Fundamental Limits for LTE Radio and Network Planning

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***Abstract*—A comprehensive study on the variation of the carrier-to-noise-plus-interference ratio (CNIR) with different system parameters at the DL/UL is of fundamental importance in the context of LTE planning. From a detailed analysis of its variation with the coverage and reuse distances for different values of the channel quality indicator (CQI) in the DL and given empirical propagation models, an evaluation of the possible range for the reuse pattern is performed. By considering the CQI and reference CNIR requirements recommended by 3GPP. DL peak bit rates along with the Transport Block Size (TBS) assumed for single stream and bandwidth of 5 MHz, physical and supported throughputs are analysed. These formulations shows the clear decrease of the supported throughput for the longest coverage distances in the LTE 2.6 GHz band, a behaviour that is not so clear at 800 MHz, and gives hints to the optimization of the use of different frequency bands in the optimization of carrier aggregation between two different bands in LTE-A scenarios.**

Keywords—LTE; CNIR; radio and network planning; system capacity

I. INTRODUCTION

Long Term Evolution (LTE) offers higher data throughput to support new and advanced mobile broadband services [1]. It provides seamless Internet Protocol (IP) connectivity between user equipment (UE) and the packet data network (PDN), and an air interface based on Orthogonal Frequency Division Multiplexing (OFDM) in the downlink (DL) and single-carrier frequency-division multiple access (SC-FDMA) in the uplink (UL), both providing high flexibility in the frequency-domain scheduling. LTE has the flexibility to support time-/frequency-division duplexing (TDD/FDD), and half-duplex FDD schemes.

The main goal of cellular coverage is to offer access to mobile users within the cell, whilst ensuring the quality of the received signal in both DL and UL directions, even for the users at the cell edge, who may suffer from low connection quality. Due to the radio resources scarcity, frequency channels need to be reused in different geographical zones, thus, leading to increasing interference among co-channel cells, which needs to be evaluated in both directions. In an LTE multi-cell scenario, inter-cell interference is the main limiting factor for the system performance due to frequency reuse deployment; furthermore, this interference is heavier in users at cell edge.

A comprehensive study on the variation of the UL/DL carrier-to-noise-plus-interference ratio (CNIR) from/at the Mobile Station (MS) with different system parameters is therefore of fundamental importance in the context of LTE cellular planning. The variation of CNIR with the coverage and reuse distances is analysed for different values of the channel quality indicator (CQI) in the DL. Table I shows the CQI and reference CNIR requirements recommended by 3GPP for DL, as well as the spectral efficiency, S_{ef}. A similar approach was considered in [2] for WiMAX networks, considering different modulation and coding schemes (MCSs) and an implicit function formulation to obtain the supported throughput.

TABLE I. MINIMUM CNIR, MODULATION AND SPECTRAL EFFICIENCY VERSUS CQI FOR LTE AND VALUES FOR THE VERTICAL ASYMPTOTE

CQI	$CNIR_{min[dB]}$	Modulation	S_{ef}	$R_{asymptote[m]}$ f = 800 MHz	$R_{asymptote[m]}$ f = 2.6 GHz
0		out of range	0		
1	-4.63	QPSK	0.15	9,359	4,432
2	-2.60	QPSK	0.23	8,009	3,793
3	-0.12	QPSK	0.38	6,621	3,135
4	2.26	QPSK	0.60	5,515	2,612
5	4.73	QPSK	0.88	4,563	2,161
6	7.53	QPSK	1.18	3,680	1,743
7	8.67	16-QAM	1.48	3,372	1,597
8	11.32	16-QAM	1.91	2,751	1,303
9	14.24	16-QAM	2.41	2,199	1,041
10	15.21	64-QAM	2.73	2,041	967
11	18.63	64-QAM	3.32	1,570	744
12	21.32	64-QAM	3.90	1,277	605
13	23.47	64-QAM	4.52	1,083	513
14	28.49	64-QAM	5.12	737	349
15	34.60	64-QAM	5.55	461	218

Table II presents DL/UL peak bit rates along with Transport Block Size (TBS) considered for single stream and bandwidth of 5 MHz. Power and gains assumed in the considered LTE scenario are presented in Table III (800 MHz/2.6 GHz).

TABLE II. DL AND UL PEAK BIT RATES WITH TBS CONSIDERED FOR SINGLE STREAM AND A BANDWIDTH OF 5 MHZ-25 RESOURCE BLOCKS

Modulation	DL peak rates [Mbps]	UL peak rates [Mbps]
QPSK	4	4.4
16-QAM	7.7	12.6
64-QAM	18.3	18.3

TABLE III. POWER, GAINS AND NOISE PARAMETERS

Parameters	f = 800 MHz	f = 2.6 GHz
$P_{t[dBW]}$	13	13
$G_{t[dBi]}$	3	3.5
$G_{r[dBi]}$	0	0
$BW_{[MHz]}$	5	5
$N_{f[dB]}$	8	8

The remainder of the paper is organized as follows. Section II addresses the interference, noise and reuse trade-offs involved in LTE radio and network planning considering different values of the CQI. Section III presents a detailed analysis of LTE system capacity considering elaborated assumptions for the different levels of CQI, and discusses results for the equivalent supported throughput as a function of the coverage distance. Finally, conclusions are drawn in Section IV.

II. CELLULAR PLANNING

An efficient use of the radio frequency spectrum requires choosing a frequency reuse scheme guarantees coverage and enhanced system capacity whilst minimizing interference. As there would be limitations arising from an independent analysis of the coverage (noise) and frequency reuse (interference) issues, cellular planning has to simultaneously consider carrier-to-noise and carrier-to-interference constraints. Improvement techniques as sub-channelization and tri-sectored antennas can be considered to improve coverage and avoid interference.

A. Formulation for Carrier-to-noise-plus-interference Ratio

This section addresses aspects related to the analysis of the cell coverage distance (or radius), R, the co-channel reuse factor, r_{cc}, the ratio between the reuse and the coverage distances, and the reuse pattern, K, for several levels of LTE CQI. The conclusions taken out facilitate the appropriate selection of the reuse pattern and efficient frequency planning.

If one considers the interference-to-noise ratio, defined by:

$$M = I/N \quad (1)$$

and the equation for the carrier-to-noise-plus-interference ratio (CNIR) to be used in the dimensioning process is the following:

$$\left(\frac{C}{N+I}\right) = \left(\frac{C}{N}\right)_{min} \quad (2)$$

Equation (2) can be re-written in the two following ways

$$\left(\frac{C}{N}\right) = \left(\frac{C}{N}\right)_{min}(1+M) \quad (3)$$

$$\left(\frac{C}{I}\right) = \left(\frac{C}{N}\right)_{min}(1+M^{-1}) \quad (4)$$

In (2) one is considering the model for CNIR from [2] while assuming equal weights for noise and interference. From equation (3) one obtain the following equation for the interference-to-noise ratio:

$$M(R) = \left(\frac{\left(\frac{C(R)}{N}\right)}{\left(\frac{C}{N}\right)_{min}}\right) - 1 \quad (5)$$

where $C(R)=P_R(R)$ is computed by applying the modified Friis equation with γ =3 (suburban environment).

Values of $M(R)$ are proportional to the interference still tolerable for a given coverage distance R while (still) agreeing with the quality requirements for a given CQI/MCS.

With a hexagonal cell topology, in the DL, Fig. 8.1 from [2], as the distance associated with interference is D, i.e., the reuse distance itself, by considering the modified Friis propagation model the carrier-to-interference ratio is given by:

$$\frac{C}{I} = \frac{1}{2(r_{cc}+1)^{-\gamma}+2r_{cc}^{-\gamma}+2(r_{cc}-1)^{-\gamma}} \approx \frac{r_{cc}^{-\gamma}}{6} \quad (6)$$

where r_{cc} is the co-channel reuse factor, given by $r_{cc}=D/R$. The approximate expression in (6) is very useful in practice. It is worthwhile to note that, for hexagonal reuse geometries, the reuse pattern is given by $K= r_{cc}^2/3$.

As a horizontal asymptote arises in the analysis of the curves of r_{cc} as a function of the coverage distance, R, it is important to present the mathematical details associated to it. To compute the horizontal asymptote in the chart from $r_{cc}(R)$, one has to consider that $R \to 0$. From (5), if $R \to 0$ then $M \to +\infty$, and $M^{-1} \to 0$.

On the one hand, for the DL, in the limit, one obtains:

$$\lim_{R\to 0} r_{cc} = \sqrt[\gamma]{6\cdot\left(C/N\right)_{\min}} \quad (7)$$

By considering the dependence of K on r_{cc}, it is straightforward to conclude that, for each value for the propagation exponent, the reuse pattern, K, only depends on the CQI/MCS through the value of the corresponding minimum carrier-to-noise ratio, as well as on the cellular interference geometry.

While the asymptotic reuse factor is associated with the upper bound for system capacity, the maximum coverage distance is associated with the carrier-to-interference-plus-noise ratio at the cell boundary when the interference is null. Since the interference-to-noise ratio, M, represents the interference that can still be tolerated for a given R, in the limit, the maximum coverage distance for which no extra interference is tolerated is obtained when $I(R) \to 0$, i.e., when $M(R) \to 0$ (meaning that $M_{[dB]} \to -\infty$). Hence, the vertical asymptote for the $M(R)$ and $r_{cc}(R)$ charts is the following:

$$R_{asymptote} = R_{M\to 0} \quad (8)$$

It is obtained by solving the following equation:

$$M(R) = \frac{\left(C(R)/N\right)}{\left(C/N\right)_{\min}} - 1 = 0 \quad (9)$$

or, in a simplified way:

$$C(R)/N = \left(C/N\right)_{\min} \quad (10)$$

By comparing this equation (valid only when $M\to 0$) with (3), one concludes that only considering the carrier-to-noise ratio to determine the coverage distance, R, is inadequate in systems where interference is relevant, as (10) corresponds to a null M. If a cellular system is dimensioned this way there would not be an extra margin for interference, represented by $M = I/N$. Finally, it is a worth noting that, for a given propagation exponent, the maximum coverage distance corresponding to the vertical asymptote, $R_{asymptote}$, depends not only on the MCS but also on the noise power, N. This is the reason why the reduction of the noise power through sub-channelization, i.e., through the reduction of the RF bandwidth, can be so important.

B. Interference-to-noise Ratio and Reuse Pattern

By considering (5), one obtains the curves for the DL M, considering the Friis (propagation exponent γ =3) and COST-231 Hata models, for the 800 MHz and 2.6 GHz frequency bands. Considering both models we have obtained the values of interference-to-noise-ratio, M, in the DL for f = 800 MHz which depends on the CQI value and the MCS associated to it. Table I presents the values for $CNIR_{min}$ associated to each CQI as well as the corresponding values for the vertical asymptote, $R_{asymptote}$. It is observed a relevant decrease of the values for the vertical asymptote (maximum coverage) as the CQI increases, which is compatible with the highest values for $CNIR_{min}$.

By manipulating the equations for the DL one obtains the results for $r_{cc}(R)$ and $K(R)$. Charts for the interference-to-noise ratio, $M(R)$, are obtained by considering (5), for the 800 MHz frequency band (considering the modified Friis, γ=3, and COST-231 Hata models), as shown in Figures 1-4, and 2.6 GHz band (only for the Hata model), as shown in Figures 5-6. At 800 MHz, for the shortest coverage distances, M is lower with the modified Friis model but it becomes higher than for the COST-231 Hata model for the largest Rs. As a consequence, for the modified Friis and Hata models, with CQI up to 7, low reuse patterns are achievable while, with CQI 8, K lower than 7 is obtained for Rs up to circa 1500 and 1400 m, respectively.

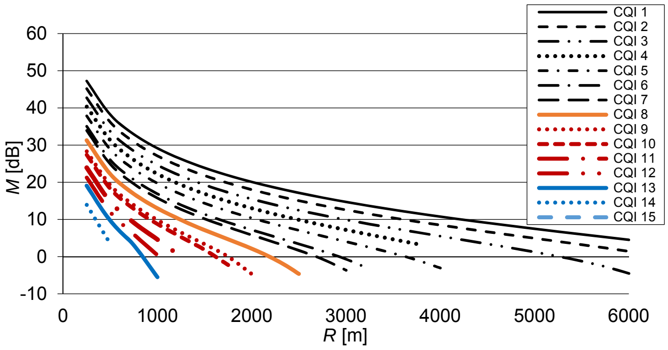

Fig. 1 Interference to noise ratio as a function of the coverage distance with CQI as a parameter for DL, in the 800 MHz band and Friis model.

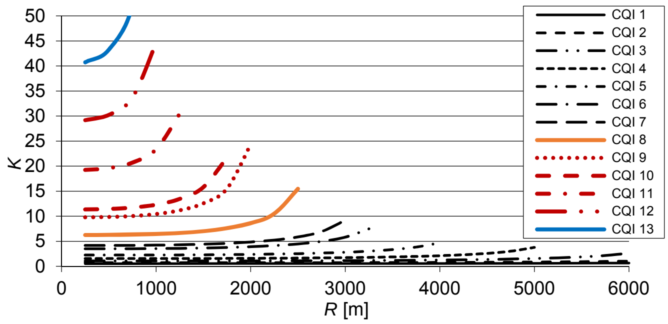

Fig. 2 Reuse pattern as a function of the coverage distance with CQI as a parameter for DL, in the 800 MHz frequency band and Friis model

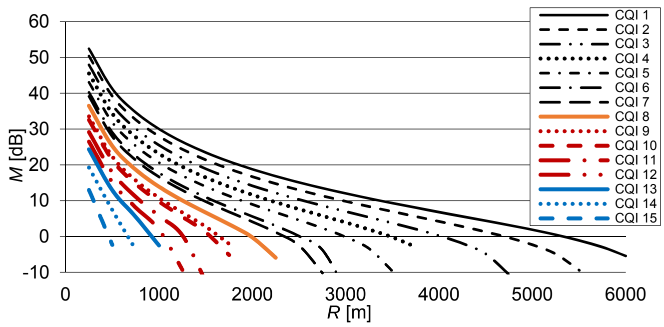

Fig. 3 Interference to noise ratio as a function of the coverage distance with CQI as a parameter for DL, in the 800 MHz band and Hata model.

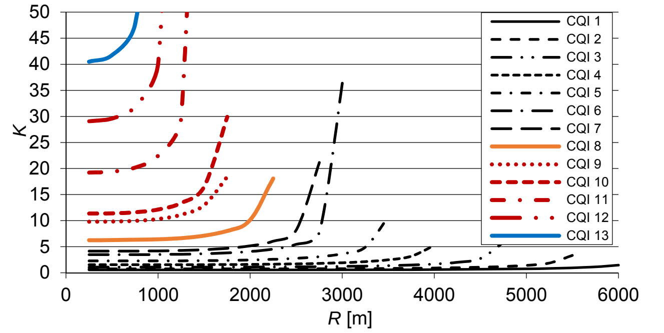

Fig. 4 Reuse pattern as a function of the coverage distance with CQI as a parameter for DL, in the 800 MHz frequency band and Hata model.

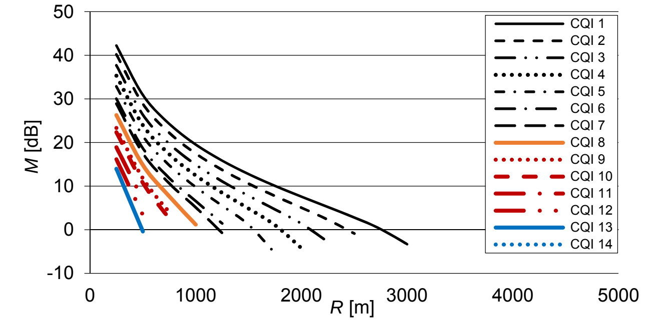

Fig. 5 Interference to noise ratio as a function of the coverage distance with CQI as a parameter for DL, in the 2.6 GHz band and Hata model.

At 2.6 GHz, M is lower than at 800 MHz but behaviour for the shortest and longest coverage distances is similar to the former one at 800 MHz.

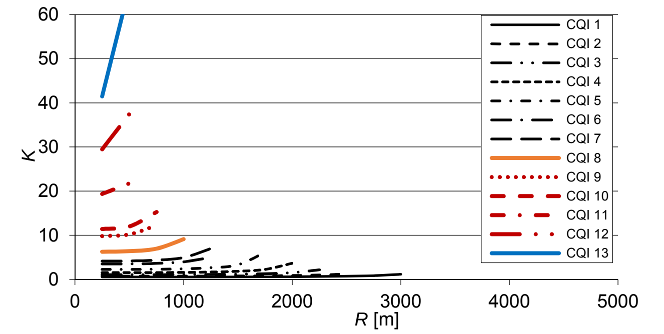

Fig. 6 Reuse pattern as a function of the coverage distance with CQI as a parameter for DL, in the 2.6 GHz frequency band and Hata model.

C. Supported Throughput and its Dependence on CNIR

From the analysis of the results it is clear that achievable values for *CNIR* are more favourable for the 800 MHz frequency band. Hence, in the step transitions observed in the curves for throughput (different MCS $CNIR_{min}$), the achieved physical throughput increases first (for lower coverage distance, R) than at 2.6 GHz, as shown in Figure 9 (example for 800 MHz).

III. Detailed Analysis of System Capacity

While previous Sections analyse the individual influence of each MCS, it is also worthwhile to study the overall impact of different MCS. Following the formulation from [3] for an implicit function procedure to compute supported throughput, the LTE system capacity is analyzed at both 800 MHz and 2.6 GHz considering the COST-231 Hata propagation model. The analysis considers the supported throughput for K = 1, 3 and 7.

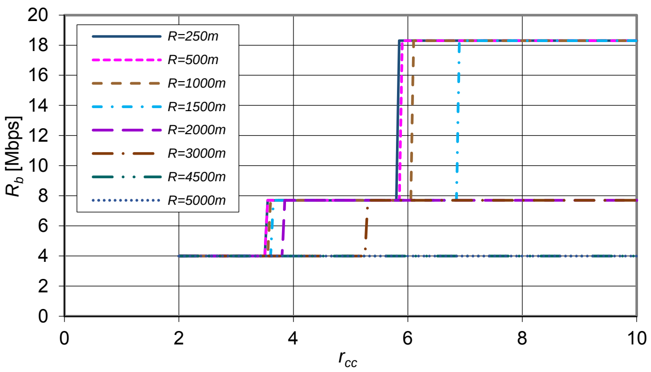

Fig. 9 Physical throughput for the DL in the 800 MHz in band.

Now G_t = 14 dBi. Additionally, to map the reference CNIR into supported throughput one has considered a formulation slightly more elaborated than in Section III and assumed the values provided by [4], more specifically in Tables 7.1.7.1-1 and 7.1.7.2.1-1. By extrapolating the gathered information it is possible to map the CNIR into CQI, Modulation Order Transport Block Size (ITBS) index and TBS. Assuming TTI = 1 ms the throughput is obtained by multiplying the TBS by this value. As 5 MHz bandwidth is considered, i.e., 25 PRBs, the column NPRB = 25 from Table 7.1.7.2.1-1 is assumed.

The main difference between the following analysis and the approach from [4] (and from Section II) is the number of coverage rings, *J*. Here, the number of coverage rings is equal to 27, i.e., equal to the number of ITBS, as each index corresponds to a different value of the throughput. Figure 10 shows the values obtained for the 800 MHz carrier component (CC), whereas Figure 11 shows the results for the 2.6 GHz CC.

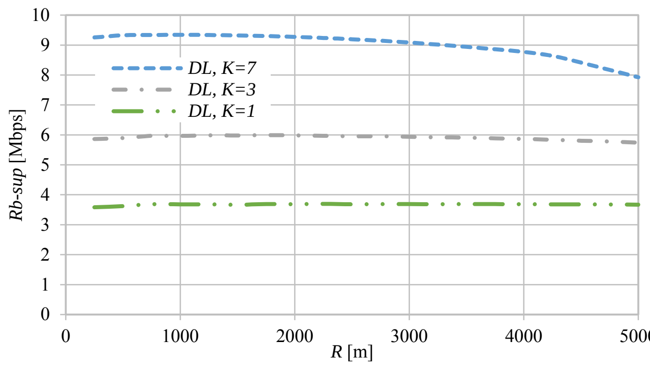

Fig. 10 Comparison of the equivalent supported throughput between cells for *K* = 1, 3 and 7 at the 800 MHz band.

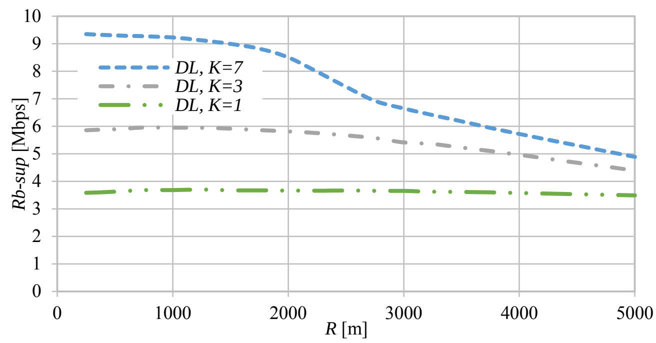

Fig. 11 Comparison of the equivalent supported throughput between cells for *K* = 1, 3 and 7 at the 2.6 GHz band.

Although the decay of the supported throughput as a function of the distance is apparent in both cases, it is more noticeable at 2.6 GHz, because of the higher path loss. Furthermore, *K* = 7 is the reuse pattern which presents the most evident reduction with the distance. In turn, the case *K* = 1 shows slightly no reduction of the supported throughput with the distance. It presents the lowest values for the throughput of the three addressed reuse patterns. Finally, *K* = 3 presents a mixed behaviour. On the one hand, the obtained values are slightly affected by the distance at 800 MHz whereas at 2.6 GHz the reduction is more apparent. On the other, supported throughputs are in-between the ones obtained for *K* = 1; 7.

It is also interesting to note that the maximum supported throughput obtained at the lowest addressed distance, *R* = 250 m, is approximately the same for both CCs, i.e., 3.6, 5.9 and 9.3 Mbps in the DL, for *K* = 1, 3 and 7, respectively. In perspective, considering *R* = 2500 m and *K* = 7 the achieved results are 9.2 Mbps (800 MHz CCS) and 7.4 Mbps (2.6 GHz CCs) in the DL.

IV. Conclusion

This work has presented a comprehensive study on the variation of the carrier-to-noise-plus-interference ratio (CNIR) with different LTE system parameters. For cellular radio and network planning purposes, the UL and DL CNIRs from/at the mobile station need to be addressed. From a detailed analysis of its variation with the coverage and reuse distances for different CQIs and given empirical propagation models, an evaluation of the possible range for the DL reuse pattern has been performed. By considering the CQI and reference CNIR requirements recommended by 3GPP, DL peak bit rates along with the Transport Block Size assumed for single stream, and bandwidth of 5 MHz, an analysis of the PHY and supported throughputs has been performed. From the analysis of LTE system capacity one can learn that the main difference between the two bands is the clear decrease of the supported throughput for the longest coverage distances in the 2.6 GHz band (as the highest CQIs are not supported), a behaviour that is not so clear at 800 MHz.

These formulations show the basic limits for system capacity and gives hints regarding the use of different frequency bands in the optimization of carrier aggregation in LTE-A scenarios.

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