Performance of LTE in Rural Areas - Benefits of Opportunistic Multi-User MIMO

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Abstract—This paper focuses on the performance of LTE in rural areas which is based on a channel measurement campaign conducted with the Eurecom OpenAirInterface LTE testbed at 800MHz. This testbed is based on LTE release 8 PHY layer and implements transmission modes 1 (single antenna - SISO), 2 (transmit diversity), and 6 (single-user MIMO - closed loop rank-1 precoding) in real time. In addition to the throughput recorded from the real modem, the raw channel estimates were stored and used for extrapolating the performance to transmission mode 5 (multi-user MIMO). This extrapolation is done by means of a mutual-information based link-quality model that abstracts the performance of multi-user (MU) MIMO for an interference aware receiver proposed by Ghaffar et al and then the results are compared with the performance of abstraction to transmission mode 2 and 6. The superior performance of MU MIMO mode (with interference aware receiver) over other transmission modes is illustrated and it is shown that if the channel admits then MU MIMO is the preferred option.

I. INTRODUCTION

The first version of 3GPP UMTS Long Term Evolution (LTE) standard has been released at the beginning of 2009. Today, mobile operators across the world are starting to roll out LTE with the first commercial networks being available to the customer in the beginning of 2011. In the first run, LTE is going to be deployed on top of existing HSPA and HSPA+ networks at a frequency of 2.6 GHz to satisfy the demand of spectrum in densely populated areas. Over the long run, operators are also pursuing the idea to provide LTE for rural areas at a frequency of 800 MHz using the recently freed spectrum from analog TV (digital dividend). Though extensive channel measurements and trials for LTE deployment in urban areas have been carried out, its extension to the rural areas in 800 MHz band has been neglected so far. The fact that the propagation conditions in rural areas at 800 MHz are quite different from urban environments at 2.6 GHz demand an extensive investigation of LTE transmission in this lucrative band. This paper presents the testbed, LTE measurements alongwith the corresponding results in 800 MHz band. These measurements were taken with Eurecom's OpenAirInterface

platform[1], which implements LTE PHY standard [1], [2], [3]. It comprises a 3 sector, dual RF high-power eNodeB (LTE acronym for the base station) and one user equipment (UE) operating at a center frequency of 859.5MHz. In addition to the throughput measurements, raw channel estimates are stored for further post processing. These measurements were taken in the TARN department in south-west France in collaboration with and under the funding of French space agency (CNES).

The goal of the measurement campaign was to estimate the best throughput achievable by an LTE release 8 nomadic terminal in a rural 5 MHz LTE deployment at 850 MHZ. One special interest was to compare the effectiveness of different LTE transmission modes (TMs) (transmit diversity, precoding, single-user MIMO and MU MIMO) in rural deployments. It was shown that the MU MIMO mode (with interference aware receiver) performs better than the single-user MIMO and transmit diversity modes once the UEs have good channel separation. This provides the fundamental guidelines for LTE deployment in the rural areas.

Rest of the paper is organized as follows: in section II we present OpenAirInterface testbed with its hardware, software components and some important parameters of LTE release 8. In section III we present the measurement description. PHY abstraction for different TMs is presented in section IV and comparison of different LTE TMs along with results is presented in V. In the end section VI presents the conclusions and future work.

II. THE OPENAIRINTERFACE TESTBED

A. Hardware

The testbed equipment is based on the CardBus MIMO I (CBMIMO1) platform developed by EURECOM, complemented with additional RF equipment to operate in the desired frequency band.

1) Base Station: The 3-sector eNodeB testbed equipment is built up of a host PC with three CBMIMO1 cards, the RF conversion subsystem, and the power amplifiers (PA) and the low noise amplifiers (LNA) subsystem. The CBMIMO1 are temporally synchronized via a logical interconnection. The RF conversion subsystem converts the intermediate frequency of 1.9 GHz to the carrier frequency is 859.6 MHz. This constitutes the equipment to be installed in the control room
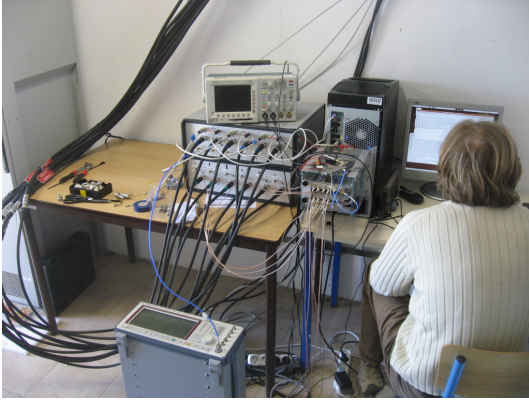
[1]http://www.openairinterface.org/

Fig. 1.   Base Station Control Room

Fig. 2.   Antennas with PAs on mast

Fig. 3.   UE with its antenna and GPS receiver

- Special subframe configuration 0 (longest guard interval)
- Extended cyclic prefix
- OFDMA Downlink
- OFDMA or SC-FDMA Uplink
- 2 TX antenna ports at eNodeB, 1 at UE
- TM 1 (SISO), 2 (Transmit Diversity), 6 (Closed loop single-user MIMO with single-layer precoding)
- Aperiodic wideband feedback
- Link adaptation
- HARQ

III. MEASUREMENT DESCRIPTION

The goal of the measurement campaign was to estimate the best achievable throughput and to estimate the maximum range of cells for high datarate services by an LTE release 8 nomadic terminal in a rural LTE deployment at 850 MHz. For these measurements, three cell-site locations were chosen in the TARN department in south-west France: *Cordes-sur-Ciel, Penne,* and *Ambialet.* The measurements covered the entire road network for each of the sites using a vehicle equipped with the test UE. The real-time throughput of the test UE was measured with the state of the art sub-optimal MODEM. Further the MIMO channel estimates were stored at the UE and the eNodeB for the realistic offline processing in order to infer the achievable results with higher performance MODEMs.

We conducted measurements for both uplink and downlink transmission between the eNodeB and the UE. But our focus in this paper shall be on the downlink transmission. For the sake of comparison between the performance of different transmission strategies, we choose the data set from the measurements in such a way that it allows us to perform MU MIMO along with SISO, transmit diversity and single layer precoding (single-user MIMO). We take channel estimates from stored measurements for two different traces and treat them as channels belonging to two different UEs which are simalteneously present in the same cell area and can possibly be served using same time/frequency resources. The two different traces are shown in figure 4 as blue and red points on the map.

beneath the mast (see Figure 1). Cables on the order of 30m are used to interconnect the RF subsystems with the PA/LNA subsystem, which is contained in hermetically sealed enclosures and is co-located with the antenna on the mast (see Figure 2). The transmission power is 43 dBm per sector and the eNodeB antennas are typical tri-sector antennas with dual (cross) polarized ports per sector from Kathrein Scala (ref 840 21000).

2) User Equipment: The UE testbed equipment is also based on the CBMIMO1 cards, complemented with additional RF equipment to operate in the desired frequency band. For the UE, the CBMIMO1 card is configured for single-antenna transmission and dual-antenna reception, in line with the first roll-out of commercial LTE equipment. The transmission power is 23 dBm. The UE antennas are the 800 MHz TETRA (from Panorama Antennas) vehicular antenna fixed to the vehicle's body. Two such antennas are used for reception, one for transmission. Another antenna for a nomadic scenario (Laptop outdoors) is the Panorama dual-band antenna.

B. Implemented LTE subset

The Eurecom testbed implements a subset of the 3GPP LTE release 8.6 [1], [2], [3] with the following characteristics:

- 5 MHz Bandwidth, 25 Resource Blocks
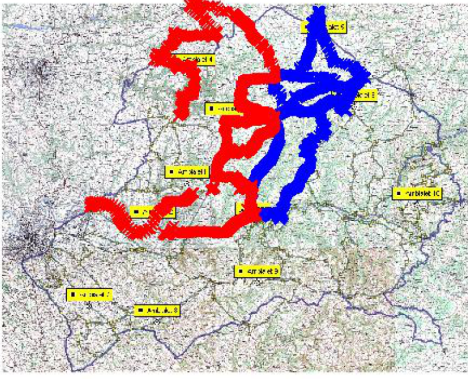- TDD UL/DL Frame Configuration 3

Fig. 4. Traces used for the multi-user MIMO comparison

IV. PHY Abstraction

PHY abstraction technique is an efficient way for reducing the complexity of huge system level evaluations by providing an accurate mapping between system level and link level simulations. Different PHY abstraction techniques have been proposed such as exponential effective SNR mapping (EESM) and mutual information based effective SNR mapping (MIESM). The accuracy of these schemes is very critical for the correct system evaluation and it is shown in [4] [5] and [6] that MIESM provides more accurate mapping results than EESM.

In this paper we use an extension of the mutual information based abstraction methodology of [5]. This is a two step methodolgy as shown in figure 5 where in the first step the maximum channel capacity for the specific symbol is calculated in terms of symbol information (SI). And in the second step we account for the implementation losses which include some other factors mentioned later in this section.
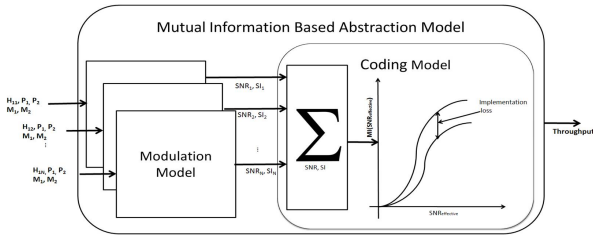

Fig. 5. Mututal information based abstraction model

A. Abstraction for multi-user MIMO

MU MIMO transmission in LTE (mode 5) is based on the low resolution precoders which need merely 2 to 4 bits of feedback from the UEs. This low level quantized CSIT fails to achieve the basic principle of MU MIMO i.e. creating independent parallel channels from cross-coupled channels (eliminating multi-user interference). Significant residual interference even if the eNodeB employs optimal scheduling

severly degrades the performance of MU MIMO. A promising way to recover the gains of MU MIMO in the presence of quantized CSIT is to employ interference aware receivers, as was shown in [7]. We therefore consider that the UEs employ interference aware receivers in TM 5. In the following we derive mutual information expressions for a MU MIMO system employing such a receiver which will subsequently be used in our abstraction model.

1) Mutual information under interference: We assume LTE baseline configuration, i.e. a dual-antenna eNodeB with 2 single-antenna UEs. We denote the received signal at UE-1 on n-th resource element (LTE acronym for subcarrier or frequency tone) by

$$y_{1,n} = \mathbf{h}_{1,n}^\dagger \mathbf{p}_{1,n} x_{1,n} + \mathbf{h}_{1,n}^\dagger \mathbf{p}_{2,n} x_{2,n} + z_{1,n}, \quad n = 1, 2, \cdots, N$$

where $\mathbf{h}_{1,n}^\dagger \in \mathbb{C}^{2\times 1}$ symbolizes the MISO channel from the eNodeB to UE-1, $\mathbf{p}_{k,n}$ is the precoder requested by k-th UE and $z_{1,n}$ is ZMCSCG white noise of variance N_0 at UE-1. Complex symbols $x_{1,n}$ and $x_{2,n}$ are assumed to be independent and of variances σ_1^2 and σ_2^2 respectively. These symbols belong to discrete QAM constellations, i.e. $\chi_{1,n}$ and $\chi_{2,n}$ respectively. The dependency on the resource element index can be ignored, since the processing is assumed to be performed on a resource element basis for each received OFDM symbol. Moreover we denote the effective channels as $\alpha_1 = \mathbf{h}_1^\dagger \mathbf{p}_1$ and $\beta_2 = \mathbf{h}_1^\dagger \mathbf{p}_2$.

The mutual information for UE-1 for finite size QAM constellation with $|\chi_1| = M_1$ takes the form as

$$I(Y_1; X_1 | \alpha_1, \beta_2) = \mathcal{H}(X_1 | \alpha_1, \beta_2) - \mathcal{H}(X_1 | Y_1, \alpha_1, \beta_2)$$
$$= \log M_1 - \mathcal{H}(X_1 | Y_1, \alpha_1, \beta_2) \quad (1)$$

where $\mathcal{H}(.) = -E \log p(.)$ is the entropy function. The second term of (1) is given as

$$\mathcal{H}(X_1 | Y_1, \alpha_1, \beta_2)$$
$$= \sum_{x_1} \int_{y_1} \int_{\alpha_1} \int_{\beta_2} p(x_1, y_1, \alpha_1, \beta_2) \log \frac{1}{p(x_1 | y_1, \alpha_1, \beta_2)} dy_1 d\alpha_1 d\beta_2$$
$$= \sum_{x_1} \sum_{x_2} \int_{y_1} \int_{\alpha_1} \int_{\beta_2} p(x_1, x_2, y_1, \alpha_1, \beta_2)$$
$$\times \log \frac{\sum_{x_1'} \sum_{x_2'} p(y_1 | x_1', x_2', \alpha_1, \beta_2)}{\sum_{x_2'} p(y_1 | x_1, x_2', \alpha_1, \beta_2)} dy_1 d\alpha_1 d\beta_2 \quad (2)$$

Note that conditioned on the channel, the precoder is not random. So there is one source of randomness i.e. the noise. So (2) can be extended as

$$\mathcal{H}(X_1 | Y_1, \alpha_1, \beta_2) =$$
$$\frac{1}{M_1 M_2} \sum_{\mathbf{x}} E_{z_1} \log \frac{\sum_{\mathbf{x}'} \exp\left[-\frac{1}{N_0} \left|\alpha_1 x_1 + \beta_2 x_2 + z_1 - \alpha_1 x_1' - \beta_2 x_2'\right|^2\right]}{\sum_{x_2'} \exp\left[-\frac{1}{N_0} \left|\beta_2 x_2 + z_1 - \beta_2 x_2'\right|^2\right]}$$
$$(3)$$

where $M_2 = |\chi_2|$, $\mathbf{x} = [x_1 \; x_2]^T$ and $\mathbf{x}' = \left[x_1' \; x_2'\right]^T$. The above quantities can be easily approximated numerically using sampling (Monte-Carlo) methods with N_z realizations of noise and N_h realizations of the channel $\mathbf{h}_1^\dagger$. The precoder is selected based on the channel realization and is therefore not random. So we can write mutual information expression for UE-1 as

(4). Using (4) we generate the look up tables for the mutual information of UE-1 which is then used for the abstraction. Similarly we can write the mutual information expression for UE-2 and generate a look up table for its abstraction.

2) Modulation Model: Modulation model provides us with the symbol information (SI) in terms of maximum channel capacity for the particular symbol and is receiver dependent. For the case of MUMIMO it is based on (4) 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 strength $\|\alpha_1\|^2$ and intereference strength $\|\beta_2\|^2$. The look up tables are generated as follows. First we carry out Monte-Carlo simulations of (4) over many number of Noise and channel realizations. For each channel realization we obtain a different set of $\|\alpha_1\|^2$, $\|\beta_2\|^2$ and mutual information. For all other required values this scatter-plot is interpolated using linear interpolation.

After generating table we used it as a modulation model for the stored measurements. From the stored measurement data we compute the signal to noise ratio (SNR) of the desired and interfering stream, desired signal strength $\|\alpha_1\|^2$ and intereferring signal strength $\|\beta_2\|^2$. Then these quantities are given as input to the modulation model which provide us with the abstracted throughput in terms of SI for the each symbol as is shown in Figure 5.

3) Coding Model: The output of modulation model is an upper bound to what the most advanced implementation of an LTE modem can achieve. It completely neglects the effects of channel estimation and interpolation in time and frequency, decoding performance, effects of RF front end. Further the mutual information formulas assume a perfect rate adaptation and a perfect feedback loop. In order to compensate for some of these effects we have carried out simulations with our modem implementation in an AWGN channel and calcuated throughput as a function of block error rate (BLER) and SNR. The difference between abstracted and simulated throughput is what we call the implementation loss. It can be attributed to the effects of channel estimation, decoding performance as well as other implementation factors such as limited accuracy due to the use of fixed point represenations. Please note that coding model still assumes perfect link adaption and neglects effects of the RF frontend.

B. Abstraction for Transmission Mode 2 and 6

The abstraction methodology for TM 2 and 6 is almost simillar to that of MU MIMO. The only difference is in the modulation model of figure 5. For TM 6, since there is no interference so the mutual information is given as

$I\left(Y;X_1|\alpha_1\right)=$

$$\log M_1-\frac{1}{M_1 N_z N_{h_1}}\sum_{x_1}^{N_{h_1}N_z}\sum_{\mathbf{h}_1}\sum_{z_1}\log\frac{\sum_{x_1'}\exp\left[-\frac{1}{N_0}\left|\alpha_1\left(x_1-x_1'\right)+z_1\right|^2\right]}{\exp\left[-\frac{1}{N_0}|z_1|^2\right]} \quad (5)$$

The calculation of mutual information for transmit diversity (i.e. TM 2) mode will be on the similar lines as (5) where the effective channel (channel×precoder) will be replaced by the effective channel (channel×matched filter) and the noise variance will be appropiately scaled as per the matched filter.

V. LTE Transmission Modes Performance Comparison

We will be comparing the performance of the LTE TMs 1, 2, 5 and 6. To compare the performance of these TMs we estimate the sum througput of the cell which consists of two users, based on the raw channel measurements and the methodology outlined in this section.

A. Feedback calculation

In LTE the feedback consists of a channel quality indicator (CQI), a precoding matrix indicator (PMI) and the rank indicator (RI). Two different feedback reporting modes exist: periodic, which is transported over the PUCCH and aperiodic, which is encoded together with the PUSCH. Further, the feedback is classified as wideband feedback, eNodeB-configured sub-band feedback (only in aperiodic reporting mode) or UE-selected sub-band feedback. In our implementation we choose to always use the aperiodic reporting mode with wideband CQI feedback and sub-band PMI feedback. In the LTE 5MHz configuration, the resource blocks (RB) are grouped into 6 subbands of 4 RBs and one sub-band of 1 RB.

In LTE release 8 with two transmit antenna ports at the eNodeB, the PMI consists of two bits that allow to choose one of the following precoders $\mathbf{p}=\begin{bmatrix}1 & q\end{bmatrix}^T$, $q\in\{\pm1,\pm j\}$. Each user calculates a PMI for each subband and each receive antenna according to [7]. Further, for every subband, the receive antenna with the stronger RX signal is determined and this information is stored at the UE. When a subband PMI feedback is requested by the eNodeB, the UE reports the PMI of the strongest RX antenna for each subband.

B. Scheduling and sum throughput

The scheduling process depends on the selected TM. In modes 1, 2, and 6, the eNodeB serves only the UE with best channel (in terms of SNR) whereas for TM 5, the eNodeB schedules both UEs jointly only if both of the UEs have asked for the orthogonal PMIs in that particular subband via feedback otherwise it selects the UE with better CQI and enables the TM 6 for the selected UE i.e. it performs *opportunistic MU MIMO* along with single layer precoding. This way we can see that how much gain we get by opportunistic MU MIMO in our system throughput and we can conduct a fair comparison between this mixed approach and pure tranmission of TMs 1,2 and 6.

C. Link level abstraction

In order to evaluate the performance of TMs we follow mutual information based abstraction methodology described in IV. To calculate the ideal throughput for a subframe we apply the following 3 steps.

1) Calculate the effective SNR based on the TM and the feedback for each channel estimate in a subframe

$$I\left(Y;X_1|\alpha_1,\beta_2\right)=\log M_1-\frac{1}{M_1M_2N_zN_h}\sum_{x_1}\sum_{x_2}\sum_{\mathbf{h}_1^\dagger}^{N_h}\sum_{z_1}^{N_z}\log\frac{\sum_{x_1'}\sum_{x_2'}\exp\left[-\frac{1}{N_0}\left|\alpha_1x_1+\beta_2x_2+z_1-\alpha_1x_1'-\beta_2x_2'\right|^2\right]}{\sum_{x_2''}\exp\left[-\frac{1}{N_0}\left|\beta_2x_2+z_1-\beta_2x_2''\right|^2\right]}\tag{4}$$
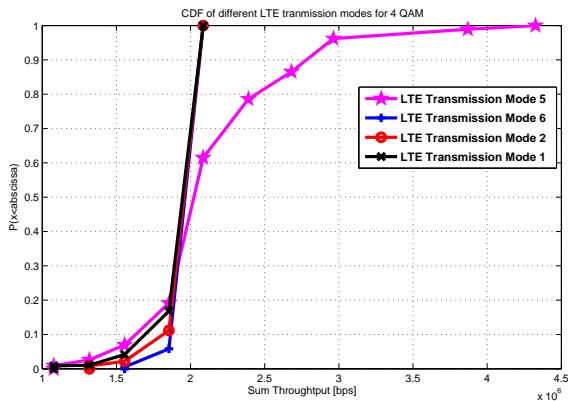

Fig. 6. CDF comparison of sum throughput of the system with 2 single antenna UEs and an eNodeB equipped with two antennas for different LTE transmission modes using 4QAM
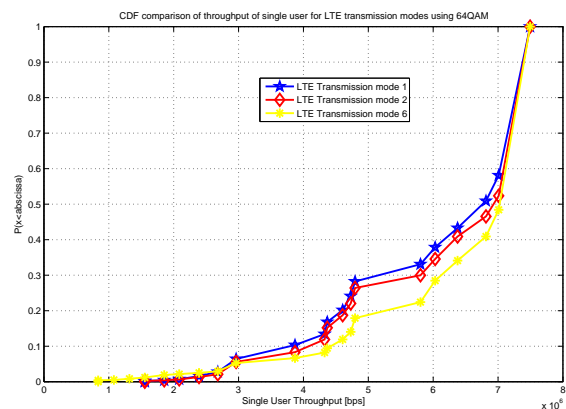

Fig. 7. CDF comparison of the best selected user throughput of a system with 2 single antenna UEs and an eNodeB equipped with two antennas for different LTE transmission modes when using 64QAM

2) Calculate the best supported modulation scheme for this subframe using respective SNRs and Shanon's AWGN capacity formula.
3) Apply the PHY abstraction from IV.

D. Results

We applied the proposed mutual information based abstraction on measurement data from traces shown in figure 4 for LTE TM 1, 2, 6 and opportunistic MUMIMO under the 4QAM constellation. Figure 6 shows the cdf comparison of sum throughput of the LTE TMs and opportunistic MUMIMO under 4QAM constellation with one eNodeB equipped with 2 antenna and 2 single antenna UEs in the system. For opportunistic MUMIMO eNodeB transmits to both UEs with equal power whereas for other TMs the eNodeB serves only one UE with all of the available power. It can be seen that opportunistic MU-MIMO transmission is performing better than the rest of the TMs for high outage rates, i.e., the peak throughput. However, for a 10% outage rate, the sum throughput of MU-MIMO is less favorable.

In figure 7 we show the cdf comparison of single user throughput using higher order modulation i.e. 64QAM and it can be seen that TM 2 is only slightly better than TM 6 and TM 6 is about 0.5 Mbps better than TM 2 at an outage rate of 10%.

VI. Conclusion

We conducted the analysis of different LTE TMs in rural areas in 800MHz frequency band and applied MI-based abstraction to compare their performance in terms of the system throughput. We see that it is advantegeous to do opportunistic MU MIMO as it gives overall better throughput even when

we restrict our results to only 4QAM. Also it is shown that there is not a big difference between the performance of TM 2 and 6 in terms of throughput in rural areas so its better to operate in TM 2 than TM 6 as it does not require the feedback from UEs. For future work we are planning to apply the mutual information based abstraction methodology for the link quality modeling in terms of block error rate (BLER) with the help of OpenAirInterface. Also we shall conduct throughput analysis for LTE TM 4 (single user MIMO) and MU MIMO for higher modulation order.

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