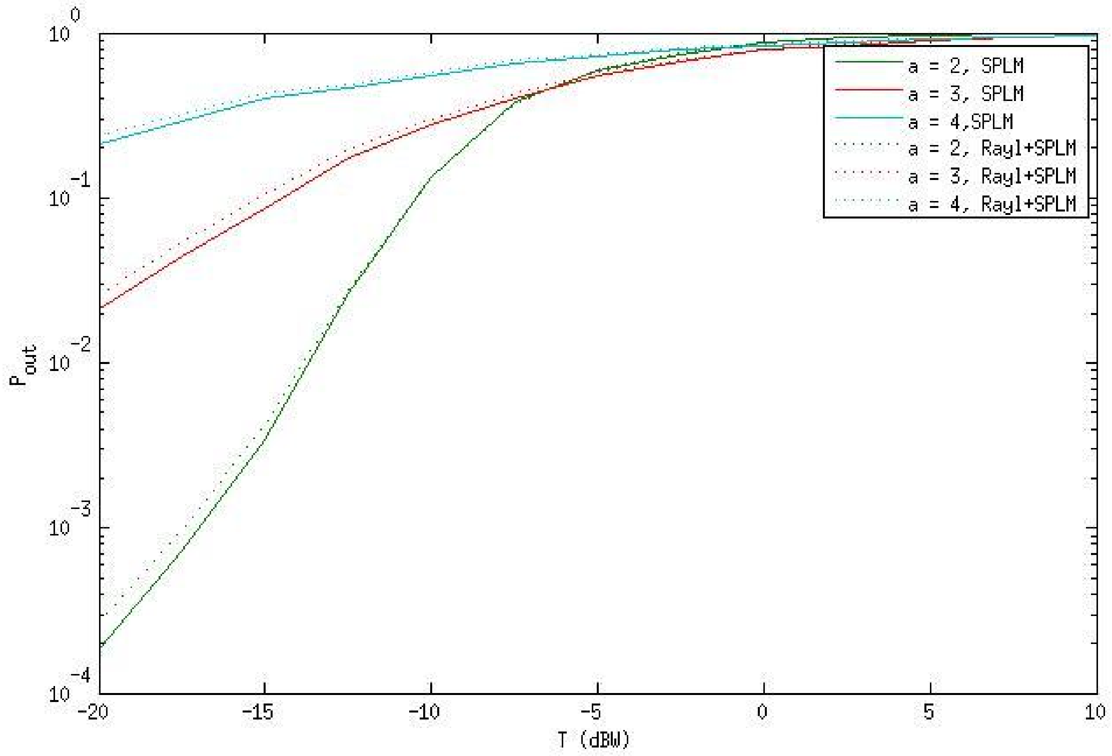

Figure 15- Simulation with the maximum power association scheme, with SPLM+Rayleigh fading (dotted lines) and with just the SPLM, for different path exponent, $\lambda_1=10^{-2}$ and $\lambda_2=10^{-3}$

Nakagami-m fading

The last simulations performed test the existence of Nakagami-m fading in the case of maximum power association scheme. The Nakagami-m is a generalization of the Rayleigh fading, and that the study of the performance with this fading type allows us to model different fading scenarios.

The simulation included the outage probability as a function of the parameter m of the Nakagami distribution. Setting the path loss exponent is equal to 2, and for different values of the threshold T, the graph in Figure 16 was generated, with different plots for different values of m.

The results show that there is no big dependence on the parameter m for T>-15dB. Lower values present a mild increase in outage probability for m=1/2.

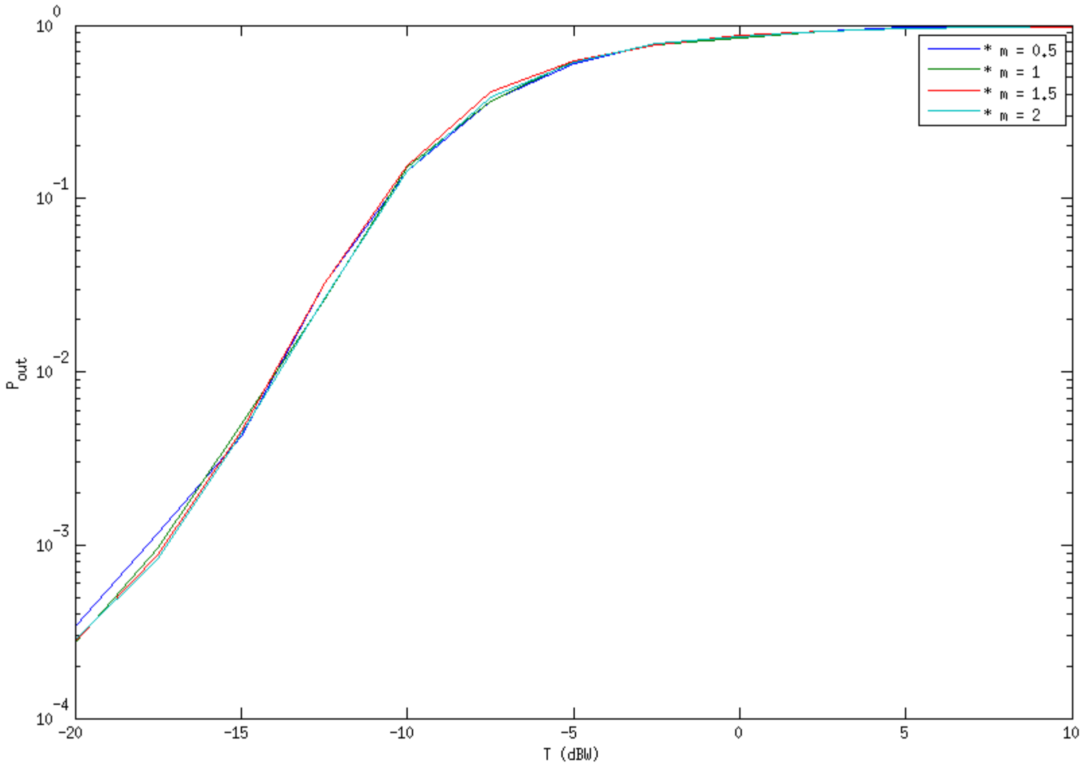

Figure 16- Simulation with the maximum power association scheme, with Nakagami-m fading, for different values of m, and with the path loss exponent equal to 2, $\lambda_1=10^{-2}$ and $\lambda_2=10^{-3}$ for different values of the threshold T.

Discussion

In the maximum power association scheme, an increase of the intensity parameter in the PPP model (higher density of stations) lead to a lower probability of outages. The possibility of having a station with maximum power that is closer to the user increases, therefore decreasing the importance of other interfers.

An increase in the pathloss exponent lead to an increase in the outage probability. The hypothesis is that lower ath loss exponents mean less fading along the same distances, therefore, a station transmitting with maximum power may dominate even more in larger areas.

Finally, for values of the threshold T less than 5dB, the Nakagami-m and Rayleigh fading are relevant in the degradation of the availability of service. In this case, though, there is no particular m for the Nakagami-m fading, that influences much the result along the tested values.

5 Final Discussion

After a detailled description of the simulations for both association schemes, a comparison between the results under the same conditions (changing one parameter while keeping the others constant) is done.

In general terms, as discussed in the theoretical background, associating with the closest station allows the user to use less energy to upload data, but, in the case of heterogeneous networks, can be receiving stronger signals from another cell that is farther away but also transmitting with higher power.

On the other hand, associating with the station that transmits the signal which is received with higher power allows good performance in downloading data.

From the set of simulations performed, some curious results have been shown:

- In the case of different PPP parameter λ_2 for one of the layers, a higher density of stations leads to a higher outage probability, while for the maximum power association scheme, the opposite happens. This is easy to explain, since having more stations nearby the closest station, leads to an increased probability of having a dominant station nearby, while in the maximum power case, the higher the density of the stations, the more probable it is to have a stronger station close to the user, leading to a reducer outage probability.

- When changing the pathloss exponent, the results are quite different for both association schemes. In the closest station association scheme, as the pathloss exponent a increases, the outage probability decreases, while in the maximum power association scheme, the opposite happens. It is intuitive to think that in the case of a user choosing the closest station, large values of a lead to a fast energy loss of the signals from the other stations that are more distant, while in the maximum energy choice, sometimes the user may be choosing a station that is not the closest, therefore a lower value of a leads to the signal of the station transmitting the signal with the maximum power not being “forgotten” and fading too fast.

- In the case of Rayleigh and Nakagami-m fading, choosing the closest station to associate leads to an increased probability of outage for lower values of the threshold T, and having Rayleigh or Nakagami-m fading has a strong influence on the performance, being important for values of T less than 0dB. In case of choosing the maximum power association scheme, the effect of the Rayleigh/Nakagami fading is not as strong, because the dominant signal power will continue to dominate in most occasions. For T > -15 dB this type of fading is not so relevant in the maximum power case.

- For different values of the parameter m in the Nakagami-m distribution, the outage probability changes very little in the case of choosing the maximum power station, while if the user chooses to associate with the closest station, for T<-10 dB and for lower values of m (< 1), the outage probability increases significantly.

Therefore, the two association schemes are in someways complementary, in terms of the parameters path loss exponent and density of the nodes present in the network. This is an interesting result, as it allows a network structure plan adapted to a certain local environment. Of course there exist other association schemes, some combining these two with a trade-off, taking also into account the capacity of the nodes. Nevertheless, the results are very interesting.

It is also to be noted that choosing the maximum power association scheme leads to more robust results when in the presence of Rayleigh and Nakagami-m fading.

6 Conclusion

In this work the outage probability due to interference in the case of two different association schemes was studied, when operating in an heterogeneous network. The simulations showed some complementary behaviour of the closest station and maximum power association schemes.

An increase of the pathloss exponent lead to a decrease in outage probability if the closest station was chosen, while that probability increased if the station with the maximum received signal power was chosen.

With respect to the PPP parameter λ_2, which is related to the density of the number of stations in a given area, an increase of this parameter resulted on an increased outage probability in the closest station association scheme, but that probability decreased if the maximum power scheme was chosen.

It was also shown choosing the maximum power association scheme lead to an increased robustness when in the presence of Rayleigh and Nakagami-m fading.

Future work

A step forward to this report would be to consider other association schemes, such that the capacity of the stations is considered, as especially in the maximum power association scheme there is often a small group of nodes that have a large number of users, which can avoid interference, but can affect capacity.

It would be also interesting to consider some ways to limit co-channel interference, which are not considered in this work.

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