Abstract – The 3GPP, which is the standardization group for Long Term Evolution (LTE), has chosen OFDMA and SC-FDMA as access technologies for the downlink and uplink respectively due their high spectral efficiency. A big part of this efficiency will rely on the channel dependent scheduling (CDS) policy used, which should react to environmental conditions. In order to study CDS and other adaptation techniques like interference management, simulations need to be performed. However, simulating a whole network system is computationally expensive, so to work around this problem System level simulators are used. In order to create a system level simulator, link level simulations must be performed first. This paper describes the implementation of such a link level simulator in MATLAB for LTE uplink based on an open source model.

Index Terms—LTE Uplink, SC-FDMA, Link-Level

I. INTRODUCTION

Research beyond 3G mobile radio systems is in progress around the world to allow future mobile networks to support different types of services and applications with high performance. The advances in mobile device technologies, together with the accessibility provided by those devices to the Internet and the numerous applications and services that come with it, are central to need for this research. The 3rd Generation Partnership Group standardized Evolved (E-)
UTRA as Long Term Evolution to be used as a Next Generation Wireless Network. Some of the main requirements in LTE included the provision for high bandwidth, lower latency and better QoS guarantees.[1]

For the downlink, LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) since it is the most appropriate technique available for achieving high spectral efficiency and meeting current network needs. For LTE uplink, Single Carrier (SC)-FDMA, a variation of OFDMA is used instead. It was chosen due to its lower Peak-to-Average Power Ratio (PAPR), which is essential for the practical aspects in the implementation of mobile devices, such as battery consumption.

SC-FDMA can be viewed as a hybrid modulation scheme that provides quasi-similar PAPR (Peak to Average Power Ratio) as single-carrier systems [2]. On one hand, SC-FDMA shows its ability to fight against frequency selective channels, thanks to the use of the OFDMA modulation whilst allowing for better power usage and easier amplifier design due to its single carrier behavior.

Due to the frequency selective nature of real word channels, it is not possible to use the full efficiency of either OFDMA or SC-FDMA. To go around this problem Channel Dependent Scheduling (CDS) is used, whereby the system adapts to changing conditions in the environment. This can become a complex optimization problem for large numbers of users and optimization variables and thus many solutions have been proposed in literature. These are based on different classes of algorithms such as search trees, heuristics, game theory, etc.[3],[4],[5].

Many aspects such as multipath fading effects, interference from other cells and power control can be included into the CDS unit, however the more variables the higher the complexity. Depending on what research aspect is being analyzed either link or system level simulation could be used. For instance, aspects revolving around efficient receiver and transmitter designs would be best studied using link level simulations, whilst aspects such as multi-cell scenario scheduling or interference mitigation would be best understood using system level simulations. This is due to the fact that while link level simulators mimic the whole system, system level simulators abstract certain parts of the system in order to allow for more complex scenarios. To create a system level simulator, link level simulations must be performed in order to observe the behavior of the components that will be abstracted.

The majority of the research proposed and discussed in literature however involves OFDMA and consequently downlink optimization in the LTE context. This project, then proposes a link Level simulator for LTE uplink based on the MATLAB open source model for the LTE downlink proposed in [6]. The open source model includes a wide range of functionality ranging from single multi-user multi-cell scenarios, different types of propagation paths, walking models, HARQ and scheduling.

The rest of the paper is organized as follows: an overview of OFDM and SC-FDM is provided in Section II. In Section III, an overview of the link level model for LTE uplink is
provided. The system parameters and results are displayed in Section IV and conclusions are drawn in section V.

II. OFDM AND SC-FDM

OFDM and SC-FDM have been around since the 70’s and are only currently being used because we finally have the necessary FFT/IFFT technology to create OFDM symbols easily [7]. In this section we take a look at OFDM and SC-FDM and some of their differences and similarities.

A. OFDM

Orthogonal FDM is a frequency domain multiplexing scheme used for the modulation of multicarrier transmissions. The information data $s_k$, represented as a high rate stream is divided into a set of parallel data streams carried by closely spaced and orthogonal sub-carriers $S_k$. Each stream is independently modulated with a conventional modulation scheme (4, 16, 64QAM).

$$X_k = QAMMOD (S_k) \quad (1)$$

Converting the symbols from serial to $M$ parallel streams increases the symbol duration on each subcarrier by a factor of approximately $M$, making the symbols larger than the channel delay spread. Combining the orthogonality of the subcarriers, the use of the Cyclic Prefix to combat ISI, the long symbol periods and simplified channel equalization, OFDM becomes very resilient and very attractive to mobile systems.

After the serial to parallel conversion each symbol is mapped onto a subcarrier which then goes through the IFFT process of conversion of the input symbols to complex time-domain symbols [8].

$$x_k = IFFT (X_k) \quad 0 \leq k \leq N_{sym} - 1$$

To avoid ISI a guard period is created by adding a Cyclic Prefix (CP) at the beginning of the symbol $x_k$. The CP is generated by duplicating the last $G$ samples of the IFFT output and appending them at the beginning of $x_k$. The complete process is shown in the fig. 1.

The symbols are converted back to a serial stream and a DAC (Digital to Analog Converter) is used to transform the stream into a continuous signal $x(t)$, ready for transmission:

$$r(t) = x(t) * h(t) + z(t) \quad (2)$$

where: $h(t)$ is the continuous-time impulse response of the channel, * represents the convolution operation and $z(t)$ is the additive white noise

The receiver side is simply the reverse of the transmitter side and can be seen on fig.2 below:

![Fig.2 OFDM symbol de-assembly](image)

B. SC-FDM

Single Carrier (SC)-DFM is fundamentally similar to OFDM with the major difference being the DFT precoding stage before symbol mapping. The first step of SC-FDM signal generation is to perform an $M$-point DFT operation on each block of MQAM data symbols. Zeros are then inserted among the outputs of the DFT in order to match the DFT size to an $N$-subcarrier OFDM which is implemented using IFFT as shown in section II A. The zero-padded DFT output is mapped to the $N$ subcarriers, with the positions of the zeros determining to which subcarriers the DFT-precoded data is mapped. The block of M data symbols is mapped to $M$ out of the $N$ subcarriers available in the system.

![Fig.3 SC-FDM symbol assembly](image)

If we denote the FFT matrix as $F$, then we can express the received SC-FDM signal in the frequency domain as:

$$r = HFx + z \quad (3)$$

C. Other differences between OFDM and SC-FDM

When the signals reach the receiver side it is necessary to perform detection to obtain the best possible signal reading. OFDM can use one-tap maximum-likelihood detection filters with low complexity. However using maximum-likelihood equalization in SC-FDM is very complex so, linear equalization methods such as Zero Forcing (ZF) and Minimum Mean Squared Error (MMSE) equalization are used. For SC-FDM, these linear equalization methods can be implemented using FFT at very low complexity. Using turbo equalization, the performance of the SC-FDM system can be improved significantly [9].

In LTE the resource block (RB) sizes that can be allocated is the same for both uplink and downlink, however the number and locations of reference symbols as well as the positions of control channels are distinct for the UL and DL.
III. IMPLEMENTATION DETAILS OF LINK LEVEL SIMULATOR

In this section we discuss the main implementation details of the link level simulator, especially where changes had to be made to the original downlink simulator as proposed in [6]. The complete system is shown in fig. 4 below.

A. Data Generation

The system starts by getting information about the MCS and retransmissions from the link adaptation (LA) unit. Packets are then generated or reloaded based on the requested size and retransmission status. Afterwards the cyclic redundancy check (CRC)-based error-detecting code is added to the corresponding packet. Packet size and the maximum code block size are determined before dividing the packet into several blocks followed by turbo channel encoding as defined in UTRA Release 6 [8]. Adjustment of the output bit rate by the rate matching block is done according to requirements. Subsequently, the output coded bits are interleaved and then passed to the modulator.

B. Data Segmentation and DFT spreading

A resource block (RB) in LTE is defined as 12 subcarriers and 7 symbols as shown in fig. 5a. Since a RB is the smallest resource unit that can be assigned to a user during a time slot of 0.5ms, we define the length M of a SC-FDMA symbol as 12 subcarriers.

Before mapping we need to understand how bandwidth is distributed in the LTE uplink. Only about 90% of the carriers are used for data, leaving the outer ones as guard bands [10] in the case of PUSCH the physical uplink channel for data.

The 3GPP’s release note [13], specifies that reference symbols used for channel estimation be inserted in the fourth symbol of each slot (blue RB’s in fig. 5a). Depending on the bandwidth configuration, up to N/M symbols can mapped onto the N active subcarriers, except for the symbol locations reserved for reference symbols.

The generation of reference signals for the uplink is different to that of the downlink. Due to the good correlation properties of Zadoff-Chu sequences they were chosen for the uplink by the 3GPP. The periodic autocorrelation function of a sequence z of length N is defined as [13]:

\[
    Z_p = \begin{cases} 
        e^{j2\pi \frac{nm}{N}}, & N \text{ even}; \\
        e^{j2\pi \frac{nm+1}{N}}, & N \text{ odd}; 
    \end{cases} 
\]

Good correlation ultimately means better channel estimation, lower PAPR and better timing synchronization between the eNodeB and a mobile terminal.

C. Channel Estimation and receiver Equalization

To estimate the channel using MMSE the following steps are done as described in [8]:

- Least squares estimate is obtained at all reference symbols positions:
  \[
  \hat{p}(i) = \frac{Z(p_i)}{d(p_i)} p_i(\text{Reference positions}) \tag{5} 
  \]
- Wiener filtering using the statistics of the channel and noise, followed by performing an MMSE interpolation of the estimates at pilot subcarriers.
  \[
  \hat{h} = R_{nh_p}^{-1} (R_{nh_p} + \sigma_w^2 I_{np})^{-1} h_p \tag{6} 
  \]

where: \( R_{nh_p} \) is the cross-correlation of the pilot subcarriers, matrix \( R_{nh_p} \) is the autocorrelation matrix, \( \sigma_w^2 \) is the noise power, \( I_{np} \) is an identity matrix.

The MMSE estimate is used in Channel dependent scheduling as well as equalization on the receiver side for better signal detection.

\[
  R = \frac{\hat{h}_{eff}}{\hat{h}_{eff}^2 + \sigma_w^2} \cdot R \tag{7} 
  \]
IV. LINK LEVEL MODEL SETTINGS AND PERFORMANCE

In this section we look at the performance of the Link Level Simulator. The following parameters were used to run the simulations:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>2GHz</td>
</tr>
<tr>
<td>Transmission BW</td>
<td>1.4MHz</td>
</tr>
<tr>
<td>Sub-frame duration</td>
<td>0.5ms</td>
</tr>
<tr>
<td>Sub-carrier spacing</td>
<td>15 kHz</td>
</tr>
<tr>
<td>DFT-size</td>
<td>12</td>
</tr>
<tr>
<td>SC-FDM symbols per sub-frame</td>
<td>14</td>
</tr>
<tr>
<td>CP duration</td>
<td>4.1μs</td>
</tr>
<tr>
<td>FFT size/Useful subcarriers</td>
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</tr>
<tr>
<td>MCS settings</td>
<td>4QAM: 1/2, 2/3, 3/4, 4/5, 5/6</td>
</tr>
<tr>
<td></td>
<td>16QAM: 1/3, 2/3, 3/4, 4/5, 5/6</td>
</tr>
<tr>
<td>Channel Code</td>
<td>3GPP Rel. 6 compliant Turbo code with basic rate 1/3</td>
</tr>
<tr>
<td>Rate Matching, Interleaver</td>
<td>3GPP Rel. 6 compliant</td>
</tr>
<tr>
<td>Channel Estimation</td>
<td>Ideal</td>
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<td>Antenna schemes</td>
<td>SISO</td>
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<td>Channel Model</td>
<td>AWGN</td>
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<tr>
<td>Speed</td>
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<td>Chase Combining</td>
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<td>Scheduling</td>
<td>RoundRobin</td>
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Below in fig. 6 we look at the behavior of SC-FDMA and OFDMA in a Pedestrian Urban channel model. Since MMSE is used we observe that the performance of SC-FDMA is superior to that of OFDMA’s when using localized allocation. This is the expected result as seen in [13].

![Fig.6 SNR vs. BER for OFDMA and SC-FDMA with MMSE equalization](image)

The main objective of a link level simulator is obtaining sets of SNR-BLER curves for various modulation and coding schemes selected. There are 15 CQI values that can be selected in LTE, and fig. 7 on the top right displays the corresponding BLER curve for each CQI value.

![Fig.7 BLER curves obtained from SISO AWGN simulations for all 15 CQI values.](image)

This set of curves will ultimately be used in a system level simulator similar to the one proposed in [14]. This will allow for the DFT, IFFT, and transmission operations which can be extremely computationally expensive to be abstracted.

V. CONCLUSION AND FUTURE WORK

A description OFDM and SC-FDM was given at the beginning of this paper. From that knowledge, a link-level description of a LTE uplink system was given in section III. The results obtained from this model were then displayed in section IV, with particular mention to the BLER curves necessary for creating a system level simulator.

Further work in terms of increasing functionality to the link level simulator is beside the point since it was created as an intermediate stage to modeling the more complex system level simulator. However the use of an AWGN channel to obtain these results poses a problem in terms of how the system will behave in other types of channel. Such channels should be also tested to see how the much difference there is in terms of BLER curves obtained and what effects this has on the system level simulator.

REFERENCES

Armando Ubisse received his undergraduate degree in 2009 from the University of Cape Town and is presently studying towards his Master of Science degree at the same institution. His research interests include resource management in LTE and in Next Generation Wireless Networks.