Deliverable D2.3

Work Package 2 – System Level Evaluation

D2.3 Final System Level Evaluation Report

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EXECUTIVE SUMMARY

The SAMURAI project Deliverable D2.3 concludes the system-level studies by incorporating knowledge gained during the development and testing of the MU-MIMO and ACCS testbeds in Workpackage 5. The studies presented in this deliverable are based on the initial investigation results achieved in Year 1, which have been extended in Year 2 with detailed findings from Workpackage 3, Workpackage 4 and Workpackage 5 studies.

This deliverable presents more in depth investigation and studies done in the last phase of the project, in three main SAMURAI focus areas: i) Effect of Channel State Information (CSI) measurement and feedback error to the system level performance estimation for downlink (MU-)MIMO; ii) Evaluation of the MIESM based link to system level interface for downlink MU-MIMO and interference aware receivers, based on findings of Work-package 3, and iii) Final performance evaluation of the proposed Autonomous Component carrier Selection (ACCS) concept using the SAMURAI ACCS demonstration platform characterises and deployment scenarios. Each section dealing with these areas is a self-contained topic with connections to other Work packages of the SAMURAI project.

Section 2 contains the latest evaluation and results regarding the interfacing and performance of the interference aware receiver structure developed in WP3. A method is presented that allows the abstraction of this receiver, hence its performance at system level in realistic circumstances can be and was evaluated. Numerical results of its performance are shown, revealing that this receiver can bring significant gain in system capacity, at the price of modestly decreasing individual average UE throughput and cell-edge UE throughput performance.

Section 3 is devoted to present the latest findings in the area of modelling and evaluation of the effect of CSI impairments. Generic framework for CSI errors is shown and is used to simulate system level quality measures when such errors are present. Further studies on the modelling of the CSI error due to frequency domain interpolation errors are also shown. Numerical results on system level throughput revealed that generally various CSI error models do not cause significant performance loss.

Section 4 describes the final system level evaluation of the Autonomous Component Carrier Selection (ACCS) method developed in WP4. Throughput performance and spectrum usage of the algorithm, as well as optimisation of various thresholds and parameters are shown, based on system level simulations conducted in numerous environments. Results of the proof of
Concept platform developed in WP5 are fed back and compared with simulations.
DISCLAIMER

The work associated with this report has been carried out in accordance with the highest technical standards and the SAMURAI partners have endeavoured to achieve the degree of accuracy and reliability appropriate to the work in question. However since the partners have no control over the use to which the information contained within the report is to be put by any other party, any other such party shall be deemed to have satisfied itself as to the suitability and reliability of the information in relation to any particular use, purpose or application.

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### Definitions, symbols and abbreviations

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<td>3GPP</td>
<td>Third Generation Partnership Project</td>
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<tr>
<td>ACCS</td>
<td>Autonomous Component Carrier Selection</td>
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<td>AMC</td>
<td>Adaptive Modulation and Coding</td>
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<td>ARQ</td>
<td>Automatic Retransmission reQuest</td>
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<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<td>BC</td>
<td>Base Carrier</td>
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<td>BLER</td>
<td>Block-Error-Rate</td>
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<td>BS</td>
<td>Base Station</td>
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<td>CA</td>
<td>Carrier Aggregation</td>
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<td>CC</td>
<td>Component Carrier</td>
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<td>cdf</td>
<td>cumulative distribution function</td>
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<td>C/I</td>
<td>Carrier/Interference</td>
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<td>CoI</td>
<td>Carrier over Interference</td>
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<td>CQI</td>
<td>Channel Quality Indicator</td>
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<td>CSI</td>
<td>Channel State Information</td>
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<td>DL</td>
<td>Downlink</td>
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<td>EESM</td>
<td>Exponential Effective SINR Mapping</td>
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<td>EGT</td>
<td>Equal Gain Transmission</td>
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<td>eNB</td>
<td>Evolved NodeB (E-UTRAN NB/BS)</td>
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<tr>
<td>ESM</td>
<td>Effective SINR Mapping</td>
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<tr>
<td>G-factor</td>
<td>geometry factor</td>
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<td>HARQ</td>
<td>Hybrid ARQ</td>
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<td>IA receiver</td>
<td>Interference Aware receiver</td>
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<tr>
<td>L2S(I)</td>
<td>Link-to-System (Interface)</td>
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<tr>
<td>LA</td>
<td>Link Adaptation</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution of UTRA(N)</td>
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<tr>
<td>LTE-A</td>
<td>Advanced Long Term Evolution of UTRA(N)</td>
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<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
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<td>MIESM</td>
<td>Mutual Information Effective SINR Mapping</td>
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<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>MSE</td>
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<td>MU</td>
<td>Multi User</td>
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<td>MU-MIMO</td>
<td>Multi User MIMO</td>
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<tr>
<td>MUI</td>
<td>Multi User interference</td>
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<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>OLLA</td>
<td>Outer Loop Link Adaptation</td>
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<td>PMI</td>
<td>Precoding Matrix Indicator</td>
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<tr>
<td>PoC</td>
<td>Proof-of-Concept</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PRB</td>
<td>Physical Resource Block</td>
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<td>PS</td>
<td>Packet Scheduling</td>
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<td>PSK</td>
<td>Phase Shift Keying</td>
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<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<td>QPSK</td>
<td>Quaternary PSK</td>
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<tr>
<td>RBIR</td>
<td>Received Bit Information Rate</td>
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<td>RRM</td>
<td>Radio Resource Management</td>
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<tr>
<td>Rx</td>
<td>Receiver</td>
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<tr>
<td>SC</td>
<td>Supplementary Carrier</td>
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<tr>
<td>SCC</td>
<td>Supplementary Component Carrier</td>
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<tr>
<td>SI</td>
<td>Symbol Information</td>
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<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
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<tr>
<td>SINReff</td>
<td>Effective SINR (compressed SINR as output from L2S)</td>
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<tr>
<td>SU</td>
<td>Single User</td>
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<tr>
<td>SU-MIMO</td>
<td>Single User MIMO</td>
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<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
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<tr>
<td>Tx</td>
<td>Transmitter</td>
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<tr>
<td>UE</td>
<td>User Equipment</td>
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<td>Uplink</td>
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1 Final WP2 conclusions

During the course of the project WP2 conducted several activities and achieved significant results (which are reported in previous deliverables D2.1 [1], D2.2 [2] and the current document) in the following areas:

- Applicability and performance of several downlink MU-MIMO receiver algorithms at system level
- Interfacing (in terms of block error ratio versus SNR) of a novel interference aware MU-MIMO receiver algorithm (developed in WP3) to system level simulator and evaluation of its performance at system level
- Analysis and modelling several channel estimation errors (interpolation, quantisation, Gaussian) and providing insights into the downlink system level performance loss during reception, due to the imperfect channel knowledge
- Develop models for channel state estimation and feedback errors (delays, losses) and detailed simulation evaluation of their impact on system level performance in case of MU-MIMO transmission
- Evaluation of feedback compression schemes applicable for LTE-A carrier aggregation schemes in order to reduce feedback overhead
- System level evaluation of downlink MU-MIMO scheduling algorithms in terms of user throughput cdfs and average cell throughputs
- Evaluation of the throughput performance of downlink carrier aggregation schemes with 2x2 SU-MIMO transmission, with focus on the performance gain of LTE-A features
- Evaluation of the throughput performance of downlink carrier aggregation schemes applied in combination with MU-MIMO transmission
- Evaluation of physical layer enhancement techniques for LTE-Advanced for uplink carrier aggregation, uplink multi-cluster scheduling and uplink MU-MIMO transmission
- Development and system level evaluation of Autonomous Component Carrier selection mechanisms including methods for selecting Base Carrier and Supplementary Carrier, mainly applicable for dense indoor Home eNodeB (femtocell) environments, or dense heterogeneous macro/pico network deployment.

1.1 Conclusions on downlink MU-MIMO

Regarding packet scheduling and link adaptation for MU-MIMO in 3GPP LTE Release 8, our studies in deliverable D2.1 [1] show that the optimal spatial scheduling of the paired UEs and the associated link-adaptation based on the limited channel information feedback available from the UEs is a challenging task. With baseline assumptions only minimal system performance gain of MU-MIMO can be obtained, compared to SU-MIMO. However, when including
improved UE receiver algorithm, the system performance can be increased to approximately 3% to 10% compared to the SU-MIMO reference.

The performance of downlink MU-MIMO system can be much enhanced when LTE-Advanced specific demodulation reference symbols are used. When applying a modified UE selection, pairing and scheduling algorithm proposed in deliverable D2.2 [2], it is possible to achieve a gain in the average cell-throughput in the order of 23%. Moreover, downlink MU-MIMO transmission technique also improves the performance of cell edge UEs with a potential gain of 7% as compared with the case they are operating in SU-MIMO transmission mode.

Considering different impairments in the estimation and reporting of the channel state information, our studies in deliverable D2.1 show that feedback delay may cause around 5 dB loss in the block error ratio (BLER) performance even for advanced receiver architectures. Channel estimation errors due to quantisation cause negligible performance loss, also estimation error due to interpolation stays in the regime of 1-2 dB in the BLER performance. The effect of PMI loss on the performance also stays at the tolerable level, when considering reasonably low loss probability of the PMI. In the deliverable D2.2 we show that MU-MIMO CQI estimation can be effectively enhanced by advanced methods, compared to the traditional fixed CQI offset approach and this can lead to an 8% improvement in average cell throughput. Our results have also shown that MU-MIMO CQI estimation based on adaptive rank shows near a constant throughput and outperforms rank-1 MU-MIMO CQI prediction significantly when SNR increases. Even adaptive rank CQI prediction requires more feedback, less precoding operations and easier channel estimations at UE is required and as such is more robust and practicable for LTE systems beyond Release8.

The unified framework of modelling different channel estimation errors lead to system-level results that show little impact of the various CSI/ CQI error models in case of rank-adaptive SU-MIMO transmission, with at most 2.5% and 4.5% degradation for the average UE throughput and cell-edge (5%-ile) UE throughput levels, respectively. As a general rule, and as expected, the highest impact from CSI/CQI errors for vehicular channels estimation errors, while with the pedestrian channel estimation errors (3 kmph) there is no significant performance degradation visible.

With regards to interfacing the novel interference aware receiver developed in WP3 into the system level simulator of WP2, we may conclude that the accurate mutual information based effective SINR mapping (MIESM) method is very effectively replaced by exponential effective SINR mapping (EESM) with two calibration factors. Using this interfacing method, system level
results in this deliverable D2.3 show that IA receiver based MU-MIMO scheme can provide 20% gain in cell capacity compared to SU-MIMO.

1.2 Conclusions on carrier aggregation

Regarding feedback compression, three main extensions of feedback schemes have been proposed and evaluated under bursty traffic conditions. The results presented in deliverable D2.1 [1] show the optimal trade-off between feedback size and the system performance is obtained when using the Average Best-M CQI (UE selected) and Wideband PMI type of feedback in each active component carrier.

Regarding carrier aggregation throughput performance, it is shown in deliverable D2.1 that for full buffer traffic load, LTE-Advanced UEs can provide up to 23% average cell throughput increase compared to the performance with LTE Release 8 UEs only. The gain in UE throughput is dependent on the component carrier settings and the highest gains are observed in the 4x10 MHz setting with 40% and 27% in the median and cell-edge UE goodput respectively. For finite buffer and bursty traffic the performance gains of CA system over a single component carrier vary according to the load conditions. At low load, the average goodput of the UEs in a CA system can be N times (N is the number of aggregated carriers) higher that of the UEs in a traditional single component carrier. The gain of the CA system gradually degrades from low to medium cell load conditions. At very high cell load the gain of the CA system becomes negligible in terms of UE goodput.

In the area of Autonomous Component Carrier Selection (ACCS) it can be concluded that there is a clear gain from using a relatively simple, matrix based initial base component carrier (BCC) selection algorithm compared to a pure random BCC selection [1]. Furthermore, this algorithm needs to be extended with supplementary component carrier (SCC) selection algorithm for optimal carrier configuration. In medium to high load scenarios, a system configuration with at least three CCs can fully benefit from the proposed ACCS interference mitigation scheme, while the required signalling complexity and overhead are kept to minimum. In large scale deployments the acceptable path-loss detection threshold between the Femto-eNBs (\textit{PLThreshold}) is in the range of 102-140dB. In smaller deployment scenarios the acceptable \textit{PLThreshold} can be lower in the range of 80-90dB. For the effective operation of the ACCS algorithm the \{BCC, SCC\} selection carrier over interference (C/I) thresholds combinations should be set in the range of \{20, 8 to 11\} dB for deployments with at least 6 neighbouring cells, while the range of \{17, 5 to 11\} dB can be used for smaller number of neighbouring cells, and regardless of the cell total downlink transmit power. System level studies show that in terms of UE throughput, ACCS performs
well in situation of high traffic load and high interference coupling between the cells [1][2]. In this deliverable D2.3, experimental and simulation studies have been conducted and documented when using practical ACCS PoC deployment scenarios [10]. In these real-life deployment scenarios, including dynamic radio channel conditions, it was shown that further optimization, and possibly also an adaptation mechanism, is needed in order to set the correct C/I threshold values used in the component carrier selection.

1.3 Conclusions on joint carrier aggregation and MU-MIMO performance

In the downlink studies with CA and SU/MU-MIMO, under full buffer load traffic assumptions the MU-MIMO transmission performed better than the SU-MIMO transmission. This result is expected and similar to the non-CA results. However, in practical traffic load conditions (finite buffer with bursty traffic), it was shown in deliverable D2.2 [2] that MU-MIMO yields performance enhancement in terms of UE goodput only in high traffic load conditions. It is highlighted that MU-MIMO techniques can only obtain gain when there are numerous UEs and the system can exploit the multi-user diversity gain. Due to the characteristic of the bursty traffic, the gain achieved with MU-MIMO transmission is amplified and the overall performance enhancement is much larger than the gain obtained in full buffer traffic load conditions (up to 20% gain compared to CA with SU-MIMO).

In uplink direction, when carrier aggregation and MU-MIMO are both deployed, several physical layer enhancement techniques were presented in deliverable D2.2 and shown to yield significant performance increase. It is shown that with proper separation between power-limited and non-power-limited LTE-A users, multi-cluster scheduling with CA has similar coverage performance as in LTE Release 8, but can achieve substantial gains, up to 56%, in average user throughput compared with LTE Release 8. Uplink MU-MIMO can further improve the throughput performance, especially when MU-MIMO is combined with multi-cluster scheduling.
2 Link-to-System interface for Interference Aware receivers

2.1 Introduction

LTE transmission mode 5 precoders are characterized by their low resolution and the principle of equal gain transmission (EGT). Therefore, even with optimal scheduling the residual MU interference is significant in this transmission mode and can lead to a degradation of the system performance. A promising way to recover the gains of MU-MIMO in this mode is to employ interference aware (IA) receivers, such as in [15].

Interference aware receivers benefit from the fact that the interfering signal belongs to a finite QAM constellation and has certain structure which can be exploited during the detection of the desired signal. In other words the interference is not considered as Gaussian in these kinds of receivers.

Link-to-system interfacing or link abstraction models are of utmost importance for large scale system level simulations where these models not only provide the accurate mapping between link level and system level simulations but can also be used for fast resource scheduling at the eNodeB.

State-of-the-art link abstraction schemes are all post processed SINR based schemes. The most popular basic scheme is the effective SINR mapping (ESM) where at first the varying SINRs of a codeword are compressed and mapped to an effective SINR value which is then used to read the equivalent BLER from the AWGN performance curves of a particular modulation and code scheme (MCS).

\[
\gamma_{\text{eff}} = \beta l^{-1} \left[ \frac{1}{J} \sum_{j=1}^{J} I \left( \frac{\gamma_j}{\beta} \right) \right]
\]

(2.1)

\[
\gamma_{\text{eff}} \rightarrow \text{BLER(mcs)}
\]

(2.2)

where \( J \) is the number of channel symbols in a codeword and \( I(\gamma_j) \) is a mapping function which transforms SINR of each channel symbol to some “information measure” where it is linearly averaged over the codeword. Then these averaged values are transformed back to SNR domain. \( \beta \) is called calibration factor and it is there to compensate for the performance of different modulation orders and the code rates.

Figure 2-1 shows the generalized link abstraction methodology for system level evaluations. System level simulator generates a multi-state channel vector in which each entry corresponds to a subcarrier. Then it calculates the
post processed SINR values for each of the subcarrier and pass this information to the link abstraction module where an effective SINR is calculated. Then this effective SINR is mapped onto a link quality metric for example BLER.

ESM can be applied for the linear receivers but for non-linear receiver, i.e., interference aware receiver, it cannot be applied directly. The main reason is that for the case of interference aware receiver, we do not know the post-processed SINR values so we need to extend the ESM in such a manner that it can be used for those kind of receivers where the knowledge of post processed SINR is not available.

There are two widely used ESM techniques for the link abstraction, expected effective SINR mapping (EESM) and mutual-information based effective SINR mapping (MIESM). In the following we shall describe how these link abstraction techniques can be used for interference aware receiver.

There are two widely used ESM techniques for the link abstraction, expected effective SINR mapping (EESM) and mutual-information based effective SINR mapping (MIESM). In the following we shall describe how these link abstraction techniques can be used for interference aware receiver.

![Abstraction in System Performance Evaluation](image)

Figure 2-1 Abstraction in System Performance Evaluation

In order to evaluate the abstraction methodology we carried out link-level simulations using EESM and MIESM and we proposed a new modulation model for the MIESM which is able to exploit the structure of interference.

### 2.2 Abstraction for MU-MIMO using EESM

EESM is based on post processed SINR for each of the subcarrier and for the non-linear receiver structures, post processed SINR is not available. However, based on the knowledge of desired user's channel, precoder, noise variance and interfering user's channel, precoder it is possible to calculate signal-to-interference plus noise ratio. For EESM \([1]\) the mapping function \(I(y_j)\) is calculated using Chernoff Union bound of error probabilities, i.e., \(I(y_j) = 1 - \exp(-y_j)\), then effective SINR is calculated as,
\[
\gamma_{\text{eff}} = \beta \ln \left[ \frac{1}{j} \sum_{j=1}^{J} \exp \left( -\frac{\gamma_j}{\beta} \right) \right]
\]  
(2.3)

and based on this effective SINR, then the link quality indicator (BLER) is computed from previously calculated AWGN performance curves.

\[
\text{BLER}(\gamma, mcs) \approx \text{BLER}_{\text{AWGN}}(\gamma_{\text{eff}}, mcs)
\]  
(2.4)

Where \( \gamma \) is the vector of the \( \gamma_j \) SINR values across all of the subcarriers. But this \( \gamma_j \) not an accurate performance metric for modeling the performance of non-linear receiver structures and it is expected to see a performance loss if it is to be used for link abstraction. This was in fact shown in [2] that using EESM as described is not able to model the performance of interference aware receiver. Therefore, we decided to investigate the MI based approach.

### 2.3 Abstraction for MU-MIMO using MIESM

We present an extension of the mutual information based abstraction methodology for the link abstraction of interference aware receivers and normal receivers. The abstraction model consists of two blocks, modulation model and coding model as shown in Figure 2-2. The inputs for the abstraction can be SINR values for each subcarrier or the channel of desired user, precoder and constellation of desired and interfering user. Based on the preferred input the modulation model calculates maximum channel capacity in terms of symbol information for every subcarrier. The modulation model only accounts for the modulator and demodulator. Then in the coding model symbol information of each subcarrier belonging to the same codeword is averaged over total number of transmitted bits during that codeword to reach the received bit information rate (RBIR). This RBIR is used to read the effective SNR from SNR-to-normalized SI (symbol information) mapping. Then finally this effective SNR is used to read the BLER from previously calculated AWGN performance curves corresponding to the specific MCS.

#### 2.3.1 Modulation Model

Modulation model as shown in Figure 2-2 provides us with the symbol information (SI) in terms of maximum channel capacity for each of the subcarrier. In this deliverable we propose a new modulation model for the specific case of MU-MIMO.
The proposed modulation model is based on:

\[
I(Y; X_1 | \alpha_1, \zeta_2) = \log M_1 - \frac{1}{M_1M_2N_2N_h} \sum x_1 \sum x_2 \sum h_1 \sum z_1 \log \left( \frac{\sum x_1' \sum x_2' \exp \left[ -\frac{1}{N_0} |\alpha_1x_1 + \zeta_2x_2 + z_1 - \alpha_1'x'_1 - \zeta_2'x'_2|^2 \right]}{\sum x_2' \exp \left[ -\frac{1}{N_0} |\zeta_2x_2 + z_1 - \zeta_2'x'_2|^2 \right]} \right)
\]  

(2.5)

from[14] and is stored in the form of a look up table. This table is a function of the modulation order of the desired stream (M1) and the interfering stream (M2), the signal to noise ratio (SNR) of the desired stream, desired signal \(\alpha_1\) and interference \(|\zeta_2|\). Since the purpose of link abstraction is to reduce complexity so table for symbol information mapping should be available as a look up. To generate these tables we performed Monte-Carlo simulations of (6) in [14] over a wide range of noise and channel realizations. For each channel realization we obtained a random set of \(\alpha_1, |\zeta_2|\) and mutual information. For all other required values this scatter-plot was interpolated using linear interpolation. As an example an interpolated graph for the SNR of 10 dB is shown in Figure 2-3 where on the x-axis is the signal strength, on y-axis is the interference strength and on z-axis is the mutual information.
2.3.2 Coding Model

The coding model corresponds to the encoding and decoding of the codeword and predicts the performance for whole codeword. The output of modulation model is a vector of symbol information for all of the subcarriers of a codeword. The first thing which coding model calculates is the collection of received coded bit information (RBI) for the desired user among J subcarriers,

$$ \text{RBI} = \sum_{j=1}^{J} \frac{\text{SI}(\alpha_{1,j}, \xi_{2,j}, M_{1,j}, M_{2,j})}{\beta} $$

(2.6)

where the first index in modulation order $M_{1,j}$ represents the user and second index represents the subcarrier. $\beta$ is an adjusting factor which compensates of practical coding loss. The optimal value of beta can be trained over a set of enough channel realizations that covers a reasonable amount of different channel variations.

RBI is then normalized by the number of total coded bits to the received bit information rate (RBIR):

$$ \text{RBIR} = \frac{\text{RBI}}{\sum_{j=1}^{J} M_{1,j}} $$

(2.7)
As is shown in Figure 2-4, RBIR can also be regarded as normalized SI and is used for calculating the effective SINR. The normalized symbol information is based on the normalized mutual information expressions for finite constellation. Then this effective SINR is used to obtain BLER from the equivalent AWGN performance curve for a specific MCS. These AWGN curves are pre-calculated for all MCS of LTE and stored in the form of a look-up table.

2.3.3 Calibration of Adjustment Factor
Calibration of adjustment factor ($\beta$) is very important for the accurate mapping of multi-state channels into one-state channel. We performed calibration through an iterative procedure which requires a starting point (normally initial $\beta = 1$) then it is chosen such that,

$$\beta = \arg \min_{\beta} \left[ \sum_{i=1}^{N_c} |BLER_{pred,mcs}(\beta) - BLER_{meas,mcs}|^2 \right] \quad (2.8)$$

where $N_c$ is the number of different channel realizations, $BLER_{pred,mcs}$ is the predicted block error rate from the respective AWGN curve which we calculated beforehand from the simulator and $BLER_{meas,mcs}$ is the error rate from $N_c$ channel realizations.

2.3.4 Results
We already presented the results of MU-MIMO abstraction for IA-Receiver using EESM and two variants of MIESM with one calibration factor in the
deliverable D2.2 [2] and we showed that MIESM with proposed changes is the best method for interference aware receiver. However, for its validation on the system level simulator it was required to implement it from the scratch and due to the time constraint, it was not possible. So we invested some more time in order to find an agreement between EESM (which is already implemented in our system level simulators) and proposed MIESM so that both can be used interchangeably. Further investigation led us to the conclusion that if two different calibration factors are used in the process of EESM instead of one calibration factor then EESM can reach very close to the accuracy of proposed MIESM where we use only one calibration factor. This is shown in Figure 2-5 and Figure 2-6.

Figure 2-5 and Figure 2-6 presents the results of MU-MIMO abstraction for MCS 10, 12, 14 and 16 using EESM and MIESM respectively. Please note that EESM used two calibration factors, whereas MIESM only used one calibration factor. The solid magenta lines in the figure represent the respective AWGN curves and the coloured stars around solid curves represent the BLER points which are measured using link level simulations for many number of different channel realizations. As can be seen from the figure that EESM with two calibration factors is able to compress and map the different realizations of MU-MIMO channel onto the respective AWGN curves.
Figure 2-5 EESM Link Abstraction for IA Receiver with two calibration factors
Therefore, based on the presented results MIESM IA link abstraction was approximated by EESM with two calibration factors. During the derivation of following system level results this method was used and hence referred as MIESM IA link abstraction.

2.4 System level evaluation results

2.4.1 Introduction

The link-to-system interface developed in Work package 3 and Work package 5 as presented in Section 2.2 and Section 2.3 has been used in downlink system-level evaluations following the procedure described in the previous Deliverables D2.1 and D2.2 [1][2].

The goal of these studies was to disclose the potential system-level gain which can be obtained when IA receivers are used for MU-MIMO reception compared to the rank-adaptive SU-MIMO transmission references. The reader should note that these studies did not aim to show absolute system
performance numbers or to investigate SU-MIMO performance, as compared to the reference 3GPP LTE/LTE-A MIMO evaluation studies.

The system-level simulations settings, parameters and scheduling algorithm used can be found in the above referenced documents. A downlink 2x2 MIMO transmission setup was used with 10MHz system bandwidth at 2 GHz carrier frequency. The 3GPP typical urban deployment and ITU based geometric channel model were employed. The main difference compared to the previous studies was due to the limitation of the available link-to-system interface mapping curves, which included only QPSK and 16QAM modulation and coding sets. Therefore, to provide a fair comparison, we have used the same QPSK and 16QAM MCS sets in all simulations presented in the following. All UE terminals simulated are assumed to have the same MIMO capability and implement the IA receiver algorithm. Furthermore, in these evaluations only the full buffer traffic model (UE download data continuously) has been used in order to have sufficient user diversity in the system (see Deliverables D2.2 [2]).

The three simulation sets to be compared are:

1. "**MU-MIMO Ideal IA**": Rank-adaptive SU-MIMO combined with rank-1 MU-MIMO using ideal IA receiver (zero residual MU interference at UE), and ideal MU-MIMO CQI compensation at the eNB
2. "**MU-MIMO MIESM-IA**": Rank-adaptive SU-MIMO combined with rank-1 MU-MIMO using realistic IA receiver, based on the MIESM L2SI curves, and ideal CQI compensation at the eNB
3. "**SU-MIMO**": Rank-adaptive SU-MIMO

### 2.4.2 Results and discussions

Figure 2-7 shows the main system level performance metrics obtained from the MU-MIMO IA evaluations along with the reference SU-MIMO results, in terms of average cell throughput and UE throughput statistics.

Compared to the ideal case of using ideal MU IA (zero residual MU interference at the UE) the results for the MIESM-IA show very good performance and only 3% degradation; the MIESM IA yields an overall cell throughput gain of approximately 20% compared to reference SU-MIMO transmission case. Furthermore, looking at the UE throughput statistics, it is clear that this gain comes at the cost of sacrificing the cell-edge performance, with a loss of approximately 35% compared to the SU-MIMO case.

Figure 2-8 shows more in-sight into the cell throughput gain mechanisms in these studies, in terms of the achieved system throughput vs. geometry factor. It is evident from these results that MU-MIMO transmission schemes can take advantage of the high G-factor (good SINR conditions at the UE)
hence improves the overall system spectral efficiency. A second observation is that UEs in low-medium G-factor conditions are better scheduled in SU-MIMO mode due to the rank-adaptation.

![Average cell throughput](image1)

![UE throughput](image2)

**Figure 2-7** System-level performance metrics from the MU-MIMO IA receiver evaluation studies.

![System throughput versus G-factor](image3)

**Figure 2-8** System-level cell throughput versus Geometry factor from the MU-MIMO IA receiver evaluation studies.

### 2.5 Conclusions and practical considerations

The performed system level simulation studies using IA receiver have revealed the following main findings to be considered in practical deployments:

1. The user diversity order has to be relatively high in given cell in order to be able to take advantage of the MU-MIMO transmission scheme.
2. Adaptive switching between SU and MU transmission modes as provided in LTE-Advanced is required in order to fully utilize the user diversity and their various SINR conditions in the cell.

3. A rank-adaptive MU-MIMO transmission scheme does not necessarily enhance the performance when combined with rank-adaptive SU-MIMO.

4. IA receivers have a positive impact on the overall system performance and can provide significant gain.

5. Appropriate system-level modelling of (advanced) IA receivers can be successfully achieved with MIESM based link-to-system interface.
3 Imperfect CSI modelling for downlink MU-MIMO

3.1 Introduction
For exploiting the full capabilities of downlink MU-MIMO transmission, the accurate and timely knowledge of the state of the whole wideband channel would be required, namely the instantaneous complex channel gains for each subcarrier, between each pairs of transmit and receive antennas. However, in practical systems the actual status of the channel is not perfectly known at the transmitter, nor at the receiver.

This is caused by several factors:
- channel status in terms of quality is reported by the UE with a finite granularity, that refers to applicable transport format (Channel Quality Indicator, CQI values), but not actual channel gain values
- MIMO transmission is helped by UE measurements, but the results of these measurements are reported only in terms of Rank Indicator (RI) and Precoding Matrix Indicator (PMI)
- reporting has an inherent delay after the actual measurements, hence the status of the channel until the instant of reception might change compared to the state when the report was sent
- channel state reporting messages might become corrupted or lost
- channel measurements at the UE (used for receiving and calculating reported values) are possible based on known reference signals, however these are sent with finite granularity in both time and frequency dimensions, hence channel status between (both in frequency and time domain) these reference symbols should be estimated

In this Section the latest results of WP2 studies regarding CSI imperfections are summarised. Work was focusing on the evaluation of the system level performance, when different imperfections in the channel knowledge are present. Efforts on the derivation of CSI imperfection models applicable to be used in system level simulations were also conducted and are reported.

3.2 Modelling CSI measurement and feedback errors in system level studies
Currently there is no common and concrete way of modelling the error in measurement and feedback of the CSI. Being able to understand the mechanism and thereby model this type of errors is desirable for the design and implementation of the simulator at system level. Currently, the measurement error in the CQI report is simply modelled as a lognormal distribution with standard deviation of 1 dB [1][2]. The channel and the PMI are assumed to be perfectly estimated. The model may not be correct for all CQI range. Most importantly, the model is derived as a rule of thumb and no
reasoning to support the use of this model was given. In this section we propose a framework to model the CSI measurement error. The sources for error in the reported CSI include the feedback delay, channel estimation error and error in the feedback channel.

\[ CSI_{Error} = FeedbackDelay + ChannelEstimation_{Error} + FeedbackChannel_{Error} \]  

(3.1)

The delay in the feedback would cause an outdated feedback information. Due to the outdated CQI and PMI information, RRM decisions including the packet scheduling and link adaptation are no longer optimal. The delay in the feedback of the CSI for LTE-Advanced system includes the time required for estimating the CSI and the time required to update the CSI.

The channel estimation error would cause incorrect estimation of the PMI and therefore the CQI as a consequent. The channel estimation error is dependent on the algorithm used in the estimation process as well as the condition of the channel. A common MMSE (Minimum Mean Square Error) channel detection for LTE system would give a MSE (Mean Square Error) varying according to the channel condition or the received SINR. The channel estimator performs best at high SINR and degrades at low SINR. The relationship between the MSE and the SINR of channel estimators for LTE systems have been reported extensively in literature e.g., [22]-[27]. Here, we use the results from [24], which are derived for 2x2 MIMO LTE systems, for illustration purpose. From the measured MSE vs. SNR curve it is possible to model the behaviour of the MSE vs. SINR by using a simple linear regression approach. Using this method, we can derive a best fit for the MSE vs. SINR curve provided in [24] as follows

\[ \log_{10}(MSE) = -0.0943 \times SINR - 0.8 \]  

(3.2)

To reduce the complexity of the model we propose to use the wideband SINR i.e. the G-factor instead of using the per symbol SINR in order to derive the MSE.

\[ \log(MSE) = -0.0943 \times G_{factor} - 0.8 \]  

(3.3)

Since the error in the channel estimation can be considered as white noise, the error in the channel can be modelled as a Gaussian distribution with the variance equivalent to the MSE. The estimated channel can be derived as

\[ \hat{H} = H_{ideal} + H_{error} = H_{ideal} + \phi(0, MSE) \]  

(3.4)

where \( \phi(0, MSE) \) is a Gaussian distribution with mean zero and variance MSE.
By calculating the PMI and CQI based on this channel estimation, the effect of channel estimation error to the CSI is reflected.

Even though the feedback channel is well protected, it can happen that the feedback CSI is in error. According to [24], the typical error rate of the feedback control channel is 4%. Since it is not possible to correct the error, a practical solution for this case is to reuse the previous correct CSI feedback. This requires a continuous update of the correct CSI feedback.

Figure 3-1 shows our proposed framework to model the CSI measurement and feedback error.

![Diagram](image)

**Figure 3-1** The developed system-level modelling framework for the CSI measurement and feedback error.
3.3 Modelling CSI error due to frequency domain interpolation for system level studies

The goal of this section is to provide further insight into the modelling of CSI imperfection, by means of providing error models that can be used as direct input for system level studies. The basic model of describing CSI error as a Gaussian random variable, with variance depending on the wideband SINR (G factor) is extended to cover some important channel types.

3.3.1 Basic description of the CSI error model

For the description of imperfect CSI, the time-variant transfer function of the multipath Rayleigh-fading channel was calculated according to the well-established and widely used framework of discrete FIR filter, representing the taps of the different channel paths [27]. The frequency selectivity of the channel is then determined by calculating the frequency response of the FIR filter model. In the current model, the frequency response realization will be considered time-invariant for the duration of the transmission interval of a 1 ms LTE subframe.

In this study the effect of frequency selectivity is evaluated. In particular, LTE defines reference signals that do not cover all the OFDM subcarriers, hence channel state between these subcarriers should be estimated by interpolation. The reference signals are disturbed by white noise, so the channel state on subcarriers not containing reference symbols should be estimated based to measurements over noisy nearby subcarriers.

Accordingly, within this realistic model, the actual CSI will be estimated with the help of a frequency-domain interpolation, based on the reference signals with known content at well-defined positions in the time-frequency resource grid. In a frequency non-selective case the channel has the same effect on the reference signals/symbols as on the useful data transfer, i.e. the transmitted reference signals are attenuated and phase shifted by the radio channel. Namely, a received complex \( \hat{r}(n,n_r) \) reference signal sequence for a narrowband model (i.e. the channel transfer function is considered constant for the calculations within the bandwidth of an OFDM subcarrier) can be expressed as \( \hat{r}(n,n_r) = H(n,n_r)r(n,n_r) + v(n,n_r) \) in which \( n \in \{1,2,\ldots,N_c\} \) represents the subcarrier index of the reference signals according to the frequency mapping of them, \( H(n,n_r) \) denotes the radio channel's transfer function at the subcarrier positions, selected by \( n \) and \( v(n,n_r) \) refers to the complex samples of the AWGN over the same subcarrier set. Finally, let \( r(n,n_r) \) denote the transmitted reference symbol sequence, which can be used to estimate the actual state of the radio channel as
\[ \hat{H}(n, n_s) = \frac{\hat{r}(n, n_s)}{r(n, n_s)}, \]

where \( \hat{H}(n, n_s) \) denotes the estimated channel samples at the frequency positions. Certainly, the channel samples can only be estimated, since the random noise samples are not known at the receiver. However, we can forecast, that the

\[ \varepsilon = E \left( \left| H(n, n_s) - \hat{H}(n, n_s) \right|^2 \right) \]

Average squared channel estimation error will be proportional to the \( N_0 / 2 \) variance (i.e. the spectral power density) of the AWGN and inversely proportional to the SNR.

In a frequency selective channel the channel estimates obtained for the subcarriers which contain reference symbols are then used to obtain estimates for the other subcarriers, using spline (piecewise polynomial) interpolation.

An example of the effect of channel state estimation based on noisy reference symbols and the interpolation based channel state estimation over a frequency selective channel is shown in Figure 3-2 and Figure 3-3.

**Figure 3-2** Illustration of the channel equalization with the actual and the estimated channel.
The SNR for the reference signals can be defined as
\[ \gamma = \frac{E_s}{N_0} = \frac{P_r}{N_0 \Delta f_c} = \frac{P_r |H|^2}{N_0 \Delta f_c}, \]
where \( E_s \) represents the energy, carrying a single (reference)symbol, \( P_r \) and \( P_t \) are representing the transmitted and the received power at the investigated receiver respectively. In the current model we will assume unit power gain for the radio channel, resulting in a normalized frequency response. The AWGN will be modelled as an additive complex Gaussian process with zero mean and \( \sigma^2 \) variance, equivalent to \( \sigma^2 = \frac{N_0}{2} \) [W/Hz].

Let us consider the SNR in [dB], i.e.
\[ \gamma = \frac{P_r}{2\sigma^2 \Delta f_c}, \]
from which we get the
\[ \sigma^2 = \frac{P_r}{\gamma 2\Delta f_c} \]

adjustable \( \sigma^2 \) variance to represent a desired SNR value within the simulations. In order to follow the common plotting methods of the SNR, let us define the desired SNR in [dB], i.e. the
\[ \sigma^2 = \frac{P_r}{10^{\gamma_{dB}/10} 2\Delta f_c} = 10^{\frac{\gamma_{dB}}{10}} \frac{P_r}{2\Delta f_c} \] [W/Hz].
value of variance should be considered for the complex Gaussian process added to the complex reference symbols within the expression of the estimated radio channel for pre-defined $\gamma_{\text{dB}}$ SNR values.

### 3.3.2 Simulation assumptions

The goals of the investigation simulation are the

- Determination of the average squared channel estimation error for different SNR values and for different settings of average tap delay values.
- Provide empirical realizations of the probability density function of the estimation error (by histograms) by different simulation parameter settings.

**Simulation parameters:**

- $B_{\text{ch}} = 5$ MHz
- $\gamma_{\text{dB}} = 0, \ldots, 30$
- $f_c = 2.6$ MHz
- $\Delta f = \frac{1}{T_s} = 15$ kHz ($T_s$ denotes the symbol period)
- Number of realizations (time samples) $N_s = 1000$.
- Frequency-domain reference symbol spacing: $6 \cdot \Delta f = 90$ kHz
- Content of the complex reference symbols: integer values from the uniform distribution on the set $(0,3)$, and modulated by 4-QAM.
- $P_r$ is ‘measured’ on the received symbol set (including data symbols) over the frequency domain.

### 3.3.3 Investigations for different channel models

During the simulations six different channel models have been considered according to the ITU multipath channel model definitions[21], which are determining the path delay and the average path gains setting (containing implicitly also the number of the channel taps).

By setting the parameters of the different channel models within the multipath FIR filter model, the statistics of the $\varepsilon$ channel squared estimation error was investigated in terms of the expected value over different SINR settings.

In Figure 3-4 the $\varepsilon$ expected value of the squared channel estimation error is illustrated for the different ITU channel models (Indoor A, B; Pedestrian A, B; Vehicular A, B). The curves are confirming our intuition, that the average interpolation error should be higher with a channel with higher frequency selectivity.
In Figure 3-5 the logarithm of the mean square error of the channel estimation is plotted in case of ITU Pedestrian A channel, as the function of wideband SINR. This mean square error directly can be used in system level studies for generating a Gaussian distributed random CSI error. As reference, the expression used in Section 3.2 \( \log_{10}(MSE) = -0.0943 \cdot SNR - 0.8 \) is also plotted. It is visible that for this channel this reference expression gives higher value for the estimated MSE of the CSI error.

The simulated results of the MSE of channel interpolation error are then used to obtain a linear expression for the logarithm of the MSE. The resultant expression is:

\[
\log_{10}(MSE) = -0.09557 \cdot SNR - 1.4821
\]

(3.5)

During the simulations we observed that the logarithm of the MSE as function of SNR becomes less steep for higher SNR values, thus linear approximation is not very accurate in high SNR region. This is more apparent for other ITU multipath profiles, shown in the Appendix. Therefore we propose to use a cubic expression obtained by interpolation, for modelling the effect of CSI. For the ITU Pedestrian A channel this is:

\[
\log_{10}(MSE) = -0.0000351 \cdot SNR^3 - 0.000743 \cdot SNR^2 - 0.0966 \cdot SNR - 1.4601.
\]

(3.6)
In Figure 3-6 the behaviour of the channel estimation error is plotted, for the ITU Vehicular A multipath profile. As we expected, in this case the channel estimation errors are more severe, as this channel is more frequency selective. Here the reference curve gives more optimistic estimates for the error.

The linear approximation for the Vehicular A channel has the form of

$$\log_{10}(\text{MSE}) = -0.09404 \cdot \text{SNR} - 0.01292. \quad (3.7)$$

Here the applicability of the cubic interpolation is more visible. After interpolation, the expression obtained is

$$\log_{10}(\text{MSE}) = 0.0000333 \cdot \text{SNR}^3 - 0.000581 \cdot \text{SNR}^2 - 0.09839 \cdot \text{SNR} + 0.16406. \quad (3.8)$$

In the Appendix the results obtained for the other four ITU multipath profiles are also shown.
3.4 System level evaluation results for CSI with interpolation error

3.4.1 Introduction

The CSI error mode developed in Workpackage 3 as presented in Section 3.2 through Section 3.3 has been used in downlink system-level evaluations following the procedure described in the previous Deliverables D2.1 and D2.2 [1][2].

The goal of these studies was to disclose the potential impact on the system-level performance of various CSI/CQI error modelling approaches. The reader should note that these studies did not aim to show absolute system performance numbers or to investigate SU-MIMO performance, as compared to the reference 3GPP LTE/LTE-A MIMO evaluation studies.

The system-level simulations settings, parameters and scheduling algorithm used can be found in the above referenced documents. A 4x2 downlink MIMO transmission setup was used with 10 MHz system bandwidth at 2 GHz carrier frequency. The 3GPP typical urban deployment and ITU based geometric channel model were employed.

All UE terminals simulated are assumed to have the same MIMO capability and implement the same CSI/CQI estimation algorithm. Furthermore, in these evaluations only the full buffer traffic model (UE download data continuously) has been used in order to have sufficient user diversity in the

Figure 3-6 Frequency domain interpolation error for ITU Veh. A.
system (see Deliverable D2.2 [2]). Both the rank-adaptive SU-MIMO and the adaptive SU/MU-MIMO transmission schemes have been evaluated with the selected set of CQI/CSI error models.

The three simulation sets to be compared are:

1. **"Ideal CE and CQI"**: Ideal channel estimation and no CQI errors (zero quantization & estimation errors).
2. **"CQI Error"**: A Gaussian CQI quantization & estimation error model is applied with standard deviation of 1 dB (in the corresponding SINR domain).
3. **"CSI Error#X"**: ImperfectCSI estimation model for interpolation errors (Section 3.3) combined with no CQI errors (zero quantization & estimation errors), where X has the value corresponding to:
   a. 1 = reference model presented in Eq. (3.3);
   b. 2 = MIMO de-correlated interpolation error presented in Eq. (3.6) for ITU pedestrian A channel;
   c. 3 = MIMO de-correlated interpolation error presented in Eq. (3.8) for ITU vehicular A channel.

### 3.4.2 Results and discussions

Figure 3-7 shows the distribution of the user throughput statistics for SU-MIMO and MU-MIMO LTE-Advanced scenarios.

These results show very little impact of the various CSI/CQI error models in case of rank-adaptive SU-MIMO transmission, with at most 2.5% and 4.5% degradation for the average UE throughput (MEAN) and cell-edge (5%-ile) UE throughput levels, respectively.

When LTE-Advanced SU/MU-MIMO transmission is used the impact of CSI/CQI errors is higher, up to 8% degradation for the cell-edge (5%-ile) UE throughput levels, while the average UE throughput (MEAN) degradation is in the same range as for the rank-adaptive SU-MIMO transmission case.

As a general rule, and as expected, the highest impact from CSI/CQI errors for vehicular channels estimation errors, while with the pedestrian channel estimation errors (3 kmph) there is no significant performance degradation visible.
In order to further analyze the above results and to determine why there is no significant impact on the system performance from applying CSI/CQI errors, we have to look at one of the outer loop control mechanisms in the link-adaptation process. Previous studies have shown the importance of the outer loop link adaptation (OLLA) scheme, which is used to ensure a constant 1st transmission BLER according to the desired target [19][20]. The OLLA mechanism is used to compensate for CQI errors, i.e. cases where the CQI reports from the UE and used for LA (Link Adaptation)/PS (Packet Scheduling) in the eNB yield consistently higher or lower 1st transmission BLER compared to the set target. The OLLA adjust the CQI values to be used in the LA/PS in small incrementing or decrementing with a given OLLA offset value the CQI received from the given terminal before using for LA/PS. The same mechanism can be used also for multi-stream MIMO as discussed in [20].

In these CQI/CSI studies and the results presented above the MIMO OLLA mechanism was enabled and a 10% BLER target was used. Significant CSI/CQI errors would have as main results a more aggressive compensation by the OLLA mechanism in order to maintain the desired BLER target, i.e. larger OLLA offset values.

Figure 3-8 shows the cdf of the OLLA offset values which have been determined by the OLLA algorithm when various CQI/CSI errors have been applied. These results show indeed that the CQI error model and the CSI error model for vehicular channels are the most critical ones because they yield higher OLLA offset values. The range of average OLLA offset values is higher in the SU/MU-MIMO case because the OLLA is not aware of the MU-MIMO CQI compensation which is applied only for MU-MIMO LA; hence when a switch from SU to MU transmission modes occurs (allowed by LTE-Advanced Advanced TM9) there is larger step in the input CQI values to the OLLA.
Nevertheless, even in the SU/MU-MIMO scenario the OLLA is able to converge regardless of the CQI/CSI errors by using slightly higher average OLLA offset values.

Figure 3-8 Outer Loop Link Adaptation CQI offset distribution from the CSI error modelling evaluation studies when using SU-MIMO transmission scheme.

Figure 3-9 Outer Loop Link Adaptation CQI offset distribution from the CSI error modelling evaluation studies when using SU/MU-MIMO transmission scheme.
3.5 Conclusions and practical considerations

In these studies we have analyzed the sources for error in the UE-side CSI measurement/estimation in LTE-Advanced systems. We have proposed a framework to model these errors at system-level, which gives much more insight to the CSI measurement errors than the commonly used CQI measurement error model with 1dB standard deviation lognormal distribution. It is also fairly easy to apply and implement the proposed CSI error model to any system level simulator.

Further investigations of the effect of channel estimation error caused by frequency domain interpolation show that the usual linear approximation of the $\log_{10}(MSE)$ as function of wideband SNR (G factor) is less accurate than using a cubic approximation, especially for high SNR values. As expected, in more frequency selective environment the channel estimation error is generally higher.

However, system-level results show little impact of the various CSI/ CQI error models in case of rank-adaptive SU-MIMO transmission, with at most 2.5% and 4.5% degradation for the average UE throughput (MEAN) and cell-edge (5%-ile) UE throughput levels, respectively.

When LTE-Advanced SU/MU-MIMO transmission is used the impact of CSI/ CQI errors is higher, up to 8% degradation for the cell-edge (5%-ile) UE throughput levels, while the average UE throughput (MEAN) degradation is in the same range as for the rank-adaptive SU-MIMO transmission case.

As a general rule, and as expected, the highest impact from CSI/CQI errors for vehicular channels estimation errors, while with the pedestrian channel estimation errors (3 kmph) there is no significant performance degradation visible.
4 Autonomous Component Carrier Selection evaluation in real-life scenarios

4.1 Introduction

In these investigations we continue to focus on the ACCS evaluation in deployment scenarios based on the current ACCS PoC development [9] activities. Previously in Deliverable D2.2 we have presented preliminary results based on the PoC deployment scenarios. As a reminder we re-iterate here the main findings of the first studies presented in D2.2 [2].

Assuming that the Femto-eNB cells detect each other ‘over-the-air’ during the initial BCC (Base Component Carrier) selection phase, in large scale deployments – such as used in the 3GPP evaluations – the acceptable path-loss detection threshold between the Femto-eNBs (PLThreshold) is in the range of 102-140dB. In smaller deployment scenarios – such as the selected SAMURAI PoC scenario with 4 indoor cells – the acceptable PLThreshold can be lower in the range of 90-100 dB.

Furthermore, based on first simulations studies, for both large and small scale deployments scenarios with random activation sequence of the deployed Femto-eNBs, a large value for the initial BCC selection time window (BCCInitSel_MaxTimer) parameter seems to make good sense. When the absolute duration of the Initial BCC selection phase is not critical then the maximum possible setting for the BCCInitSel_MaxTimer should be used. In other scenarios, a medium value setting of 10-20 ACCS SubFrames (e.g. 10-20 s) length can still provide sufficient performance gains.

In these final SAMURAI ACCS simulation studies we expand the Deliverable D2.2 studies – to be read as direct continuation of the D2.2 Section 5.5.3.3 – and provide the recommendations for the settings to be used for the main system wide ACCS parameters in typical low-scale small-cell indoor deployment scenarios. The full ACCS mechanism is evaluated in various deployment cases derived from real-life ACCS PoC platform scenarios. In addition to the simulation-based studies the experimental analysis of the ACCS performance over the PoCtestbed is also included. Such investigation enables to provide further insight about the ACCS parameters to be adopted, in a realistic operative scenario also considering human presence.

The main characteristics describing the investigations in this Deliverable D2.3 are:

1. Address downlink performance, with 2x2 MIMO LTE rank-adaptive transmission, and total eNB transmit power of 20 dBm or 0 dBm.
Investigate only the L3 ACCS mechanisms and abstract the L1-L2 link-adaptation and fast scheduling mechanisms.

2. Consider only indoor local area deployment scenarios, without any interaction with macro or pico coverage layers. Two dedicated SAMURAI ACCS PoC scenarios with ‘4-rooms’ and ‘6-rooms’ are used for detailed performance evaluation studies and ACCS parameter fine-tuning.

3. Assume fully random deployment and activation of the indoor Femto-eNB (cells) with one indoor Femto-UE (terminals) to be served per cell.

4. Assume the existence of a low-capacity control plane signalling between all the deployed Femto-eNBs. Existing LTE UE measurements (RSRP, RSRQ) are assumed as feedback information in the ACCS algorithm. The UE CSI feedback (i.e. the CQI/PMI/RI information) is considered as part of the L1-L2 abstraction and not addressed explicitly in these studies (see ptc. 1).

5. Use the main characteristics of the SW/HW ACCS platform when simulating the ACCS PoC performances. The main input from the ACCS PoC are the receiver sensitivity and the path-loss measurements which replace in these studies the typical 3GPP models used in the earlier evaluations [1][2].

6. Assume a total system bandwidth of 10MHz with 3 component carriers (CC). Although the exact bandwidth of the assumed CCs (e.g. 3 CCs in 10MHz) is not always 3GPP LTE standard compliant, all the presented results are scalable to practical LTE CC bandwidths when the offered load in the cell is scaled correspondingly to the total system bandwidth (20-40MHz).

**4.2 Scenarios and assumptions**

Rather than suing the standard 3GPP indoor deployment scenarios and models, in these final studies we have replaced them with real-life scenarios as used in the ACCS PoC testing and development using 12 nodes. The full path-loss matrix, between all 12 nodes, has been measured with the PoC platform as described in deliverable D5.2 [10].

All the deployment scenarios are based on the ‘template’ layout presented in Figure 4-1. Any of the nodes depicted in Figure 4-1 can be simulated as either “eNB” or “UE”, hence a quite large set of different scenarios can be generated. We have used three basic configurations, each with a certain number of scenarios selected as the most representative (labelled A0 to A7):

1. “6-rooms” with all UEs in the same room as the serving eNBs: all the nodes #1 to 12 are used in 3 different configurations (A0 to A2), see example in Figure 4-2.
2. “4-rooms” with two UEs in different room than the serving eNBs: all the nodes #1 to 12 are used in 2 different configurations (A3 and A4), see example in Figure 4-3.

3. “4-rooms” with all UEs in the same room as the serving eNBs: the nodes #2,3,4,5,8,9,10 and 11 are used in 3 different configurations (A5 to A7), see example in Figure 4-2.

The utilized scenarios and configuration are summarized in Table 4-1.

---

**Figure 4-1** ACCS PoC measurement layout used to derive deployment scenarios for the system-level studies.

**Figure 4-2** Example of “6-room” A0 and “4-room” A5 deployment scenarios with UEs in the same room as the serving eNBs (TX=eNB, RX=UE).
The A8 scenario is used for the experiments with live ACCS execution over the PoC testbed. 3 cells are considered.

The other main system parameters are summarized in Table 4-2 and are similar to the ones listed in Deliverable D2.2, Section 5.5.3, in Table 5-5 [2]. All 192 combinations between the UE average OFF-time, PLThreshold, CoI_Target_BCC and CoI_Target_SCC settings have been evaluated.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting/ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System BW / #CCs</td>
<td>10 MHz (3 CCs)</td>
</tr>
<tr>
<td>eNBTx Power per CC</td>
<td>15.3 dBm (20dBm total), or -4.7 dBm (0dBm total)</td>
</tr>
<tr>
<td>Frequency band</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Number of UEs per eNB (CSG)</td>
<td>Fixed: 1</td>
</tr>
<tr>
<td>eNB deployment ratio</td>
<td>4 eNBs or 6 eNBs (100 %)</td>
</tr>
<tr>
<td>eNB (cell) activation (&quot;switch-ON&quot;)</td>
<td>Spatially random sequence with 1 eNB activated per SF</td>
</tr>
<tr>
<td>Total time-duration simulated</td>
<td>200 SF = 100 s</td>
</tr>
<tr>
<td>UE buffer size</td>
<td>50 Mbit per UE (downlink)</td>
</tr>
<tr>
<td>UE average OFF-time</td>
<td>{10.0, 5.0, 1.0} s={low,medium, high} load</td>
</tr>
<tr>
<td>PLThreshold</td>
<td>{70, 80, 90, 100} dB</td>
</tr>
<tr>
<td>ACCSSubFrameLength</td>
<td>1 SF = 500 ms</td>
</tr>
<tr>
<td>ACCSFrameLength</td>
<td>5 SF = 2500 ms</td>
</tr>
<tr>
<td>BCCInitSel_MaxTimer</td>
<td>10 SF, iterative selection (small-scale setting)</td>
</tr>
<tr>
<td>BCCInitSel_TimerWin</td>
<td>2 SF, fast iteration</td>
</tr>
<tr>
<td>CoI_Target_BCC</td>
<td>{14, 17, 20, 23} dB</td>
</tr>
<tr>
<td>CoI_Target_SCC</td>
<td>{3, 5, 8,11} dB</td>
</tr>
</tbody>
</table>

*Table 4-2: Simulation parameter settings for the evaluation of the ACCS mechanism in the final PoC deployment scenarios (A0-A7).*
4.3 Component carrier selection thresholds

The first part of the studies is aimed to identify the best combination of the \textit{Col\_Target\_BCC} and \textit{Col\_Target\_SCC} parameter settings under the assumption of the best inter-eNB path-loss ranging threshold value, $PL\text{Threshold} = 100\text{dB}$\textsuperscript{1}. We choose as criteria for deciding the optimal parameter combination the performance in terms of average downlink UE throughput across the various offered traffic load conditions and deployment scenarios: highest and consistent UE throughput performance is the desired behaviour of ACCS.

Table 4-3 lists the legend notation used for the simulation sets indicated on the x-axis for the results presented in Section 4.3.

<table>
<thead>
<tr>
<th>Sim index</th>
<th>Scenario description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4*p+1</td>
<td>$Col_Target_SCC = 3 \text{ dB}$</td>
</tr>
<tr>
<td>4*p+2</td>
<td>$Col_Target_SCC = 5 \text{ dB}$</td>
</tr>
<tr>
<td>4*p+3</td>
<td>$Col_Target_SCC = 8 \text{ dB}$</td>
</tr>
<tr>
<td>4*p+4</td>
<td>$Col_Target_SCC = 11 \text{ dB}$</td>
</tr>
<tr>
<td>where $p={0,1,2,3}$</td>
<td>\text{For}$Col_Target_BCC = {14, 17, 20, 23} \text{ dB}$, respectively</td>
</tr>
</tbody>
</table>

\textbf{Table 4-3 Legend for the Sim index groups indicated on the x-axis for the results presented in Section 4.3.}

4.3.1 High transmit power (20 dBm)

In these studies the total MIMO transmit power of the eNB nodes has been set to 20 dBm (sum over all 3 CCs) with equal power on each CC.

Figure 4-4 and Figure 4-5 show the downlink average UE throughput statistics for various combinations of the $Col\_Target\_BCC$ and $Col\_Target\_SCC$ parameter in low and high load conditions, respectively. Table 4-3 lists the legend notation used for the simulation sets indicated on the x-axis for the results presented in Figure 4-4 to Figure 4-7.

4.3.2 Low transmit power(0 dBm)

In these studies the total MIMO transmit power of the eNB nodes has been set to 0 dBm (sum over all 3 CCs) with equal power on each CC.

Figure 4-6 and Figure 4-7 show the downlink average UE throughput statistics for various combinations of the $Col\_Target\_BCC$ and $Col\_Target\_SCC$ parameter in low and high load conditions, respectively.

\textsuperscript{1} In the studies reported in the Deliverable D2.2 \cite{2} it has been reported that the acceptable path-loss detection threshold between the Femto-eNBs ($PL\text{Threshold}$) is 90-100dB.
Figure 4-4 Average ACCS downlink UE throughput performance in low offered traffic load conditions, with 20dBm eNB Tx power, versus the CoI_Target_BCC and CoI_Target_SCC parameter combinations. See Table 4-3 for the x-axis legend.
Figure 4-5 Average ACCS downlink UE throughput performance in high offered traffic load conditions, with 20dBm eNB Tx power, versus the CoI_Target_BCC and CoI_Target_SCC parameter combinations. See Table 4-3 for the x-axis legend.
Figure 4-6 Average ACCS downlink UE throughput performance in low offered traffic load conditions, with 0dBm eNB Tx power, versus the CoI_Target_BCC and CoI_Target_SCC parameter combinations. See Table 4-3 for the x-axis legend.
Figure 4-7 Average ACCS downlink UE throughput performance in high offered traffic load conditions, with 0dBm eNB Tx power, versus the CoI_Target_BCC and CoI_Target_SCC parameter combinations. See Table 4-3 for the x-axis legend.
4.3.3 Conclusions on BCC-SCC selection thresholds

One first immediate conclusion from these results is that in Scenarios A3 and A4 - “4-rooms”, with two of the UEs located in different rooms than their serving eNBs – the UE throughput performance can drop significantly compared to the other selected scenarios, A0-A3 and A5-A7; especially the 5%-ile cdf results are very low or close to zero throughput, while the median/average remains in the same range as for the A0-A3 and A5-A7 scenarios.

The second main conclusion is that there is no obvious optimal setting combination for CoI_Target_BCC and CoI_Target_SCC parameters across all the considered deployment scenarios and traffic load cases, which maximizes both 5 percentile and median/average UE throughput values. Hence, in a fully adaptive system each eNB would have to be able to estimate the ‘interference density’ and adapt the BCC and SCC selection thresholds accordingly.

Thirdly, the best CoI_Target_BCC and CoI_Target_SCC parameter settings are dependent on the number of cells “4-rooms” (A5-A7) vs. “6-rooms” (A0-A2). As expected, with more active cells, the interference levels are higher hence the CoI_Target_BCC and CoI_Target_SCC thresholds should be set somehow lower in order to achieve comparable 5 percentile performance.

Analyzing the results for different eNB transmit power levels, we can conclude that the general results trends are the same for both low (0dBm) and high (20dBm) transmit powers settings. Although the absolute performance degrades slightly when using low transmit power the sensitivity to the CoI_Target_BCC and CoI_Target_SCC settings is higher, especially in high load conditions.

Based on these results, we recommend the {CoI_Target_BCC, CoI_Target_SCC} combinations to be set in the range of {20, 8 to 11} dB for deployments with at least 6 neighbouring cells, while the range of {17, 5 to 11} dB can be used for smaller number of neighbouring cells, and regardless of the cell total downlink transmit power.
4.4 Inter-eNB path loss ranging threshold selection

The second part of the studies is aimed to identify and confirm the best \textit{PLThreshold} parameter setting under the assumption of a set of \textit{CoI\_Target\_BCC} and \textit{CoI\_Target\_SCC} parameter values as identified in Section 4.3 i.e., \{\textit{CoI\_Target\_BCC, CoI\_Target\_SCC}\} = \{20, 8\} dB and \{17, 11\} dB for the “6-rooms” A0-A2 and “4-rooms” A3-A7 scenarios, respectively.

We choose as criteria for deciding the optimal parameter setting the performance in terms of average downlink UE throughput across the various offered traffic load conditions and deployment scenarios: highest and consistent UE throughput performance is the desired behaviour of ACCS.

The \textit{PLThreshold} values are set so that they cover both the expected achievable/measurable values on the ACCS PoC platform (80-100dB) [8][9][10] and the values correspond also to the realistic LTE eNB sensitivity levels.

Table 4-4 lists the legend notation used for the simulation sets indicated on the x-axis for the results presented in Section 4.4.

<table>
<thead>
<tr>
<th>Sim index</th>
<th>Scenario description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3*p+1</td>
<td>UE average OFF-time = 10 s</td>
</tr>
<tr>
<td>3*p+2</td>
<td>UE average OFF-time = 5 s</td>
</tr>
<tr>
<td>3*p+3</td>
<td>UE average OFF-time = 1 s</td>
</tr>
<tr>
<td>where p = {0,1,2}</td>
<td>For PLThreshold = {70, 80, 90, 100} dB, respectively</td>
</tr>
</tbody>
</table>

\textbf{Table 4-4 Legend for the Sim index groups indicated on the x-axis for the results presented in Section 4.4.}
Figure 4-8 Average ACCS downlink UE throughput performance in increasing traffic load conditions, versus PLThreshold and transmit power settings. See Table 4-4 for the x-axis legend.
4.4.1 Conclusions on path loss ranging threshold selection

We have to note here that the inter-eNB path-loss ranging threshold parameter alone cannot be used to optimize the performance of the system but a properly selected value can, however, ensure consistent behaviour across various deployment scenarios and traffic load conditions.

*From these studies, combined with the findings presented in deliverable D2.2 Section 5.5.3, we can conclude that in typical small-scale deployment scenarios a minimal inter-eNB path-loss ranging threshold of 80-90 dB is desirable.*

4.5 Resource utilization performance

In this final section we highlight some of the results obtained on the resources utilization when using the optimal parameter settings determined in Section 4.3 and Section 4.4 for the CC selection thresholds and the inter-eNB path-loss ranging threshold, respectively. Hence, we do not perform any further parameter optimization but rather show the impact of various deployment conditions on some of the system metrics such as overall spectral utilization and spectral resource sharing among the cells.

4.5.1 Deployment scenario with 6 cells

Figure 4-9 shows the average resource utilization in the “6-rooms” scenarios A0-A2 for each of the eNBs in terms of the fraction of time a certain number of CCs is allocated for the downlink transmission to the served UE. The effect of the increased cell load conditions is clearly visible, where cells converge to utilize in average only 2 CCs out of the 3 CCs available. Even in the low load conditions only certain nodes can allocate 3 CCs and for relatively low 10-12% fraction of time. These CC allocations are not exclusive per cell and several cells can share the physical resource blocks available in one given CC at any given time.

Figure 4-10 shows an example of spectral resource sharing, averaged over all simulation time, for each pair of eNBs in the scenario A0. The more interference coupled eNB pairs tend to allocate orthogonal resources, hence share less CC resources e.g., eNB#1–eNB#4, eNB#2–eNB#3/4, etc.

Figure 4-11 shows an example of time traces (realizations) in the “6-rooms” scenario A0 for the CC sharing factor. The higher this factor is for a given cell, labelled ‘eNB#x’, the more resources (physical resource blocks) per allocated CC are shared with other cells; the average sharing factor over all cells is labelled ‘All eNBs’. Conversely, the lower the sharing factor the less cells share the same allocated CCs.
Overall in the network of 6 cells, a time averaged CC sharing factor of approximately 85% is obtained in both low and high traffic load conditions. Among the active cells, the traces indicate quite large variations in the CC sharing factor, with time average values between 80% and 90%. The cells which tend to share most of their allocated CCs are the ones which are more de-coupled in terms of downlink interference and where the ACCS algorithm selects for use of the same CCs more often (in time).

Figure 4-9 Average spectral resource utilization (number of CCs) in the deployment scenarios A0-A2 for low and high traffic load conditions.
Figure 4-10 Examples of average spectral resource sharing (fraction of shared CC resources) for each eNB pair, in the deployment scenario A0 for low and high traffic load conditions.
Figure 4-11 Examples of spectral resource sharing (fraction of shared CC resources) realization versus time, in the deployment scenario A0 for low and high traffic load conditions.

4.5.2 Deployment scenario with 4 cells

Figure 4-12 shows the average resource utilization in the “4-rooms” scenarios A5-A7.

The same conclusions and observations can be made as in the case of the “6-rooms” scenarios A0-A2, presented in Section 4.5.1. Specifically, the interference decoupled cells eNB#1 and eNB#4 tend to allocate more often all 3 CCs available.

Figure 4-13 shows an example of spectral resource sharing, averaged over all simulation time, for each pair of eNBs in the scenario A5. The more interference coupled eNB pairs tend to allocate orthogonal resources, hence share less CC resources e.g., eNB#1–eNB#2/3 and eNB#4–eNB#2/3.

Figure 4-14 shows example of time traces (realizations) in the “4-rooms” scenario A5 for the CC sharing factor.

Overall in the network of 4 cells, a time averaged CC sharing factor of approximately 80% to 75% is obtained in low and high traffic load conditions.
Among the active cells, the traces indicate quite large variations in the CC sharing factor, with time average values between 68% and 80%.

**Figure 4-12** Average spectral resource utilization (number of CCs) in the deployment scenarios A5-A7 for low and high traffic load conditions.
Figure 4-13 Examples of average spectral resource sharing (fraction of shared CC resources) for each eNB pair, in the deployment scenario A5 for low and high traffic load conditions.
Figure 4-14 Examples of spectral resource sharing (fraction of shared CC resources) realization versus time, in the deployment scenario A5 for low and high traffic load conditions.

4.6 ACCS on the demonstrator testbed

In this section we evaluate the ACCS performance when executing it in real-time on the PoC testbed. We also compare the obtained results to simulations in an identical deployment scenario.

The experiments have been executed considering the scenario A8 with 3 cells, previously described in Section 4.2. The experiments consist of 1 hour long sessions during which eNBs and UEs are active. Finite buffer data traffic emulation in the cells is enabled. The experimental sessions have been repeated with variable traffic conditions (low and heavy traffic) and also considering a reuse 1 resource allocation scheme as term of comparison for the ACCS performance. In order to add further elements of comparison, experimental runs have been executed both during working hours and night time. During working hours the human presence in the office premises contributes to a great dynamicity in the propagation environment (Dynamic Environment), while the complete absence of people during night hours allows to experiment in almost-static conditions (Static Environment).
The system configuration for the testbed and simulation is compliant to the parameters reported in Table 4-2. BCC selection CoI threshold is set to 15dB, while the SCC threshold is set to 8 dB.

### 4.6.1 ACCS performance comparison with simulations

The first set of results provides direct comparison between the simulated performance of ACCS and the results provided by the runtime execution over the testbed. In Figure 4-15 the UE downlink SINR distributions in the cells are reported for bot low and high traffic cases. The points in the cdfs correspond to the SINR value experienced in the cell during 1 hour with 1 second granularity. Similar CDFs are reported in Figure 4-16 for the UE DL Throughput statistics. The results show very similar performance between the three considered evaluation methodologies. However, even minor inaccuracies in the estimation of path loss relations in the scenario can impact the simulated signal and interference levels. These variations may have a non-negligible effect on the resources allocation of a threshold-based algorithm such as ACCS. This aspect justifies the differences between the simulated and experimental results.

The experimental results show a major contribution of the inter-node path loss relations to the algorithm performance in respect to the dynamicity of the deployment scenario.
Figure 4-15 Cumulative Distribution Functions of UE DL SINR in the cells in low traffic conditions (lambda=0.1) and high traffic conditions (lambda = 1)
4.6.2 Analysis of C/I thresholds in a dynamic environment

The ACCS performance is sensitive to the variations of the inter-cell CoI values in relation to fixed thresholds for BCC and SCC allocation. The performed experiments enabled a better understanding of the CoI dynamics in realistic dynamic environment conditions. As example Figure 4-17 shows the measured traces of CoI by cell 1 with respect to cells 2 and 3, in all the considered experimental conditions. The time snapshot (about 25 minutes) highlights the complexity of the CoI variations due to human activity in the cells. As term of comparison the same CoI values obtained from the static environment analysis show an almost constant profile. The experiments provided two main indications:

- A high degree of human activity (e.g. movement of people) generates high excursions of the CoI on a short-term basis (e.g. from 1500 to 2300 seconds in the plot)
- Modifications in the scenarios (e.g. movement of furniture) generate a shift of the average CoI values.

In such conditions the system optimization based on fixed thresholds becomes a difficult task to accomplish. It is recommendable to implement variable BCC and SCC thresholds to be updated on a periodical basis (8-10 minutes) in order to cope with scenario variations.
Figure 4-17 Time Snapshot of the Carrier to Interference variations in Cell 1 during an experimental run. In the Figure the values for different environment conditions are reported.

4.6.3 ACCS performance in comparison to reuse 1

As last input from the PoC testbed, the ACCS performance has been also validated against the performance of a reuse 1 of frequency resources. The obtained results in terms of UE DL throughput in the cells have been reported in Figure 4-18. Low and High traffic conditions have been considered.
Figure 4-18 Cumulative Distribution Functions of UE DL Throughput in the cells for ACCS and REUSE 1 schemes. Dynamic Environment experimental results have been compared to the Hybrid Simulation.

The reuse 1 scheme has been executed in real-time on the testbed as previously done for ACCS. The results provide indications compliant with the prior simulation studies. ACCS performs well in situation of high traffic load and high interference coupling between the cells.
4.7 Conclusions and practical considerations

These final ACCS investigations have focused on the identification of the system-wide parameters and their values (range) to be used in practical small-scale indoor deployments, namely: the \textit{CC selection C/I thresholds} and the \textit{inter-eNB path loss ranging threshold}. The sensitivity and impact of these parameters in several deployment scenarios and various traffic load conditions has been also investigated.

We have used the deployment scenarios from the ACCS PoC deployment cases as targeted in the Workpackage 5 platform development and demonstration activities [8][9]. The selected deployment layout has been imported in the system-level simulation tool using the path-loss matrix (between each node pair) as measured by the PoC platform [8][9]. Several typical scenarios have been generated and evaluated, labelled as “4-rooms” and “6-rooms” scenarios. The benefits provided by ACCS in comparison to frequency reuse 1 in high traffic load conditions have also been confirmed.

The experiments with the ACCS PoC testbed provided validation of the ACCS performance in relation to simulation-based studies. Both reuse-1 and ACCS system performance have been verified to be identical in the simulator and the demonstrator testbed.

4.7.1 Main findings and recommendations

We recommend the \{BCC, SCC\} selection C/I thresholds combinations to be set in the range of \{20, 8 to 11\} dB for deployments with at least 6 neighbouring cells, while the range of \{17, 5 to 11\} dB can be used for smaller number of neighbouring cells, and regardless of the cell total downlink transmit power.

Combined with the findings presented in deliverable D2.2 Section 5.5.3, we can conclude that in typical small-scale deployment scenarios a minimal inter-eNB path-loss ranging threshold of 80-90 dB is desirable.

In these small-scale indoor deployment scenarios, a time averaged CC sharing factor of approximately 80% to 75% is obtained in low and high traffic load conditions.

Confirming the correct functionality of the proposed ACCS algorithm, the cells which tend to share most of their allocated CCs are the ones which are more de-coupled in terms of downlink interference and where the ACCS algorithm selects for use of the same CCs with higher probability.
In real-life deployment scenarios, including dynamic radio channel conditions, it was shown that further optimization, and possibly also an adaptation mechanism, is needed in order to set the correct C/I threshold values used in the component carrier selection.
References


[17] 3GPP R1-091342 “Comparison of PMI-based and SCF-based MUMIMO”, Motorola, TSG-RAN WG1 58, August 2009


5 Appendices

5.1 Appendix A Frequency domain interpolation errors for several ITU multipath profiles

ITU indoor A profile

![Graph of Frequency domain interpolation error for ITU Indoor A.](image)

**Figure 5-1 Frequency domain interpolation error for ITU Indoor A.**

Linear approximation result:

\[
\log_{10}(MSE) = -0.0831 \cdot \text{SNR} - 1.2008
\]

Cubic approximation result:

\[
\log_{10}(MSE) = 0.0000426 \cdot \text{SNR}^3 - 0.000243 \cdot \text{SNR}^2 - 0.0996 \cdot \text{SNR} - 1.1451
\]

Reference:

\[
\log_{10}(MSE) = -0.0943 \cdot \text{SNR} - 0.8
\]

ITU indoor A is not strongly frequency selective, the reference is overestimating the interpolation error in this case.
ITU indoor B profile

Figure 5-2 Frequency domain interpolation error for ITU Indoor B.

Linear approximation result:

\[ \log_{10}(MSE) = -0.08314 \cdot \text{SNR} - 0.8 \]

Cubic approximation:

\[ \log_{10}(MSE) = 0.0000426 \cdot \text{SNR}^3 - 0.000243 \cdot \text{SNR}^2 - 0.0996 \cdot \text{SNR} - 1.14511 \]

Reference:

\[ \log_{10}(MSE) = -0.0943 \cdot \text{SNR} - 0.8 \]
ITU pedestrian B profile

Figure 5-3 Frequency domain interpolation error for ITU Pedestrian B.

Linear approximation result:

\[
\log_{10}(MSE) = -0.09547 \cdot SNR + 0.16153
\]

Cubic approximation:

\[
\log_{10}(MSE) = 0.000027 \cdot SNR^3 - 0.000496 \cdot SNR^2 - 0.09832 \cdot SNR + 0.18401
\]

Reference:

\[
\log_{10}(MSE) = -0.0943 \cdot SNR - 0.8
\]

As Ped B is more frequency selective, interpolation error is underestimated by the reference.
ITU vehicular B profile

Figure 5-4 Frequency domain interpolation error for ITU PedestrianB.

Linear approximation result:

\[ \log_{10}(MSE) = -0.07127 \cdot \text{SNR} + 0.05415 \]

Cubic approximation: with this very highly frequency selective channel we observe major difference in favour of the fitted cubic polynomial.

\[ \log_{10}(MSE) = 0.0000293 \cdot \text{SNR}^3 - 0.000656 \cdot \text{SNR}^2 - 0.10115 \cdot \text{SNR} + 0.12485 \]

Reference:

\[ \log_{10}(MSE) = -0.0943 \cdot \text{SNR} - 0.8 \]

As Veh. B is more frequency selective, interpolation error is underestimated by the reference.