signals the preferred precoder that is stemming from a finite code book as specified in [39]. Very similar feedback values are also employed in other systems such as WiMAX and WiFi. The simulator provides algorithms that utilize the estimated channel coefficients to evaluate these feedback indicators [16]. Researchers and engineers working on feedback algorithms can implement other algorithms by using the provided feedback functions as a starting point to define their own functions.

Given this receiver structure, the simulator allows to investigate various aspects, such as frequency synchronization [48], channel estimation [47], or interference awareness [49].

### B. Complexity

Link level simulators are in practice a direct standard-compliant implementation of the Physical (PHY) layer procedures, including segmentation, channel coding, MIMO, transmit signal generation, pilot patterns, and synchronization sequences. Therefore, implementation complexity and simulation time are high. To obtain a simulator with readable and maintainable code, a high level language (MATLAB) has been chosen. This choice enabled us to develop the simulator in a fraction of the time required for an implementation in other languages such as C. Furthermore, MATLAB ensures cross-platform compatibility. While MATLAB is certainly slower than C, by means of code optimization (vectorization) and parallelization by the MATLAB Parallel/Distributed Computing Toolbox, simulation runtime can be greatly reduced. Severely difficult-to-vectorize and often-called functions are implemented in C and linked to the MATLAB code by means of MEX functions. Such functions include the channel coding/decoding [50], Cyclic Redundancy Check (CRC) computation [51], and soft sphere decoding.

Furthermore, it is possible to adjust the scale of the simulation to the specific needs. This is achieved by introducing three different simulation types with largely different computational complexity (Figure 4):

1) **Single-downlink:** This simulation type only covers the link between one eNodeB and one UE. Such a set-up allows for the investigation of channel tracking, channel estimation [47], synchronization [14, 52], MIMO gains, AMC and feedback optimization [16], receiver structures [53] (neglecting interference and impact of the scheduling¹), modeling of channel encoding and decoding [18, 54], and physical layer modeling [55], which can be used for system level abstraction of the physical layer. To start a simple single-downlink simulation, run the file `LTE_sim_batch_single_downlink.m`.

2) **Single-cell multi-user:** This simulation covers the links between one eNodeB and multiple UEs. This set-up additionally allows for the investigation of receiver structures that take into account the influence of scheduling, multi-user MIMO resource allocation, and multi-user gains. Furthermore, this set-up allows researchers to investigate practically achievable multi-user rate regions. In the current implementation, the simulator fully evaluates the receivers of all users. However, if receiver structures are being investigated, the computational complexity of the simulation can considerably be reduced by only evaluating the user of interest. In order to enable a functional scheduler it is sufficient to compute just the feedback parameters for all other users. To start a simple single-cell multi-user simulation, run the file `LTE_sim_batch_single_cell_multi_user.m`.

3) **Multi-cell multi-user:** This simulation is by far the computationally most demanding scenario and covers the links between multiple eNodeBs and UEs. This set-up allows for the realistic investigation of interference-aware receiver techniques [56], interference management (including cooperative transmissions [57] and interference alignment [58, 59]), and network-based algorithms such as joint resource allocation and scheduling. Furthermore, despite the vast computational efforts needed, such simulations are crucial to verify system level simulations. To start a simple multi-cell multi-user simulation, run the file `LTE_sim_batch_multi_cell_multi_user.m`.

The simulation time, which depends mainly on the desired precision and statistical accuracy of the simulation results, the selected bandwidth, the transmission mode, and the chosen modulation order is for most users a crucial factor. It should be noted that by a smart choice of the simulation settings, the simulation time can be decreased (e.g., when investigating channel estimation performance, the smallest bandwidth can be sufficient).

### III. THE VIENNA LTE SYSTEM LEVEL SIMULATOR

In this section, we describe the overall structure of the Vienna LTE System Level Simulator, currently (January 2011) version 1.3.r427. We furthermore show how the PHY layer procedures have been abstracted in a low complexity manner.

#### A. Structure of the Simulator

In system level simulations, the performance of a whole network is analyzed. In LTE, such a network consists of a

¹Note that the scheduler in a multi-user system will change the statistics of the individual user’s channel, thus influencing the receiver performance.