Limiting the Power of 4G Dynamic Green Cellular Networks: Impact on Capacity and Quality of Service

Jean-Marc Kelif[1], Marceau Coupechoux[2], Frederic Marache[3]

Abstract—**The main objectives of the design of wireless networks is to answer the increasing demand of users in terms of capacity and coverage. However, a new challenge for future wireless networks consists in limiting the energy consumption with a limited impact on the network performance. Therefore, reducing the base stations (BS) transmit power should be an objective while designing green cellular networks. However, decreasing the BSs transmit powers may degrade network performance. This paper proposes an evaluation of the degradation of the capacity and coverage/quality of service (in terms of outage probability) due to a reduction of the BS transmit power. In this aim, we first establish closed form formulas of the capacity and coverage/QoS (quality of service), taking into account a dynamic traffic. This allows to quantify in a simple way the fundamental importance of the BS transmit power. We particularly show that the transmit power can be decreased, without impacting the quality of service, as long as a small capacity decrease is accepted according to networks characteristics.**

I. Introduction

A new demand in the design of wireless networks is becoming more and more important, which consists in energy saving and efficiency. Indeed, this should allow decreasing the energy consumption, and reaching multiple objectives: an improvement of the spectrum frequency use due to a decrease of the amount of interference, a reduction of the cost of the network, an improvement of the environment preservation, a limitation of the electromagnetic pollution. For these reasons, the limitation of BS transmit represents one of the main features of *future green cellular networks*.

A wide field of research in wireless networks focuses on green network concept, aiming to minimize the energy, and to analyze the trade-offs between energy consumption and performance characteristics of networks such as reachable throughput, quality of service, coverage... Paper [1] focuses on four tradeoffs, qualified as fundamental by its authors, between energy consumption and deployment, spectral efficiency, bandwidth and delay. Authors of [2] introduce the concept of cell zooming: in the aim to improve BS energy efficiency, the cell size is adjusted according to the characteristics of the system such as the traffic load or channel conditions. In [3], authors propose to shut down BS, when the traffic demand is relatively low. Authors of [4] propose an architecture for wireless networks, aiming at minimal emission from mobile stations. This architecture is based on adding receive only devices in the network, which allow minimizing the emission from mobile stations. In [5], authors present a way to improve the energy efficiency by deploying macrocells jointly with picocell. Another means which can contribute to the limitation or decrease of the transmit power may consist in proposing a wireless network based on the concept of cognitive radio communication. It may moreover improve spectral efficiency. Let us cite for example the paper [7], whose authors propose a power control scheme to diminish cognitive radio energy consumption.

However, as BS transmit power may represent an important source of energy consumption of a wireless network, it appears important to evaluate the impact of BS transmit power decrease on performance and quality of service. In this paper, we propose an analytical approach, to quantify in a easy way this impact on capacity and coverage/QoS (in terms of outage probability). Moreover, in the aim to be more realistic, the approach we develop takes into account the dynamic of the data transmissions.

The interference plays a fundamental role on capacity and coverage of wireless networks. Focusing on the downlink (but the approach is easily extended to the uplink) we consider the other-cell interference factor f (OCIF), since this parameter allows the evaluation of the Signal to Interference plus Noise Ratio (SINR) distributions, needed for coverage and capacity evaluations. Different methods are developed to evaluate this parameter: let us cite [21] for the uplink. On the downlink, [8] [9] [12] [11] [10] aimed at evaluate the OCIF with more or less accuracy .

Literature often neglects the impact of thermal noise in the analysis of coverage [11], [12], [10]. This assumption seems reasonable for typical output powers in urban environments. However, for low BS output power and rural environments, this assumption may become questionable.

<u>Our Contribution</u>: We first derive closed form formulas for the outage probability, and we analyze the effect of decreasing BS transmit power on capacity coverage/QoS in terms of outage probability. In this aim, we extend the results given by expressions of the OCIF without shadowing established in [20] and with shadowing established in [23], by taking into account the impact of termal noise to calculate analytically the outage probability. Moreover, we establish analytical expressions of

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the cell capacity by considering a dynamic traffic. This allows to evaluate the importance of BS transmission power in different realistic environments and for different configurations and the impact of a decrease of BS transmit power. This paper extends [15] to 4G networks.

In section II, we first introduce the model and the notations. In section III we establish analytical expressions of the LTE or LTE-A network cell capacity, considering a dynamic system. In section IV, we present a validation of the approach proposed in section III. In section V, we propose an application to green networks and show that it is possible to decrease the transmit power of a wireless network with a limited impact on the quality of service. In section VI, we conclude.

II. System Model

We consider a single frequency 4G wireless network, composed of B omni-directional base stations. We focus our analysis on the downlink, in the context of an OFDMA based wireless network (e.g. WiMax, LTE).
Let us consider:

- $\mathcal{B} = \{1, \ldots, B\}$ the set of BS, uniformly and regularly distributed over the two-dimensional plane.
- $P_{ij}^{(k)}(u)$ the transmitted power assigned by base station k to sub-carrier i in sub-band j towards user u. We assume that a BS allocates the same power to all sub-bands, sub-carriers and users: $P_{ij}^{(k)}(u) = P$.
- $g_{ij}^{(k)}(u)$ the propagation gain between transmitter k and user u in sub-carrier i in sub-band j.

A. Radio Quality

We assume that time is divided into slots. Each slot consists in a given sequence of OFDMA symbols. Since an orthogonal multiple access scheme is assumed, transmissions within each cell do not interfere one with each other. We assume that there is no interference between sub-carriers. The total amount of power received by a user equipment (UE) u connected to a BS b, on sub-carrier i of sub-band j is given by the sum of : useful signal $P_{ij}^{(b)}(u)g_{ij}^{(b)}(u)$, interference due to the other transmitters $\sum_{k\in\mathcal{B},k\neq b} P_{ij}^{(k)}(u)g_{ij}^{k}(u)$ and thermal noise N_{th}.
We consider the SINR $\gamma_{ij}(u)$ defined by:

$$\gamma_{ij}(u) = \frac{P_{ij}^{(b)}(u)g_{ij}^{(b)}(u)}{\sum\limits_{k\in\mathcal{B},k\neq b} P_{ij}^{(k)}(u)g_{ij}^{k}(u) + N_{th}} \tag{1}$$

as the criterion of radio quality. To compute the total interfering power received by an UE, we consider the fluid model network approach [6]. As we investigate the performance issue, we consider a worst case scenario where all the subcarriers are allocated to UEs. Consequently, each sub-carrier i of the sub-band j of any station is used and interferes with the ones of other stations. Dropping the indices i and j, the SINR (1) for UE u can be written :

$$\begin{aligned}\gamma_u &= \frac{S_u}{I_{ext,u} + N_{th}} \\ &= \frac{1}{\frac{I_{ext,u}}{S_u} + \frac{N_{th}}{S_u}} \\ &= \frac{1}{f_u + h_u},\end{aligned} \tag{2}$$

where the useful signal is given by $S_u = P^{(b)}(u)g^{(b)}(u)$ and the interference is given by $I_{ext,u} = \sum\limits_{k\in\mathcal{B},k\neq b} P^{(k)}(u)g^{(k)}(u)$, and where f_u is the interference factor[1] of the mobile u.

This definition should be understood for each sub-carrier. $P^{(b)}$ is then the BS transmit power *per sub-carrier* and in the expression of the noise power $N_{th} = N_0 W_{sc}$, W_{sc} is the sub-carrier bandwidth.

B. Serving Policies and Channel Models

In this paper, we will consider two serving policies. With the *best server* policy, UEs are served by the BS providing the highest received pilot power. With the *nearest server* policy, UEs are attached to the closest BS. The former is an ideal case that provides an upper bound on the system performance. Indeed, real systems implement hysteresis factors to avoid ping pong effects due to channel variations [13] and due to these factors the best server assumption is often not verified. On the contrary, the nearest server assumption provides lower bounds for the system performance because UEs are not necessary attached to the BS, which provides the best radio quality.

In this paper, we will consider the following channel model: $g^{(b)}(u) = Kr_{b,u}^{-\eta}A_b$, where $r_{b,u}$ is the distance between the base station b and the mobile u and $A_b = 10^{-\xi_b/10}$ is a lognormal random variable (RV), which characterizes the shadowing, with logarithm mean and standard deviation 0 dB and σ (dB) respectively and K is a constant, which depends on the carrier frequency and on the considered environment (urban or rural). We will show in section IV that the shadowing variable can be neglected when the best server policy is assumed. Index b will be sometimes dropped when no confusion is possible, so that $r_u = r_{b,u}$.

C. Throughput calculation

The maximum theoretical throughput achievable by any user u can be calculated by using Shannon relation:

$$D(\gamma_u) = W \log_2(1 + \gamma_u) \tag{3}$$

However, in the aim to establish results close to a real system, we choose to use link curves established by Orange Labs, which give a more precise correspondence between the user received SINR and the reachable throughput.

[1]The interference factor is defined as the ratio between the power coming from the serving BS and the sum of other BS powers received by an UE, considering all BS transmit with power P.

III. Cell Capacity in 4G Networks

A. M/G/1/PS Model

In this section, we adopt the approach developed by Bonald and Proutiere in [14]. In this dynamic model, users arrive with a uniform distribution over the cell area, download a file and leave the system. The underlying scheduling model is round robin and the system is thus modeled as a M/G/1/PS queue. In this approach, the cell capacity is defined as:

$$C = \left(\sum_{k=1}^{n} \frac{p_k}{c_k} \right)^{-1}. \tag{4}$$

In this definition, it is assumed that the cell area is divided in n areas. In area k, the data rate is constant equal to c_k and the arrival probability is p_k. In [14], the propagation model is assumed to be deterministic depending solely on the distance to the BS.

In this section, we extend this approach for a propagation model with shadowing and outage. First, we assume there is a SINR threshold γ_{min} below which mobiles are in outage. Then, we consider infinitesimal areas of constant SINR. The arrival probability in the area associated to SINR γ_0 is given by:

$$\mathbb{P}\left[\gamma_0 \leq \gamma \leq \gamma_0 + d\gamma_0 | \gamma \geq \gamma_{min}\right] = \frac{p_\gamma(\gamma_0)d\gamma_0}{1 - P_{out}}, \tag{5}$$

where

$$P_{out} = \int_0^{\gamma_{min}} p_\gamma(\gamma)d\gamma \tag{6}$$

is the outage probability and p_γ is the spatial probability density function (PDF) of the SINR. In this area, the peak data rate is $D(\gamma_0)$. As a consequence, the cell capacity is given by:

$$C = \left(\int_{\gamma_{min}}^{\infty} \frac{p_\gamma(\gamma_0)d\gamma_0}{(1 - P_{out})D(\gamma_0)} \right)^{-1}. \tag{7}$$

B. Best Server Policy

We assume that the shadowing random variable can be neglected when the best server policy is assumed. This assumption will be validated in section IV. As a consequence, the SINR (2) at UE u can be written:

$$\begin{aligned} \gamma_u &= \frac{P^{(b)} K r_{b,u}^{-\eta}}{\sum_{k \neq b} P^{(k)} K r_{k,u}^{-\eta} + N_{th}} \\ &= \frac{1}{f_u + \frac{N_{th}}{P^{(b)} K r_{b,u}^{-\eta}}}. \end{aligned} \tag{8}$$

where f_u can be written (since $P^{(b)} = P^{(k)} = P$) :

$$f_u = \frac{\sum_{k \neq b} r_{k,u}^{-\eta}}{r_{b,u}^{-\eta}}. \tag{9}$$

For a mobile at the distance r from its serving base station (dropping the indices b and u), the interference factor f_u can be written as $f(r)$ [20] [22]:

$$f(r) = \frac{2\pi\rho_{BS} r^\eta}{\eta - 2}(2R_c - r)^{2-\eta}. \tag{10}$$

where $1/\rho_{BS} = \pi R_e^2$ represents the cell area and $2R_c$ the distance between two neighbour BS. We have $R_e = R_c\sqrt{2\sqrt{3}/\pi}$. Dropping the indices b and u using (10), we obtain:

$$\gamma(r) = \frac{1}{\frac{2\pi\rho_{BS} r^\eta}{\eta-2}(2R_c - r)^{2-\eta} + \frac{N_{th}}{PKr^{-\eta}}}, \tag{11}$$

which is a strictly decreasing deterministic function of the distance to the serving BS. In this particular case, there is a r_{max} corresponding to γ_{min} beyond which the service is not available and (7) can be written:

$$C = \left(\int_0^{r_{max}} \frac{2rdr}{R_c^2(1 - P_{out})D(\gamma(r))} \right)^{-1}. \tag{12}$$

The cumulative distributed function (CDF) of the SINR is given by:

$$P(\gamma < \gamma^*) = 1 - \frac{\gamma^{-1}(\gamma^*)^2}{R_c^2}. \tag{13}$$

C. Nearest Server Policy

We now consider the nearest server policy. We rewrite the SINR expression (2) as follows:

$$\begin{aligned} \gamma_u &= \frac{1}{\frac{I_{ext,u}}{S_u} + \frac{N_{th}}{S_u}} \\ &= \frac{1}{f_u + h_u}. \end{aligned} \tag{14}$$

Because of our model for the computation of f_u and h_u, γ_u is here a random variable for any given distance r. In the expression, f_u is a sum of lognormal RVs that can be approximated by a lognormal RV such that $\ln(f_u) \sim N(m_f, a^2 s_f^2)$, where $a = \frac{log10}{10}$. The variable h_u is also a lognormal RV such that $\ln(h_u) \sim N(\ln\frac{N_{th} r^\eta}{P_b K}, a^2\sigma^2)$. The RV $T_u = f_u + h_u$ can also be approximated by a lognormal RV using the Fenton-Wilkinson method [18]. The parameters of this RV are given by:

$$\begin{aligned} \sigma_T^2 &= \ln\left[\frac{e^{2\mu_1+\sigma_1^2}(e^{\sigma_1^2} - 1) + e^{2\mu_2+\sigma_2^2}(e^{\sigma_2^2} - 1)}{(e^{\mu_1+\sigma_1^2/2} + e^{\mu_2+\sigma_2^2/2})^2} + 1 \right], \\ m_T &= \ln\left[e^{\mu_1+\sigma_1^2/2} + e^{\mu_2+\sigma_2^2/2} \right] - \frac{\sigma_T^2}{2}, \end{aligned} \tag{15}$$

where $\mu_1 = m_f$, $\sigma_1^2 = a^2 s_f^2$, $\mu_2 = \ln\frac{N_{th} r^\eta}{P_b K}$ and $\sigma_2^2 = a^2\sigma^2$. The SINR γ_u can thus be approximated by a lognormal RV such that $\ln(\gamma_u(r)) \sim N(-m_T(r), \sigma_T(r)^2)$. We recall in this last expression that m_T and σ_T are functions of r.

We now consider the RV γ, which gives the SINR of a user randomly and uniformly located over the cell area. Randomness comes both from the shadowing and from the UE location. The CDF of γ is obtained from the previous calculations as follows:

$$\begin{aligned} P[\gamma \leq \gamma_0] &= \int_0^{R_e} P[10\log_{10}\gamma \leq 10\log_{10}\gamma_0] p_r(r)dr \\ &= \int_0^{R_e} \left(1 - Q\left(u(r)\right)\right) p_r(r)dr \end{aligned} \tag{16}$$

where Q is the error function: $Q(u) = \frac{1}{2}erfc(\frac{u}{\sqrt{2}})$, $u(r) = \frac{\log\gamma_0 + m_T}{\sigma_T}$, and $p_r(r)$ is the density probability for a UE to be at distance r from the serving BS. We use the following formula for any function g of a RV X to express the cell capacity:

$$E[g(X)] = g(0) + \int g'(t)P[X > t]dt. \quad (17)$$

As a consequence:

$$C = \int \frac{-2C'(t)}{D(t)^2}\left(\int_0^{R_e} v(r,t)p_r(r)dr\right)dt, \quad (18)$$

where $v(r,t) = 1 - Q\left(\frac{10\log_{10} t + \frac{10m_T}{\ln(10)}}{\frac{10\sigma_T}{\ln 10}}\right)$.

Let $p_{\gamma(r)}(\gamma)$ be the PDF of the SINR at distance r. The cell capacity (7) can now be written for the nearest server assumption as:

$$C = \left(\int_0^{R_c}\int_{\gamma_{min}}^{\infty} \frac{p_{\gamma(r)}(\gamma)d\gamma}{D(\gamma)(1-P_{out})}\frac{2rdr}{R_c^2}\right)^{-1}. \quad (19)$$

Note that we have:

$$\int_{\gamma_{min}}^{\infty} \frac{p_{\gamma(r)}(\gamma)d\gamma}{D(\gamma)} = \int_{\gamma_{min}}^{\gamma_{max}} \frac{p_{\gamma(r)}(\gamma)d\gamma}{D(\gamma)} \quad (20)$$

$$+ \int_{\gamma_{max}}^{\infty} \frac{p_{\gamma(r)}(\gamma)d\gamma}{D_{max}}. \quad (21)$$

where $\int_{\gamma_{max}}^{\infty} \frac{p_{\gamma(r)}(\gamma)d\gamma}{D_{max}} = Q\left(\frac{\ln(\gamma_{max})+m_T}{\sigma_T}\right)$, and P_{out} is given by (6).

This approach can be further simplified by assuming that the SINR follows a log-normal distribution over the cell area. Let M_γ and S_γ be the spatial average and spatial standard deviation of γ_u respectively, i.e., $\ln(\gamma_u) \sim N(M_\gamma, S_\gamma^2)$. We have:

$$M_\gamma = \int_0^{R_e} -m_T(r)p_r(r)dr \quad (22)$$

$$S_\gamma^2 = E[\ln(\gamma)^2] - M_\gamma^2, \quad (23)$$

where

$$E[\ln(\gamma)^2] = \int_0^{R_e} E[\ln(T_u)^2]p_r(r)dr \quad (24)$$

$$= \int_0^{R_e} (\sigma_T^2 + m_T^2)p_r(r)dr. \quad (25)$$

IV. Validation

In this section, we compare our model with Monte Carlo simulations in an hexagonal network. We focus on the best server policy and select some typical LTE/LTE-A scenarios.

We consider urban and rural environments (see table I [24]) and two frequency bands (800 MHz and 2 GHz). We assume also the following parameters: $W = 20$ MHz, $N_0 = -174$ dBm/Hz, $t = 0.5$ the correlation coefficient of the shadowing. The standard deviation of the shadowing and penetration losses (PL) are $\sigma = 9$ dB and $PL = 9.8$ dB for an indoor coverage and $\sigma = 7$ dB and $PL = 0$ dB for an outdoor coverage. Concerning these 4 network configurations, we validate our model by comparing the SINR distributions obtained by Monte Carlo simulations and analysis in two different environments and with different output powers. Results are shown on figure 1. In all cases, analysis and simulations match well. Figure 1 shows that the assumption we have done, consisting to neglect the shadowing in the best server policy case, is justified. Indeed, the CDF of the SINR established by using expression (13), which does not take into account the shadowing, is very close to the CDF given by Monte Carlo simulations which take into account the shadowing. For values of outage probability less than one 0.1 (which is the maximum standard value acceptable in a real network), this difference is negligible: less than 0.5 dB. Moreover, the matching is better when the transmit power is high. We observe that the difference between the two curves (simulated and analytical) increases when the transmit power decreases. This difference remains however low with a maximum of 4 dB in urban environment when transmit power is 10 dBm, for an outage probability higher than 0.2.

Table I
PROPAGATION PARAMETERS

	f (MHz)	K	η
Rural	800	2.037	3.48
	2000	0.1837	3.48
Urban	800	0.0121	3.57
	2000	$2.68e-4$	3.48

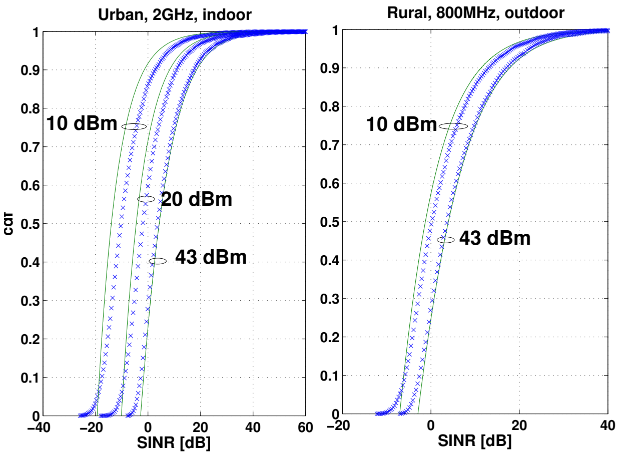

Figure 1. SINR distribution, simulations (x) vs. analysis (–) – 4G networks, urban environment, 2 GHz, indoor (left) and rural environment, 800 MHz, outdoor (right), best server.

V. Power Reduction

We present in this section, results based on our analysis focused on the reduction of BS transmit power and its impact on the capacity and the coverage/ QoS of 4G base stations.

Figure 2 and 3 show the impact of the transmit power on capacity and outage, in an urban environment in the frequencies 800 MHz and 2 GHz, for indoor and indoor users. Figure 4 and 5 show the impact of the transmit power on capacity and outage, in a rural environment in the frequencies 800 MHz and 2 GHz, for indoor and indoor users. These figures allow to quantify the loss of capacity observed when transmit power is decreased.

A. Thermal noise impact on outage and capacity

It can be observed in figures 2 and 4 that for any transmit power, the capacities at 800 MHz are at a higher level than the ones reached 2 GHz. This can be explained by the thermal noise impact. Indeed, table 1 shows that the factor K decreases when frequency increases. Therefore, as we can see in expressions (11) and (12), the SINR increases when the frequency decreases. As a consequence, the cell capacity increases when the frequency decreases. Considering the objective to analyze green networks, these results show that the thermal noise plays an important role in realistic networks.

Moreover, an analogue phenomenon can be observed for indoor and outdoor capacities. Indeed indoor users receive a lower useful power due to the penetration loss. Therefore, the impact of the thermal noise increases. Consequently, the SINR increases and the cell capacity decreases, as also observed in figures 2 and 4.

These figures depend on the chosen set of parameters and in particular on the propagation model. But they also show that our equations can provide very quick results on the impact of power reduction on the network performance.

B. Low capacity degradation

We now study the effect of a low degradation of the capacity while setting the target outage to $P^*_{out} = 1\%$.

In the two types of environments analyzed, urban and rural, we established the possibility of transmit power reduction. Figures 3 and 5 show that the minimum transmit power needed to reach a maximum outage probability of 1% is 24 dBm, whatever the frequency used (800 or 2600 MHz, in indoor or in outdoor). We could decrease the power even more in some cases, but we chose a unique benchmark valid in all scenarios

Table II summarizes the amount of transmit power reduction, when a low reduction of the cell capacity is accepted (here 5 or 10%), according to the environment (urban and rural), the frequency (800 MHHz or 2 GHz) and the location of users (indoor or outdoor). In general this reduction is lower for indoor than outdoor users. We particularly observe that this reduction may reach 19 dBm (which means a reduction by a factor close to 100, compared to the standard transmit power of 43 dBm) in the frequency of 800 MHz. However, that reduction is relatively low for indoors users in 2 GHz. For example, it reaches 8.3 dBm when a capacity reduction of 10% is accepted.

Table III summarizes the impact of the frequency bandwidth on the amount of transmit power reduction. For the rural case, frequency 800 MHz outdoor, the maximum reduction of 19 dBm is reached whatever the bandwidth. For the urban case 2 GHz indoor, the reduction of power increases when the bandwidth decreases. The maximum reduction reaches 14.2 dBm.

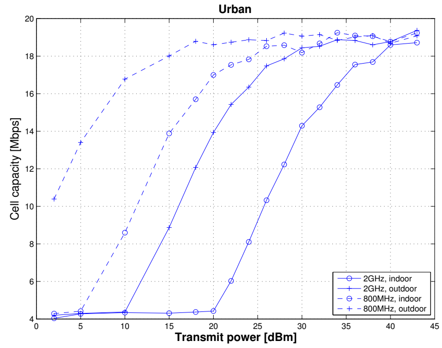

Figure 2. Cell Capacity vs transmit power – 4G network, urban environment, best server.

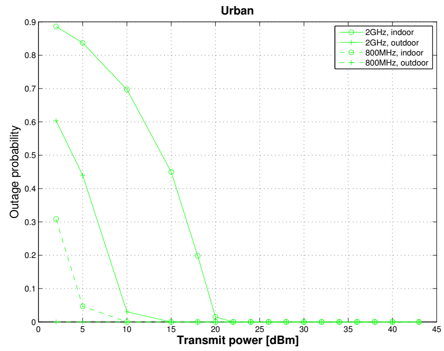

Figure 3. Outage probability vs transmit power – 4G network, urban environment, best server.

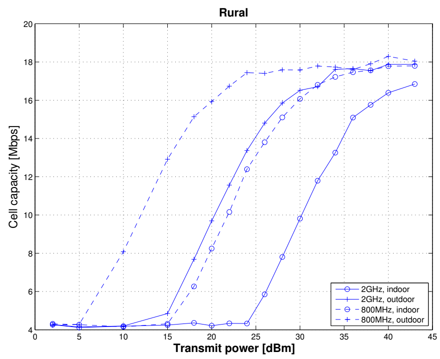

Figure 4. Capacity vs transmit power – 4G network, rural environment, best server.

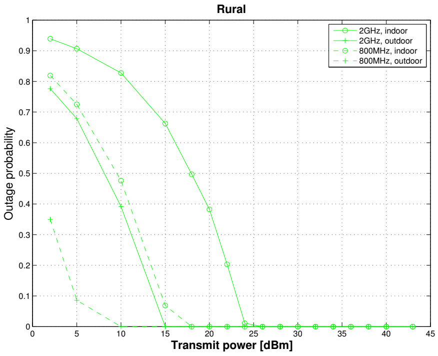

Figure 5. Outage probability vs transmit power – 4G network, rural environment, best server.

Table II
TRANSMIT POWER REDUCTION [DBM] (DIFFERENCE W.R.T 43 DBM WITH A MINIMUM TRANSMIT POWER OF 24 DBM, $W = 20$ MHZ.)

Capa Reduc	Urban				Rural			
	2 GHz		800 MHz		2 GHz		800 MHz	
	in	out	in	out	in	out	in	out
5 %	5.5	14.5	18.9	19.0	3.6	11.1	9.5	19.0
10 %	8.3	17.6	19.0	19.0	5.7	13.9	12.7	19.0

VI. CONCLUSION

In this paper, we established closed form formulas of the outage probability and capacity of cellular networks, which take into account a dynamic traffic. This allowed to quantify with accuracy and in a quickly way, the impact of transmit power on the capacity and coverage/QoS of a cellular network, in realistic configurations. We established that it is possible to drastically reduce power emissions, if a low degradation of the capacity is accepted, and without loss of coverage/QoS in terms of outage probability.

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Table III
TRANSMIT POWER REDUCTION [DBM] – INFLUENCE OF W (DIFFERENCE W.R.T 43 DBM WITH A MINIMUM TRANSMIT POWER OF 24 DBM.), FOR A BANDWIDTH OF 5, 10 AND 20 MHZ

Capa Reduc	Urban 2 Ghz indoor			Rural 800 MHz outdoor		
	5	10	20	5	10	20
5 %	11.2	8.2	5.5	19.0	19.0	19.0
10 %	14.2	11.2	8.3	19.0	19.0	19.0

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