BER based Assessment of Spectral and Energy Efficiency in a Two-tier Heterogeneous Network

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Abstract: In this paper, we analyze an arbitrary heterogeneous cellular network applying stochastic geometry, and propose a modified model for assessing network spectral and energy efficiency. With this regard, we recognize that, in practice, determining Signal-to-Noise-and-Interference Ratio (SINR) as the key performance indicator, requires complex field test equipment, which might not be available or affordable. Therefore, we propose here a simple model that is based on the relatively easy measurable Bit-Error Rate (BER), whose degradation caused by various impairments is considered here as if it was due to the according additive white Gaussian noise (AWGN), thus abstracting any specific non-AWGN distortion. The proposed analytical model is verified by ns3 software network simulator, whose test results are found to match the corresponding estimated values. This indicates that both spectral and energy efficiencies of small-cell networks are higher than in larger-cell networks, even more for heterogeneous two-tier networks.

1 INTRODUCTION

It has been quite a while since it has become evident that homogeneous cellular network architecture cannot adequately fulfil the fast growing users' demand for capacity and Quality- of Service (QoS) (Parkvall, 2008), as well as efficient spectrum and energy consumption.

Starting with the fourth generation (4G) mobile networks, it has become evident that smaller cells enhance the network performance, and off-loads the macro network from excessive traffic. So, for example, simple plug-and-play installed femto cells are more profitable than macrocells, due to reduced backhaul costs and less transmitted power required in small cells.

Specifically, state-of-the-art Radio Access Systems (RAS) encompass cells of different classes to make up a Heterogeneous Cellular Network (HetNet), which includes at least two same-class groups – tiers (Slamnik, 2016; Slamnik, 2017).

The actual explosive growth of data traffic implies severe demand on energy efficiency (EE), so with the 4G Long-Term Evolution (LTE) and its extension LTE Advanced (LTE-A), as well as with the incoming 5G HetNets, transmission performance enhancements include reduction of the distance between the transmitting and the receiving antennas.

With respect to EE of wireless access networks, the metrics is focused (Bousia, 2014 – ETSI TS 2011)) on the energy per information [J/b], enriched by some QoS-related features (ETSI TR 2021) to improve HetNet's capacity and coverage, which both depend on Signal-to-Interference-plus-Noise Ratio (SINR).

Therefore, we investigate various HetNet performance scenarios, but using Bit-Error Rate (BER) rather than SINR at each User Equipment (UE) (Mukherjee, 2014) within the serving tier area of a single BS, and a single candidate-serving BS.

We will pursue BER analysis towards network spectral efficiency (SE) and EE. Concretely, instead of the classic hexagonal-grid based cellular network composition with a BS-cantered each cell (Baccelli, 1997 – Baccelli, 2001); we used stochastic geometry to capture randomness in network topology (Baccelli, 1997 – Brown 2000).

With this regard, the Herne topology is modelled through Poisson Point Process (PPP) (Mukherjee, 2014), which describes irregular placements of BSs within a real network, better than the classic hexagonal-grid model (Baccelli, 1997).

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Although the PPP-based topology analysis is not new (Baccelli, 1997; ElSawy, 2013; Dhillon, 2012), it was not long ago when the PPP-distributed BSs were introduced in various Herne (Brown, 2000), (Dhillon, 2012 – Heath, 2013) and MIMO inclusive network scenarios.

In Section II, we firstly provide a short basic theoretical review, specifically considering performance limits and related trade-off between SE and EE. The short-term BER, SE and EE based analytical model is presented as applicable for large Honest who's serving and candidate-serving BSs have random distribution in the actual serving tier area. Finally, the analytical model is verified in Section III by presenting the test results obtained by means of ns3 simulation tool that provided the short-term BER values for all UEs of the network under test. Conclusions are summarized in Section IV.

2 ANALYSIS

Complex relationship between SE and EE of multiuser radio networks is determined by compromises involving throughput, overall system energy, frequency resources distribution, traffic flow patterns, acceptable erroneous protocol data unit rates, and achieved vs. target QoS level.

Generally, SE of wireless communication networks is the ratio of the transmission rate *R* [b/s] to the bandwidth *B* [Hz] that is needed to achieve *R* (Musovic, 2021).

Moreover, the radio channel *EE* [b/J] is the ratio between the energy per bit *E*b and the noise spectral density *N*0, i.e. EE expresses the count of information bits per energy unit.

So, the Shannon formula for radio channel capacity *C* [b/s] originally depending on channel bandwidth *B* and mean power P_S, can be expressed by *SE* and *EE* as it follows (Musovic, 2021):

$$C = B \cdot log_2\left(1 + \frac{P_S}{P_N}\right) = B \cdot log_2\left(1 + \frac{E_b}{N_0} \cdot \frac{R}{B}\right) = \\ = B \cdot log_2(1 + SE \cdot EE) \quad (1)$$

Specifically, for transmission over the Additive-White-Gaussian-Noise (AWGN) channel, having given P_S and *B*, where we consider *EE* as the ratio *C*/*B*, (1) implies that:

$$SE = \log_2(1 + SE \cdot EE) \quad (2)$$

Thus, we can explicitly express *EE* as a function of *SE*:

$$EE = \frac{2^{SE} - 1}{SE} \quad (3)$$

In the utmost simple case of a single-BS and a single-UE wireless network, (3) enables the analysis of *SE* vs. *EE* relationship in linear and non-linear power and energy regions, Figure 1, thus aiming to enable considerably enlargements of throughput and data rate (Musovic, 2021).

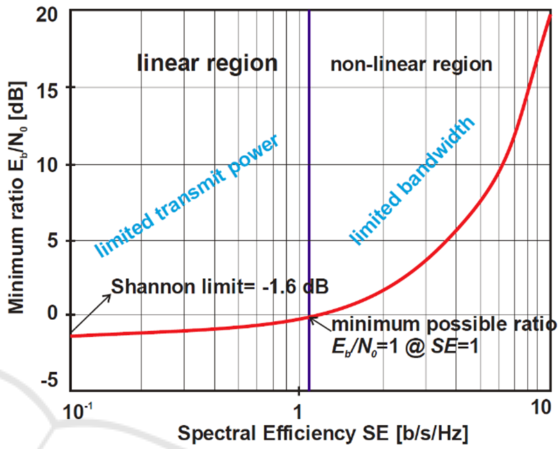


Figure 1: *EE* vs E_b/N_0 relationship.

From these considerations, it is obvious that increasing data rate requires significantly larger received signal power (Musovic, 2021).

This implies the BS-to-UE distances of the order of tens of meters, whereas still in the linear-region tolerating considerably larger values (but with considerably smaller *SE*, due to *EE* reduction by propagation impairments.)

In the non-linear-region, however, considerably larger *EE* can be achieved, as stronger received signals enable reduction of cell dimensions as low as tens of meters, with the variety of cell classes comprising: micro, nano, pico and femto cells. These enable close-to-uniform *EE* distribution, considerably larger *SE* and thus the throughput and rational coverage with still good enough *EE*, especially in areas crowded with active users, and considerably lower electromagnetic radiation (Musovic, 2021).

So far, the HetNet overall efficiency was analyzed by considering both SE and EE, and determining SINR for each UE within the *k*-tier of HetNet having N_T tiers overall (Musovic, 2021).

Each tier (e.g. *k*-th) is modeled by a homogeneous PPP Φ_k, with the transmit power P_k, BSs density λ_k, and the SINR threshold τ_k (often referenced as "bias") at UE, respectively.

2.1 BER based Analytical Model

Degraded SINR usually implies constellation symbol errors, and thereby SINR is often tested, which requires complex equipment to measure the noise and inter-symbol interference (ISI) (Lipovac, 2021). Instead, estimating BER, can be an alternative, i.e. an easy-to-measure performance trade – off "currency", rather than SINR (where by "easiness", we consider the possibility to estimate BER in-service, simply by counting the retransmissions at the physical/MAC layer whose count determines the Block-Error ratio (BLER). Then an appropriate model can be applied to estimate BER from BLER.

This could be useful in practice encompassing various phases of a product related research, development, manufacturing, and finally its exploitation of a product in LTE and 5G New Radio environment.

Let us review the classical BER expression as a function of Signal-to-Noise Ratio (*SNR*), for the M-QAM signal transmission over AWGN channel (Rumnay, 2013):

$$BER = \frac{4}{\log_2 M} \cdot Q\left(\sqrt{\frac{3 \cdot SNR}{M-1}}\right) \qquad (4)$$

where Q stands for the Gaussian tail function, represented by the "waterfall" - steep curves in Fig. 2, which visualize the threshold effect that is immanent to digital radio receivers.

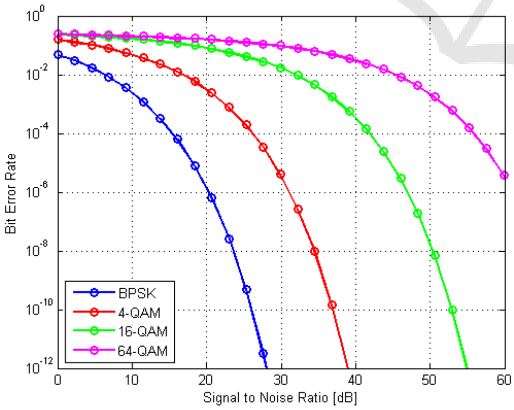


Figure 2: Waterfall BER vs SNR curves (for Nyquist BW).

Furthermore, it is quite often that in various propagation environments, specifically in very small cells, presuming strong received signals (i.e. high SNR) is realistic, which implies successful elimination of the time-dispersion-caused inter-symbol interference (ISI) by long-enough cyclic prefix (CP) (Lipovac, 2021).

This practically reduces *SINR* to *SNR*, so (4) implies that:

$$SINR \approx SNR = \frac{M-1}{3}\left[Q^{-1}\left(\frac{BER \cdot \log_2 M}{4}\right)\right]^2 \qquad (5)$$

where Q^{-1} denotes the inverse function of the Gaussian tail.

In addition, it is quite justifiable to consider the radio interference to be a dominant impairment, which (as a sum of enough many mutually independent RF interfering signals, and according to the Central Limit Theorem), is a Gaussian random variable.

Moreover, applying link abstraction, any distortion, be it additive or not, or non-Gaussian, can be considered equivalent to that much additive Gaussian noise which would produce the same BER degradation, i.e. shift the *BER*(*SNR*) curves from Fig. 2 to the right for the adequate *SNR* degradation, which is in Fig. 3 expressed as the ratio of E_b to N_0.

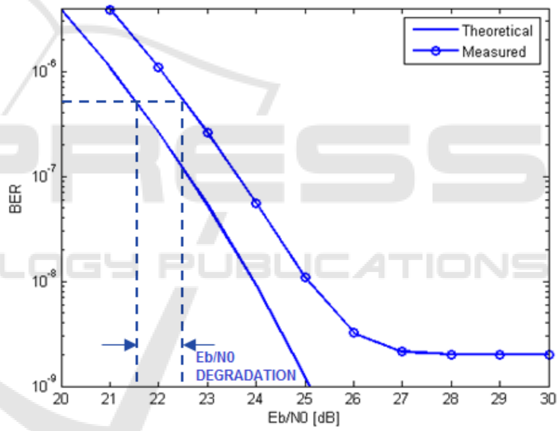


Figure 3: AWGN abstraction of non-AWGN impairments.

With this regard, we can justifiably assume successful CP-aided mitigation of channel time dispersion, i.e. that the standard CP is long enough (e.g. as the "normal" one in LTE) to eliminate the vast majority of error bursts mostly arising from multipath propagation, and retain only sporadic bit errors that mostly occur sporadically in residual bursts (to be scattered by interleaving, anyway) (Lipovac, 2021).

Finally, as the simple and common BER tests have been "ex-communicated" from the LTE (and 5G as well) transmission performance specifications for network operators, in favor of BLER (Rumnay, 2013), therefore, in order to estimate BER in-service, we need to adopt a certain relationship between BLER and BER.

However, although the common binomial distribution well statistically describes mutually independent bit error occurrences within a data block (e.g. the LTE code-block), in this case, we could consider that the appropriate error generating model should still preserve (moderate) mutual dependability among the individual bit-error occurrences. This conforms to the statistical model of sampling without replacement, well described by the hyper-geometric distribution of errors within an errored data block (containing one or more erroneous bits) (Lipovac, 2021):

2.2 Spectral and Energy Efficiency Model

The tiers are ranked in ascending order according to the density of access points: $\lambda_1 \le \lambda_2 \ldots \lambda_{k-1} \le \lambda_k$. For any specific λ_k, the count of access points of tier k_i (i=1,2,…,N_T) within the covered area $\mathcal{A}$ [m^2] is a Poisson random variable with mean $\mathcal{A} \cdot \lambda_k$, independent of other tiers. Moreover, all k-tier access points transmit with power P_k.

Each downlink is modeled as Rayleigh fading channel, with the BS-transmitted power P_i^{tx} and the UE-received power P_i^{rx} at R_i distance from BS.

In this model, we have chosen the path-loss exponent to be equal to 4 (Slamnik, 2016), and that macro BSs do not transmit during the Almost Blank Subframes (ABS) (Slamnik, 2017).

For each tier, we consider the frequency reuse factor of unity, and the RF band of one channel skipped between the two same-standard tiers, which implies that for a particular UE connected to tier k, all interfering BSs are within that tier (k), with the exception of the serving one.

In the considered scenario, each UE is allowed to access only the BSs in tiers 1,2,...,K_{open} from Open Access (OA) macro/femto cells, whereas the Closed Subscriber Group (CSG) femto cells are mostly not allowed to serve those users under consideration [8]. So, a certain HetNet would be represented by the count of tiers: $N_T = 3$ and the count of OA tiers: $N_{open} = 2$, with tier 1 representing the macro cells, tier 2 standing for the OA femto cells, and tier 3 for the CSG femto-cells.

Furthermore, we assume maximal allowed BS-transmitted power (for the actual tier).

Now, let us analyze the above explored relationship between the network SE and the total power so that the distribution of BSs within the tiers is in the form of PPP.

In addition, we suppose that a particular BS b_k of any serving tier k_i transmits only to a subset of users U_b served by $b_k \in \Phi_k$.

Let us consider the SINR $\Gamma(u_b)$ for the specific user $u_b \in U_b$, expressed by BER, according to (5).

Then the spectral efficiency SE_k of the link from b_k to any target u_b is:

$$SE_k = \mathrm{E}\{\log_2 \cdot [1+\Gamma(u_b)]\} = \approx \mathrm{E}\left\{\log_2 \cdot \left[1+\frac{M-1}{3}\cdot\left(Q^{-1}\left(\frac{BER\cdot\log_2 M}{4}\right)^2\right)\right]\right\}, \quad (6)$$

$$b \in \Phi, P\{U_b = u_b\} = \frac{1}{|U_b|}, u_b \in U_b$$

The proposed analytical model provides the spectral efficiency SE_k for each tier (k=1...N_T), as well as the one - SE_{TOT} for the whole HetNet.

Furthermore, the selection of serving or candidate-serving cells according to the LTE-A standard is mostly based on the pico-cell BSs range extension to enable traffic load balancing, and prevent inter-cell RF interference in the areas with evident or expected signal overlapping coverage (Musovic, 2021).

The mean levels of the UE-received pilot originating by the candidate-serving macro and pico BSs, were used for selecting the optimal small-cell tier to serve a particular UE, according to two schemes:

Firstly, we consider the macro tier i to be the serving tier, and the pico tier j to be the candidate-serving tier, otherwise it is the pico tier j to serve the UE, whereas the macro tier i is the candidate-serving tier (Mukherjee, 2014).

In the following, with R_i and R_j, we denoted the distances between the UE and the candidate-serving (i.e. the nearest) macro BS, and femto BS, respectively.

As we plan to simply model the HetNet SE we adopt that the instantaneous transmitted signal power of any macro BS is considered a random variable ranging from zero during ABS state, or to P_1^{tx} otherwise. Furthermore, we denote the instantaneous transmit power of the serving BS by P_2^{tx}.

Firstly, we adopt that a certain UE of an arbitrary location is being served by the micro tier i, whose SINR Γ_i is greater than the threshold γ with the probability $\mathcal{P}_i$.

Secondly, we consider that a certain UE is being served by the micro tier i, whereas the probability of the UE being served by the pico tier with appropriate $SINR$, is denoted as $\mathcal{P}_j$.

Thereby, from (1) and (2), SE_i and SE_j can be expressed as:

$$\mathcal{P}_i = \mathcal{P}\{\Gamma_i > \gamma \parallel \mathcal{R}_i = r_i, \mathcal{R}_j = r_j\} \quad (7)$$

$$\mathcal{P}_j = \mathcal{P}\{\Gamma_j > \gamma \parallel \mathcal{R}_i = r_i, \mathcal{R}_j = r_j\} \quad (8)$$

Integrating the (exponential) probability density functions of distances between the UE and the serving tier i, as well as from the candidate-serving tier j, provides SE_i and SE_i, as well as the overall HetNet spectral efficiency as it follows:

$$SE_{\text{TOT}} = SE_i + SE_j \quad (9)$$

3 TEST RESULTS

The above presented analytical model is software implemented using ns3 network simulator.

Our preliminary test results are aimed to just verify the proposed concept, whereas the follow-up tests of this kind can be repeated as many times as needed.

Five rounds of according simulations were made, with the *BER* results in particular, enhanced by statistical data averaging. Finally, the three considered scenarios were tested:

- single-tier, 5 macro BSs, BS power: 40 W,
- single-tier 250 pico BSs, BS power: 0.25W,
- two-tier 5 macro + 250 pico BSs.

The set up data for the simulation are presented in Table 1.

Table 1: Parameters used in ns3 simulations.

Parameter	Value
LTE code-block maximal size (*L*)	6144 Bytes
Count of macro cell BSs	5
Maximal output transmit power of the macro-cell BS	40W
Maximal output transmit power of the small-cell BS	250mW
Count of small-cell BSs	250
Population density per m^2	$3.8 \cdot 10^{-4}$
Maximal distance between BSs in the macro cell	500m
Maximal distance between BSs in the small cell	50m
Count of resource blocks with the LTE 5MHz channel bandwidth	25
Center of the frequency operating band:	2.1GHz
LTE channel bandwidth	5MHz

Furthermore, based on the set up values given in Table 1, in Table 2, are the obtained simulation results.

Table 2: Simulation results (after averaging).

BER	***SINR***	***SE*[b/s/Hz]**	***EE*[b/J]**
0.0378	11.98	17.28	0.53
0.0550	11.06	15.96	1.04
0.0659	10.55	15.22	1.65
0.0813	9.86	14.22	3.09
0.0921	9.45	13.63	4.45
0.0996	9.16	13.22	5.75

Accordingly, the proposed analytical model is graphically represented in Fig. 4, reflecting various exemplar scenarios that we considered. Coming out of the presented curves, it is evident that SE of the entire HetNet of interest grows exponentially with transmit power ratio, when small cells are implemented surrounding a typical macro cell. However, it is quite different with only a single macro tier, where SE does not change with transmit power ratio.

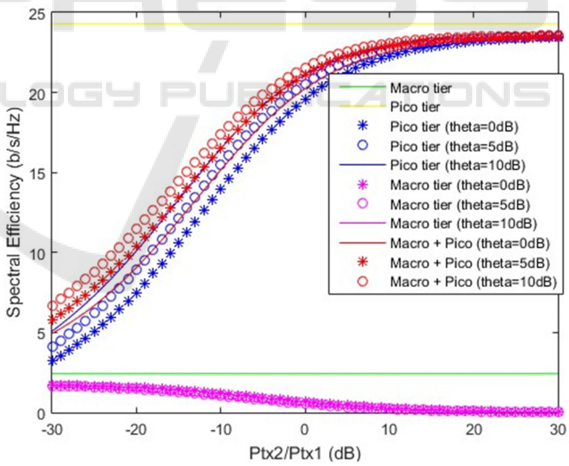
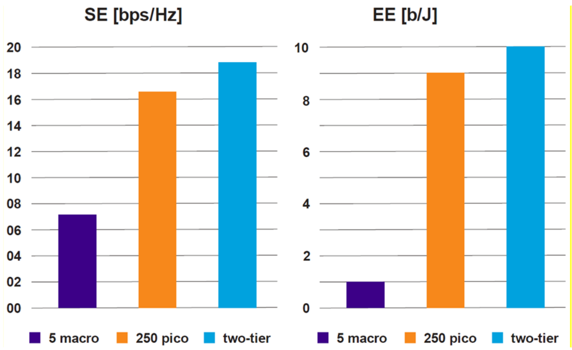


Figure 4: Spectral efficiency vs. relative transmit power and cell range expansion bias (theta).

Therefore, more pico cells in the network inevitably imply higher spectral efficiency, which complies to the expected values obtained by the proposed analytical model.

Accordingly, the diagrams in Fig. 5(a) and (b) represent *SE* and *EE*, respectively, resulting from simulations of the three above reviewed scenarios and parameters' values in Table 1:



(a) (b)

Figure 5: Simulation results for: a) SE, b) EE.

In both above diagrams, it can be seen that the two-tier scenario exhibited the most efficient network performance.

Furthermore, the small-cell scenario (250 pico BSs) came out to be more efficient than what was achieved with macro cells (5 BSs), while still preserving the same count and layout of users.

Finally, considering various transmit power in the pico tier with the macro-tier transmit power remaining constant, *SE* shows growing trend with respect to the ratio of transmit powers.

4 CONCLUSIONS

Instead of SINR, we proposed the simpler-to-measure BER as the key performance indicator, by abstracting the performance degradation due to various (generally non-AWGN) impairments, by the according AWGN ones which have the same effect on BER as any specific distortion.

It came out that inserting small cells into HetNets of any distribution of BSs, significantly improved both the energy and spectral efficiency.

So, with smaller distances in between BSs and UEs of contemporary networks – e.g. LTE and LTE-A, the trend is rationalization and optimization of signal coverage by reinforcing it in the areas of increased traffic.

Such a strategy seems to be appropriate in the tested exemplar environments, but needs to be enhanced and fine-tuned with other sophisticated tests taking into account other impairments e.g.: RF interference, traffic patterns, bandwidth and channel allocation etc., whose management is aimed enable the projected QoS level, complexity reduction, and fair distribution.

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