Efficient Link-to-Systemlevel Modeling for Accurate Simulations of MIMO-OFDM Systems

V. Pauli, I. Viering, C. Buchner, E. Saad, G. Liebl
Nomor Research GmbH
Munich, Germany
Email: {pauli,viering,buchner,saad,liebl}@nomor.de

A. Klein
Nokia Siemens Networks
Munich, Germany
Email: axel.klein@nsn.com

Abstract—This paper focuses on emulation of the linklevel processing for efficient systemlevel simulations of MIMO-OFDM based mobile communication systems. While the downlink of 3GPP’s Long Term Evolution (LTE) and the various MIMO transmission modes used therein stand in the focus of our considerations, the proposed techniques can be applied to other MIMO-OFDM based communication systems such as WiMAX. In particular, we compute effective fading gains and interference levels that allow us to very accurately emulate the signal processing at linklevel, i.e. channel en-/decoding, (de-)modulation, layer (de-)mapping, precoding and equalization, with minimal complexity during systemlevel simulations.

I. INTRODUCTION

In the development of new mobile communication systems early accurate systemlevel simulations are of utmost importance to uncover effects that only appear if the system operates as a whole, i.e. that cannot be observed by considering the individual parts of the protocol stack, such as link aware radio resource management. For instance, the MIMO mode and the modulation and coding scheme to be used is decided by the scheduler, which is a typical systemlevel aspect, whereas linklevel performance is strongly impacted by selecting always the best modes. In particular real-time simulations are of interest, as statistical evaluation of offline simulations also obscures many details [1]. In this context accurate and efficient emulation of the lowest level, the link- or physical level, is very important, as a full-scale simulation on standard workstations is typically computationally very expensive, thus slowing down the simulation of the overall system. This is particularly true if MIMO techniques with complex spatial equalizers are deployed in the system.

Exemplarily, we consider Long Term Evolution (LTE) which is currently being standardized by 3GPP as release 8 of Universal Mobile Telecommunications System (UMTS). As successor of High-Speed Packet Access (HSPA) in the evolution of UMTS its purpose is to simplify network architecture and achieve higher spectral efficiency, thereby providing users with ever higher data rates at shorter transmission delays. In order to achieve this goal 3GPP relies on orthogonal frequency division multiple access (OFDMA) and single-carrier frequency division multiple access (SC-FDMA) for downlink and uplink transmission, respectively, and also makes extensive use of various multi-antenna (MIMO) techniques (cf. [2] and references therein). In addition, the protocol stack has been redesigned fundamentally for packet-optimized radio access.

This paper deals with an accurate emulation of the signal processing at linklevel that can be performed offline and that provides the systemlevel simulator with data that can be processed with very low computational complexity. In particular, the effective channel of each physical resource block (PRB) is represented by only a single coefficient \( G \) (or pair of coefficients \( G, o \) per PRB and layer in case of spatial multiplexing), such that

\[
\text{SNR} = \frac{G}{\alpha G + 1/\rho} \quad \text{or} \quad \text{SNR} = G \cdot \rho
\]

for transmission without or with spatial multiplexing (SM), where \( \rho \equiv S/N \) with \( S \) and \( N \) denoting received signal and noise/interference power, respectively. While this is quite simple and the results well-known in some cases such as single-antenna transmission and transmit/receive diversity, it is somewhat more involved in case of SM especially for the so-called open loop (OL) SM-MIMO mode with large-delay cyclic delay diversity (LD-CDD) [3]. We will present expressions for all settings supported in LTE in order to provide a complete picture of the link-to-systemlevel modeling. Note that the link-to-systemlevel interface (1) pursues the same philosophy as the modeling of code interference in HSDPA via orthogonality factors [4], [5].

The remainder of the paper is organized as follows. We start by briefly outlining our approach for computationally efficient linklevel emulation in Section II. After a brief description of the common basis of the transmission system in the various MIMO configurations in Section III, we focus on the spatial-multiplexing and the transmit-diversity mode in Sections V and VI, respectively. These sections are interspersed with numerical results to corroborate the accuracy of our approach, and a summary in Section VII concludes the paper.

II. APPROACH TO LINKLEVEL EMULATION

Before we dive into the details of linklevel emulation, we will briefly outline the principles of our approach to system level simulations.

The effective channel representation mentioned in the introduction is pre-computed offline and stored in “fading files” to be read by the systemlevel simulator. For the computational complexity of the simulator to be low, it is essential that manipulations of complex numbers and matrices are kept out of the simulator. Hence, we use a representation of the channel...
by means of effective fading gains and cross-talk levels. The resolution of one sample per PRB extending over a bandwidth of 180kHz and a time of 1ms is sufficient.

Different users have independent fading processes. However, if the users access the same (long) fading file at different time offsets larger than the coherence time the fading processes appear as independent.

The above fading files are generated under the standard assumption that the average power of the channel coefficients is one. At runtime of the simulator, pathloss / sector patterns, transmit power and the aforementioned fading processes are used to compute signal powers and cross-talk levels and from those effective SINRs. The SINRs of the different PRBs transporting data corresponding to the same codeword are combined using the “mutual information per symbol” (MIS) method [6], and the resulting effective SINR is used to look up an instantaneous error probability for the codeword in tables which contain block error rate results for the AWGN channel (cf. also [6]). The detection of the codeword is then randomly marked as failed with this probability.

III. GENERAL SYSTEM MODEL

Fig. 1 shows the relevant part of the physical layer processing chain at the transmitter. Vectors \( \mathbf{d}[\ell] \) consisting of \( Q \in \{1, 2\} \) information carrying (QAM) symbols \( d_q[\ell] \), \( 1 \leq q \leq Q \), of \( Q \) codewords are mapped by the layer mapper to \( v \)-dimensional vectors \( \mathbf{x}[\ell] \), where \( v \in \{1, 2, 3, 4\} \) denotes the number of layers. If the number \( v \) of layers exceeds the number \( Q \) of codewords, the layers are distributed among the codewords. Otherwise there is a one-to-one mapping between codewords and layers (cf. [3, Section 6.3.3] for details).

The vector \( \mathbf{x}[\ell] \) in turn is transformed by the precoder into a \( P \)-dimensional vector \( \mathbf{y}[\ell] \), where \( P \in \{1, 2, 4\} \). At this point, transmit diversity and spatial multiplexing differ. While Alamouti’s space-time block code (STBC) [7] is used as precoder for transmit diversity, in spatial-multiplexing mode precoding is a linear operation of the form

\[
\mathbf{y}[\ell] = \mathbf{W}[\ell] \mathbf{x}[\ell].
\]

Further details on this will be presented below.

The elements of the vector \( \mathbf{y}[\ell] \) are transmitted simultaneously from the \( P \) Tx antennas at some resource element in the time-frequency grid, i.e. using one subcarrier in one OFDM symbol uniquely determined by the single index \( \ell \). In fact, the \( \mathbf{y}[\ell] \) are mapped to the available physical resource elements (not blocks!) first in direction of frequency, then in direction of time. This will be crucial, when we discuss linklevel emulation for OL-SM MIMO.

Due to the fact that OFDM decouples the transmission on the individual subcarriers, we can treat the different resource elements separately and describe the transmission over a MIMO channel with \( P \) Tx and \( N_R \) Rx antennas corresponding to an individual resource element indexed by \( k \) in vector-matrix notation as

\[
r[\ell] = \sqrt{p} \mathbf{H}[\ell] \mathbf{y}[\ell] + \mathbf{n}[\ell],
\]

where the \( \ell \)th element \( r_i \) of \( r, h_{ij} \), in the \( i \)th row and \( j \)th column of \( \mathbf{H} \), and \( n_i \) denote the received signal at antenna \( i \), the channel coefficient between Tx antenna \( j \) and Rx antenna \( i \), and the additive noise at receive antenna \( i \), respectively. \( y_i[\ell], h_{ij}[\ell] \) and \( n[\ell] \) are normalized such that \( p \) represents the SNR of the channel. For conciseness of exposition, we omit the index \( k \) wherever expendable.

IV. SINGLE TX ANTENNA

In the case of a single Tx antenna, things are quite simple, as there is no layer mapping or precoding. The instantaneous SNR with maximum ratio combining (MRC) at the receiver is given by \( \text{SNR} = ||\mathbf{H}||^2 \cdot p \), where \( \mathbf{H} \) collapses to an \( N_R \)-dimensional vector. Hence, the effective fading gain \( G \) to be passed to the systemlevel simulator reads

\[
G = ||\mathbf{H}||^2.
\]

V. SPATIAL MULTIPLEXING

In the spatial-multiplexing mode of LTE, the different antennas are not (solely) used to increase robustness of transmission by exploiting spatial diversity inside a single codeword. Instead up to two codewords are transmitted simultaneously with up to four layers over the up to four Tx antennas.

In terms of transmitter processing the open-loop (OL) and the closed-loop (CL) mode are very closely related. The only difference lies in the precoding, where in CL the precoding matrices are chosen adaptively with the help of feedback from the mobile, while in OL the precoding matrices are selected in a deterministic (round-robin) manner to gather some diversity.

A. Precoding

The precoder assigns the layer symbols \( x_u \) to the different antenna ports. As mentioned above, the precoding for spatial multiplexing differs in closed-loop and open-loop mode.

1) Closed Loop: In CL mode the eNodeB is provided by the user equipment (UE) with some additional channel state information to aid its selection of an appropriate matrix \( \mathbf{W}[\ell] \). Precoding is done according to

\[
\mathbf{y}[\ell] = \mathbf{W}[\ell] \mathbf{x}[\ell].
\]

The underlying codebooks of precoding matrices \( \mathbf{W}[\ell] \) can be found in [3, Section 6.3.4.2.3].

2) Open Loop: In OL mode the eNodeB does not receive any such information from the UE and therefore performs deterministic precoding, namely large-delay cyclic delay diversity (LD-CDD), to gather some diversity for its transmissions. Here, the precoding operation is described by (cf. [3])

\[
\mathbf{y}[\ell] = \mathbf{W}[\ell] \mathbf{x}[\ell], \quad \mathbf{W}[\ell] \triangleq \mathbf{W}[\ell] \mathbf{D}[\ell] \mathbf{U},
\]
where $\tilde{W}[k]$ is a scaled identity matrix for $P = 2$ and may assume four values in the case of $P = 4$ Tx antennas. These are used in a round-robin manner with the codebook index being computed according to $\text{mod}(\lfloor k/v \rfloor, 4) + 1$, i.e. each precoding matrix $\tilde{W}[k]$ is used for as many successive $y[k]$ as there are layers. Together with the matrices $D[k] \triangleq \text{diag}\{1, e^{-j2\pi k/\nu}, \ldots, e^{-j2\pi (k-1)/\nu}\}$, and the $v$-point DFT matrix $U$, both introduced for LD-CDD, this provides us with a number of different precoding matrices which are applied to the $x[k]$ with the same frequency within each PRB / codeword.

The introduction of LD-CDD has the effect that the effective channel conditions experienced by the $v$ symbols $x_u$, $1 \leq u \leq v$, are averaged within and over the layers. In fact, the channel conditions experienced on all layers are equal on average. For every $\tilde{W}[k]$ in the codebook $\mathcal{W}$ of all $\tilde{W}[k]$ there is a $W[l] \in \mathcal{W}$ such that the channel experienced by some $x_{u_i}[k]$, when precoded with $W[k]$ is the same as that experienced by $x_{u_i}[l]$, $i \neq i_k$, when precoded with $W[l]$. This implies that for open-loop spatial multiplexing our system-level simulator won’t need different channel representations for the different layers or codewords.

### B. Computation of the Effective SINR

In essence the cascade of Tx processing, MIMO channel and Rx processing for spatial multiplexing (cf. left part of Fig. 2) appears to the system level as the system depicted in the right part of Fig. 2, i.e. as a system, where $\hat{x}_i$ is equal/similar to the transmitted $x_i$ perturbed by some cross-talk from the other $x_j, j \neq i$, due to imperfect spatial separation. The level of cross-talk depends of course on the channel conditions and the type of spatial equalizer. Hence, we focus on linear MMSE equalization, but note that the methods presented in the remainder of paper are equally applicable to other receivers.

1) **Arbitrary Number of Layers**: In order to obtain an effective SINR description based on the model shown in the right part of Fig. 2 we start from the SINR after MMSE equalization, which reads for $\hat{x}_i$ (cf. e.g. [8])

$$
\text{SNR}_i = \frac{\sum_{j=1, j \neq i}^{P} |f_i^H \hat{h}_i|^2}{\sum_{j=1, j \neq i}^{P} |f_i^H \hat{h}_j|^2 + ||f_i||^2 \rho} \geq \frac{G_i}{\sigma_i G_i + 1/\rho}, \tag{6}
$$

where $\hat{h}_i$ and $f_i$ are the $i$th columns of $\hat{H} \triangleq HW$ and $F \triangleq H^H \hat{H}^H + 1/\rho \rho^{-1}$, respectively.

By associating the various terms in (6), we directly obtain

$$
G_i \triangleq \frac{|f_i^H \hat{h}_i|^2}{|f_i^H f_i|^2} \quad \text{and} \quad \sigma_i \triangleq \sum_{j=1, j \neq i}^{P} \frac{|f_i^H \hat{h}_j|^2}{|f_i^H f_i|^2}. \tag{7}
$$

This method can be readily applied to compute the effective SINRs for both the open- and the closed-loop mode.

2) **Special Case: Single Layer in Closed-Loop Mode**: In the closed-loop mode “spatial multiplexing” with a single layer is also prescribed in the standard. In this case, the aggregate channel matrix $\hat{H}$ degenerates to an $N_R$-dimensional vector. Hence, the optimal linear receiver is —as in the single-Tx-antenna case— the MRC, leading to an effective fading gain (cf. Section IV)

$$
G = ||\hat{H}||^2. \tag{8}
$$

3) **Verification**: Exemplarily, Fig. 3 shows a comparison of uncoded bit error rates (BER) for a 20MHz LTE system, i.e. 1200 subcarriers with 15kHz inter-carrier spacing, with two Tx and Rx antennas and with QPSK, 16QAM and 64QAM modulation when transmitting over a channel with Pedestrian B power delay profile at a velocity of the mobile of 3km/h. The dashed lines represent full-scale linklevel simulations, whereas the results represented by the solid lines were obtained by looking up the BER in AWGN reference curves with the instantaneous SINR computed as described in Section V-B1 with one pair $[G_i, \sigma_i]$ per PRB and layer. It clearly illustrates the accuracy of our approach with a minor deviation occurring only for QPSK modulation.

### C. Link-to-Systemlevel Modeling

We note that the ratio $\rho$ required for the computation of the MMSE equalizer is not known at the time of fading file generation. Hence, we propose to use a number of operating points $\hat{\rho}$ covering the range of SINRs of interest, e.g. $10 \log_{10}(\hat{\rho}) = [5, 10, 15, 20]$ dB. For each operating point $\hat{\rho}$, we generate a set of fading files for the $G_i$ and $\sigma_i$ and let the systemlevel simulator —based on the actual operating point
for the transmission to be modeled—choose the appropriate fading file from which to take the coefficients.

1) Closed Loop: In CL mode things are quite simple. Here, we only have a single precoder per PRB and hence only one fading file for \( G_i \) and \( v \) fading files for \( G_{i, o} \) and \( o_i \), regardless of the number of Tx or Rx antennas. In consequence, increasing the number of antennas does not have an impact on the complexity of the system-level simulator.

2) Open Loop: In the OL mode things are more complicated due to the use of LD-CDD. The reason is that we would have to provide the simulator with two pairs of coefficients \([G_i, o_i]\), i.e., as harmonic mean over the \( o_k \) in \( O_i \), i.e., with \( o_k \) and \( G_k \) into sets \( O_i \) and \( G_k \) into (9) and solve for \( G_i \) according to (10) and (12), respectively.

\[
\tilde{G}_i = \frac{\text{SNR}_i}{(1 - \tilde{\rho}) \tilde{\rho}}.
\] (12)

Grouping the \( o_k \) and \( G_k \) into sets \( O_i \) and \( G_k \): Since we want to have \( v \) effective \( \tilde{\rho} \), and any simplified averaging, e.g., based on linear approximation of a fairly well-behaved function can be expected to be more accurate if the samples to be averaged lie closer together, we sort the \( o_k \) according to their magnitude into the \( v \) sets \( O_i \), \( 1 \leq i \leq v \), of equal cardinality 4 and compute the \( \tilde{o}_i \) and \( \tilde{G}_i \) according to (10) and (12), respectively.

Shifting the Operating Point: One source of inaccuracy of our approach is the dispersion of the true operating point around the assumed operating point both due to uncertainty about the operating point and the values of \( G_k \) and \( o_k \). Hence, we introduced an offset \( \Delta \rho \) to the operating point \( \tilde{\rho} \) to reduce the error of our approximation by computing \( \tilde{G}_i \) based on (9) and (12) using the shifted operating point \( \Delta \rho \).

Remark: Alternatively, one could take things even further and directly average all 4\( v \) individual effective SINRs for the different precoders \( W \) into a single effective SINR \( Q \) and SINRs and therefore into a single pair or Q pairs \([G_i, \tilde{\rho}]\) as described above with \( K = 4v \) or \( K = 4v/Q \), respectively. While this would lead to further complexity savings, it would come at the expense of further inaccuracies in the modeling.

c) Verification: In order to check the accuracy of our approach of representing the numerous different effective channels per PRB in \( 4x4 \), \( x \in \{2,4\} \), OL mode by only \( v \) pairs of coefficients \([G_i, \tilde{o}_i]\), \( 1 \leq i \leq v \), we computed the estimation error of our approximation. This means, we compute the exact effective SINR \( \text{SNR}_{\text{eff}} \) according to the left equation of (9) with \( K = 4v \) and the correct value of \( \rho \), and compare it with the effective SINR estimate

\[
\overline{\text{SNR}_{\text{eff}}} = \text{MIS}^{-1}\left(\frac{1}{v} \sum_{i=1}^{v} \text{MIS}\left(\frac{\tilde{G}_i}{\tilde{o}_i \tilde{G}_i + \rho}\right)\right),
\] (13)

computed from our channel representation \([G_i, \tilde{o}_i], 1 \leq i \leq v \). Note, that at this point, we can use the correct value of \( \rho \), because this computation would take place in the simulator, where \( \rho \) is known. Our figure of merit is the estimation error

\[
\varepsilon \leq 10 \log_{10}(\text{SNR}_{\text{eff}}) - 10 \log_{10}(\overline{\text{SNR}_{\text{eff}}}),
\] (14)
along with mean \( m_\varepsilon \triangleq \mathbb{E}\{\varepsilon\} \) and variance \( \sigma_\varepsilon^2 \triangleq \mathbb{E}\{|\varepsilon - m_\varepsilon|^2\} \). All simulations were generated for a Pedestrian B channel averaged over 100 PRBs of bandwidth 180kHz and 1000 random channel realizations. In order to account for the lack of knowledge of the true operating point \( \rho \) at fading file generation and the quantization of our assumed operating point \( \hat{\rho} \) in intervals of 5 dB in the fading generator, we assumed that the true operating point \( \rho \) is uniformly distributed with a maximum deviation from \( \hat{\rho} \) of \( \pm 2.5 \) dB.

Fig. 4 shows the CDF \( F(\varepsilon) \) of the estimation error \( \varepsilon \) for \( v = 2, P = 4 \) and \( N_R = 2 \). One can observe that our approximation is quite exact with absolute mean and variance both below 0.1. We would like to point out, that the \([v, P, N_R] = [2, 4, 2]\) setting shown here represents the worst case scenario for our approximation, in all other cases mean and variance of the estimation error were even smaller.

For the same scenario the PDF \( f(10 \log_{10}(\text{SNR})) \) of the approximated effective SINR compared to the true effective SINR is depicted in Fig. 5, showing that the distributions of the effective SINRs are widened slightly by our approximation, i.e. for effective SINRs below the operating point, the approximation tends to be too pessimistic, whereas for relatively high effective SINRs, the approximation is a bit too optimistic.

VI. TRANSMIT DIVERSITY

A. Precoding

When designing the precoder for the transmit diversity mode in LTE the standardization body solely relied on Alamouti’s famous orthogonal space-time block code (OSTBC) originally designed in [7] for systems with two transmit antennas.

1) Two Tx Antennas: In the case of two transmit antennas, i.e. \( v = P = 2 \), this means that transmit symbols \( y_p[k] \) are obtained from the \( x_i[k] \) via

\[
\begin{bmatrix}
  y_1[2k] \\
  y_2[2k]
\end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix}
  x_1[k] & x_2[k] \\
  -x_2^*[k] & x_1^*[k]
\end{bmatrix} .
\]

2) Four Tx Antennas: In the case of 4 Tx antennas 3GPP opted for an extension of Alamouti’s 2-Tx OSTBC, namely

\[
\begin{bmatrix}
  y_1[4k] \\
  y_2[4k] \\
  y_3[4k+1] \\
  y_4[4k+1]
\end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix}
  x_1[k] & x_2[k] & 0 & 0 \\
  0 & 0 & x_3[k] & x_4[k] \\
  -x_2^*[k] & x_1^*[k] & 0 & 0 \\
  0 & 0 & -x_4^*[k] & x_3^*[k]
\end{bmatrix} ,
\]

i.e. the two pairs \([x_1[k], x_2[k]]\) and \([x_3[k], x_4[k]]\) are transmitted using the regular 2-Tx OSTBC from disjoint pairs of Tx antennas in different locations of the time-frequency grid, in order to maintain orthogonality between the transmissions and statistical independence between the corresponding channels.

B. Computation of the Effective SINR

The fact that both the 2-Tx and the 4-Tx transmit diversity methods are based on Alamouti’s OSTBC greatly simplifies matters for us when computing effective SINRs for system-level simulations.

It is well known (cf. e.g. [9]) that Alamouti’s OSTBC is the same as (MRC) with two Rx antennas if the per-antenna Tx power is kept constant. It is then straightforward to find

\[
\text{SNR}_t = \sum_{j=1}^{N_R} \left( |h_{j,2(i-1)+1}|^2 + |h_{j,2(i-1)+2}|^2 \right) \cdot \rho , \quad i \in \{1,2\},
\]

Fig. 4. CDF of error \( \varepsilon \) in approximation of effective SNR in OL-SM-MIMO mode based on two tuples \([G_i, \tilde{G}_i], \ i \in \{1,2\}\), when \( 10 \log_{10}(\rho) = 10 \log_{10}(\hat{\rho}) = \mu \varepsilon = 0.02, \ \sigma_\varepsilon^2 = 0.05 \) and variance of the estimation error were even smaller.

Fig. 5. Comparison of the PDFs of the approximated effective SNR and the true effective SNR in OL-SM-MIMO mode based on two tuples \([G_i, \tilde{G}_i], \ i \in \{1,2\}\), when \( 10 \log_{10}(\rho) = 10 \log_{10}(\hat{\rho}) + r, \ r = \mathcal{U}(-2.5, 2.5) \), for \( v = 2, P = 4 \) and \( N_R = 2 \).
as the SNRs applying to the detection of \( x_1[k], x_2[k] \) and \( x_3[k], x_4[k] \) for \( i = 1 \) and \( i = 2 \), respectively.

C. Link-to-Systemlevel Modeling

Again, effective fading gains of the form \( G = \text{SNR}/\rho \) are to be computed offline and stored in fading files.

1) Two Tx Antennas: In the case of two Tx antennas the effective fading gains are directly obtained from (17) as

\[
G = \frac{1}{\rho} \cdot \text{MIS}^{-1} \left( \frac{1}{2} \left( \text{MIS} (\text{SNR}_1) + \text{MIS} (\text{SNR}_2) \right) \right).
\]

(18)

2) Four Tx Antennas: In the case of four Tx antennas we have a problem, if we want to use the same interface to and processing in the simulator in case of four Tx antennas.

We therefore resort to similar means of averaging, as we did for open-loop spatial multiplexing, i.e. we proceed as follows:

We compute the two individual SNRs \( \text{SNR}_i \) according to (17) with an assumed operating point \( \hat{\rho} \). We plug these into the MIS-based averaging and solve for \( G \) to obtain

\[
G = \frac{1}{\rho} \cdot \text{MIS}^{-1} \left( \frac{1}{2} (\text{MIS} (\text{SNR}_1) + \text{MIS} (\text{SNR}_2)) \right).
\]

(19)

Clearly, this procedure is exact, as long as the operating point is known, i.e. \( \hat{\rho} = \rho \).

a) Verification: In order to verify the accuracy of our approach of representing the instantaneous channel state by only a single effective fading gain per PRB we again present simulation results obtained by means of Monte-Carlo simulations over 1000 independent channel realizations of a Pedestrian B type of channel. To this end, we again computed the error

\[
\varepsilon \triangleq 10 \log_{10} \left( G \cdot \rho \right) - 10 \log_{10} (\text{SNR}_{\text{eff}})
\]

(20)

between the effective SNR obtained from our approximation and the true effective SNR

\[
\text{SNR}_{\text{eff}} = \text{MIS}^{-1} \left( \frac{1}{2} (\text{MIS} (G_1 \cdot \rho) + \text{MIS} (G_2 \cdot \rho)) \right).
\]

(21)

along with mean \( m_{\varepsilon} \triangleq \mathbb{E} \{ \varepsilon \} \) and variance \( \sigma_\varepsilon^2 \triangleq \mathbb{E} \{ (\varepsilon - m_{\varepsilon})^2 \} \) under the assumption of an operating point mismatch uniformly distributed in the range \( \pm 2.5 \text{dB} \).

Fig. 6 show the CDF \( F(\varepsilon) \) for \( P = 4 \) and \( N_R = 2 \). One can observe that for both antenna configurations, the estimation error is very small with absolute means \( |m_{\varepsilon}| \leq 0.01 \) and variance \( \sigma_\varepsilon^2 \leq 0.01 \), which justifies our approach.

VII. CONCLUSIONS

In this paper, we have presented a set of techniques for efficient link-to-systemlevel modeling of various transmission modes for MIMO-OFDM systems, in particular all MIMO modes deployed in the downlink of 3GPPs LTE. The methods take all complex calculations including matrix inversions offline. At systemlevel, we leave all the flexibility to the resource management which can decide between the different modes on a short term basis. We have verified the accuracy of the proposed model by means of link level simulations. Those methods significantly facilitate systemlevel simulations, both in terms of implementation and computational complexity. Such an interface even enables real-time simulations of mobile networks on standard PCs.

REFERENCES


