Experimental Analysis of Network-Aided Interference-Aware Receiver for LTE MU-MIMO

Florian Kaltenberger
EURECOM
Sophia-Antipolis, France
Email: florian.kaltenberger@eurecom.fr

Sebastian Wagner
Intel Mobile Communications
Sophia-Antipolis, France
Email: sebastian.wagner@intel.com

***Abstract*—Multiuser (MU) MIMO is a promising technique to significantly increase the cell capacity in LTE systems. However, users scheduled for MU-MIMO may still experience strong MU interference if the channel state information at the base station is outdated or in small cells with a limited number of users available. Interference-aware (IA) receivers exploit information about the interfering data stream, such as the modulation order, in the decoding process, resulting in a significant performance gain over interference un-aware (IU) receivers while maintaining a moderate complexity. In this paper we study a network-aided interference-aware (NA-IA) receiver that receives the interfering modulation order through network signaling and an IA receiver that uses heuristics to determine the interfering modulation order. We use the real-time OpenAirInterface LTE testbed to experimentally evaluate the performance of IA and IU receivers in terms of throughput under different levels of MU interference. The measurement results show that the NA-IA receiver achieves significantly higher data rates compared to the IA receiver, especially when MU interference is strong. The IU receiver on the other hand requires very low levels of MU-interference to achieve a performance comparable to the IA receivers.**

I. Introduction

It is well known that multiuser (MU) multiple-input multiple-output (MIMO) transmission can significantly increase the cell throughput compared to single-user (SU) MIMO transmission due to MU diversity. Therefore, MU-MIMO is already implemented in the 3GPP long-term evolution (LTE) standard Rel 8 [2], where it is referred to as transmission mode (TM) 5. However, since TM5 only supports two co-scheduled user equipment (UE) with a single data stream each, the MU-MIMO mode has been extended in TM8 and TM9 in LTE Rel 9 and 10, respectively, by introducing UE-specific (precoded) reference signals (RS) [3], [4]. In TM8 and TM9 the base station (referred to as eNB in the context of LTE) can schedule up to four users with a single data stream where both precoding technique and number of co-scheduled users are entirely transparent to the UE.

In MU-MIMO, the throughput at the UEs greatly depends on the amount of interference from co-scheduled users. This MU interference can be managed at the eNB through efficient precoding or at the UE via interference cancellation. If the precoding is effective, there will not be any significant MU interference at the UEs and thus no need to cancel that residual interference. However, in TM5 where the precoding is based on a very limited set of possible precoding vectors, efficient precoding can only be achieved if the number of users in the cell is large. The same holds true for non-codebook based precoding schemes as enabled in TM8 and TM9, unless very accurate channel state information is available at the eNB, which in turn is very difficult to obtain.

Consequently, the precoding is likely to be incapable of efficiently mitigating the MU interference at the UEs especially in small cells with a very limited number of users. Therefore, it is of paramount importance that the UEs are able to effectively mitigate the residual MU interference by exploiting its structure.

To achieve effective interference mitigation at the UE, different receiver designs have been proposed in the literature. The interference rejection combiner (IRC) presented in [5] is a linear receiver that requires estimation of the interference covariance matrix. The interference aware (IA) receiver proposed in [6] is based on the maximum likelihood (ML) criterion. However, the optimal IA receiver requires knowledge of the interfering symbol constellation, which is typically unavailable to the UE. Therefore, [6] propose to use a fixed constellation and shows that the performance degradation of the sub-optimal IA receiver is acceptable.

The authors in [7] on the other hand propose a method to estimate the interference modulation estimator prior to the IA receiver. They further show through simulations that various sub-optimal MU receivers achieve similar performance under low MU interference levels as the optimal IA receiver. In fact even the IU receiver performs reasonably well in such a scenario. However, when the MU interference increases, the IU receiver shows very poor performance and also the IA receivers show significant performance differences depending on the method they obtain knowledge about the interfering modulation order. Through real-time field measurements, the presented paper aims to understand the levels of MU interference required for sub-optimal MU receivers to perform close to optimal.

In one of our previous works [1] we have studied the performance of the IA receiver [6] on the OpenAirInterface real-time platform [8] under realistic channel conditions. The IA receiver either uses the assumption that the modulation order of the interfering stream is the same as its own (a

Parts of this work have been presented in [1]. This work was partially funded by the FP7 Network of Excellence Newcom#.

heuristic that was validated by simulations) or obtains knowledge of the modulation order of the interfering stream from network signaling. The latter was termed network-aided IA (NA-IA) receiver following the ongoing 3GPP study item for release 12 on Network-Assisted Interference Cancellation and Suppression (NAICS) [9]. Both receivers were compared to a standard interference un-aware (IU) receiver.

The main conclusions of the paper were the following: (i) In case of single receive antenna the measurements indicate that the IA receiver offers almost no advantage compared to the IU receiver. (ii) For both single and dual-antenna receivers, the measurements revealed that the NA-IA receiver significantly outperforms the IA receiver for higher order modulations, 64QAM. This result suggests that the signaling of the interfering modulation order can greatly improve performance in case 64QAM is applied. For lower order modulations the simplified IA receiver without knowledge of the interfering modulation order performs equally well as the NA-IA. (iii) Moreover, the measurements indicate that the IU receiver benefits significantly from line-of-sight (LOS) channels compared to the IA receivers especially at higher order modulations. In case of QPSK even the IU receiver achieves the same throughput as the IA receivers.

In this paper we deepen our experimental study of the IA and NA-IA receiver and look at the case when the precoding is not optimally matched to the channel. This can happen either when the channel information is outdated, when only wide-band precoding is available (such is in TM5), or in a small cell scenario with a few users. In particular we study the performance of the receiver as a function of the signal-to-interference ratio.

II. System Model

Consider a system with an n_t-antenna eNB and K scheduled UEs, each endowed with n_r receive antennas. We assume that the eNB transmits a *single* stream s_k to UE k ($k = 1, 2, \ldots, K$) and applies a linear precoding technique. Under narrow-band transmission, the received signal $\mathbf{y}_k \in \mathbb{C}^{n_\mathrm{r}}$ of user k takes the form

$$\mathbf{y}_k = \underbrace{\mathbf{H}_k \mathbf{g}_k s_k}_{\text{useful signal}} + \underbrace{\mathbf{H}_k \sum_{j=1, j\neq k}^{K} \mathbf{g}_j s_j}_{\text{MU interference}} + \underbrace{\mathbf{n}_k}_{\text{noise}}, \tag{1}$$

where $\mathbf{H}_k = [\mathbf{h}_{k1}, \mathbf{h}_{k2}, \ldots, \mathbf{h}_{kn_\mathrm{r}}]^\mathsf{H} \in \mathbb{C}^{n_\mathrm{r} \times n_\mathrm{t}}$ is the channel from the eNB to UE k, $\mathbf{G} = [\mathbf{g}_1, \mathbf{g}_2, \ldots, \mathbf{g}_K]^{n_\mathrm{t} \times K}$ is the concatenated precoding matrix and $\mathbf{n}_k \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}_{n_\mathrm{r}})$ is the noise vector. Defining the *effective* channels of user k as $\bar{\mathbf{h}}_i \triangleq \mathbf{H}_k \mathbf{g}_i$ ($i = 1, 2, \ldots, K$), the received signal reads

$$\mathbf{y}_k = \bar{\mathbf{h}}_k s_k + \sum_{j=1, j\neq k}^{K} \bar{\mathbf{h}}_j s_j + \mathbf{n}_k. \tag{2}$$

For future reference we also define the signal-to-interference ratio (SIR) of user k as

$$\mathrm{SIR} = \frac{\|\bar{\mathbf{h}}_k s_k\|^2}{\|\sum_{j=1, j\neq k}^{K} \bar{\mathbf{h}}_j s_j\|^2}. \tag{3}$$

The key challenge in MU-MIMO is to minimize the MU interference. This interference can be mitigated at the eNB by computing an appropriate precoder $\mathbf{G}$ or the interference can be accounted for in the receiver by exploiting its potential structure. It is well-known that efficient interference mitigation at the eNB requires precise downlink channel knowledge which can only be acquired through extensive user feedback. On the other hand, interference management at the receiver necessitates an estimate of the effective channels $\bar{\mathbf{h}}_i$ as well as the interfering symbol alphabet $\mathcal{A}_j$, $s_j \in \mathcal{A}_j$ ($j \neq k$). For a more detailed discussion of MU-MIMO in LTE see [4], [1].

A. Interference-Aware Receiver

The IA receiver design has been proposed in [6] and exploits the potentially available information about the MU interference, i.e., the interfering effective channels $\bar{\mathbf{h}}_j$ ($j \neq k$) and the interfering symbol constellation $\mathcal{A}_j$. In the following, we briefly review the principle of the IA receiver. Each user has access to the effective channels $\bar{\mathbf{h}}_j$ either through cell-specific RS and the a-priori known codebook like in LTE Rel. 8, or through UE-specific RS as in LTE Rel. 9 and beyond. Concerning the interfering symbol constellations $\mathcal{A}_j$, this information is not readily available to the UEs. The symbol alphabets $\mathcal{A}_j$ could be estimated from the statistics [7] of the received signal but this approach is rather difficult and computationally complex. However, we have shown through simulations in [1] that assuming identical alphabets, i.e., $\mathcal{A}_j = \mathcal{A}_k \forall j$ performs very well even if the true interfering constellation is different. For detailed expressions of the IA receiver under various symbol alphabets the reader is referred to [6].

B. Precoder Selection

User k selects the precoding vector $\mathbf{g}_k^\star$ that maximizes his desired *effective* channel magnitude $\|\mathbf{H}_k \mathbf{g}_k\|$, i.e.,

$$\mathbf{g}_k^\star = \arg\max_{\mathbf{g} \in \mathcal{G}} \{\|\mathbf{H}_k \mathbf{g}\|\} \tag{4}$$

and sends the corresponding precoding matrix indicator (PMI) to the eNB. Two feedback modes are supported in LTE, a sub-band PMI feedback, where the UE averages the channel over multiple sub-bands (7 in our 5MHz setting), or a wide-band PMI feedback, where averaging is done over the whole bandwidth.

III. Real-time Measurements

In this section we describe the real-time measurement setup and assumptions, the equipment and the different measurement scenarios. The throughput is measured for both IU and IA receivers in TM5.

A. Setup

The important system configuration parameters are summarized in Table I. The eNB has two antennas (TX and RX) whereas the UE uses one antenna for TX and two antennas for RX. The system is configured in TM5, but instead of the default wide-band PMI feedback we use sub-band PMI

Parameter	Value
Carrier Frequency	1907.6 MHz
System Bandwith	5 MHz
TDD Configuration	3
DL Transmit Subframe	7
UL Transmit Subframe	3
RB Allocation	8191 (all 25 RBs)
Number of PDCCH symbols	1

TABLE I
SYSTEM CONFIGURATION PARAMETERS

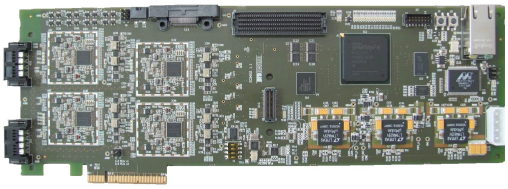

Fig. 1. Express MIMO 2 board

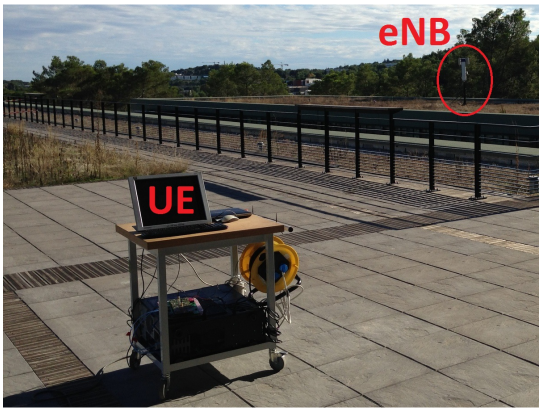

Fig. 2. Outdoor scenario with strong LOS channel

feedback. This feedback mode provides better performance (regardless of the receiver) especially in frequency selective channels. Further, this feedback mode is also found in TM8 and TM9 of LTE Rel 9 and 10.

At the eNB we implemented two different scheduling schemes: In the first scheme, the eNB always uses the sub-band PMI reported by user 1 (the desired user) and assigns orthogonal PMIs to user 2. In the second scheme, the eNB overrides the user's feedback and always uses the same wide-band PMI for user 1 and the opposite PMI to user 2. The first scheduling scheme tries to reduce the MU interference for the first user to the minimum (within the limits of LTE) and is thus optimal for user 1, while the second scheme will generally result in a higher MU interference and allows us to study the performance of the IA receiver in non-ideal conditions.

Note that in TM5, the data for the interfering UE (user 2) always occupies exactly the same time-frequency resources as the data for user 1, because the downlink (DL) power offset parameter, signaled in the control channel and indicating the presence of another user, is valid for the entire subframe.

In the measurements we use two IA receivers. One IA receiver assumes that the interference modulation order is the same as the desired modulation order. This receiver is simply termed "IA" The other receiver is assumed to obtain the correct interfering modulation order through network-aided (NA) signaling and is referred to as "NA-IA" receiver.

B. Assumptions

Since we are interested in studying the performance of the UE receiver, the measurements are carried out with one user only. The second user is scheduled by the eNB, but the signal is not exploited. The UEs measure the PMI in subframe (SF) 2 and transmit them in SF 3 on the physical uplink shared channel (PUSCH). We ensure that the uplink (UL) is always error-free by transmitting with sufficient power. This is necessary to avoid errors in the PMI that would impair our receiver performance measurements. The eNB schedules a physical downlink shared channel (PDSCH) in SF 7 and thus the channel is supposed to be approximately constant during 5 SFs or equivalently 5 ms, which is the case during the measurements.

The LTE modem ran without protocol stack (no Hybrid ARQ) and UL and DL resources were statically configured. Note that, although we disabled the higher layers for this measurements, a similar MU-MIMO setup has been successfully demonstrated with complete protocol stack during the SAMURAI project [10], [11].

During the measurements, the receiver type is changed per frame and the modulation and coding scheme (MCS) of user 1 MCS_1 is either fixed or randomly and uniformly distributed between 0 and 27. To make the MCS of the second user MCS_2 available to the NA-IA receiver without explicit signaling, it is coupled to the system frame number (SFN) as $\mathrm{MCS}_2 = \mathrm{SFN} \bmod 28$. Although MCS_2 is not truly random, no significant change in performance compared to a random MCS_2 has been observed. Moreover, each of the subsequent results was obtained by measuring over a time period of about 2 minutes.

C. Equipment

The measurements are carried out with the EURECOM experimental OpenAirInterface (OAI) platform. The OAI is a software defined radio that implements the 3GPP LTE Rel 8.6 standard. It runs on common x86 Linux machines and uses the real-time application interface (RTAI) to ensure real-time operation. The digital base-band signals are transmitted in real-time via the PCIexpress interface to the EURECOM ExpressMIMO2 board (Figure 1), which converts them to analogue radio frequency (RF) signals. The board has four independent RF chains that allow to receive and transmit on carrier frequencies from 300 MHz to 3.8 GHz. An additional RF frontend is used for amplification, filtering, and duplexing.

D. Scenario

Due to space limitations we only show results for an outdoor LOS scenario, where the eNB antenna is placed on the roof of Eurecom's lab and the UE is moved on a trolley on the terrace on the other wing of the building. Figure 2 shows the

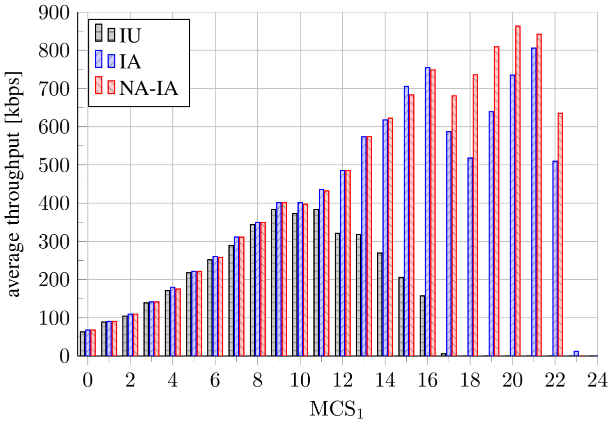

Fig. 3. MCS_1 vs. average throughput with $n_\mathrm{r} = 2$, outdoor scenario with strong LOS channel [1].

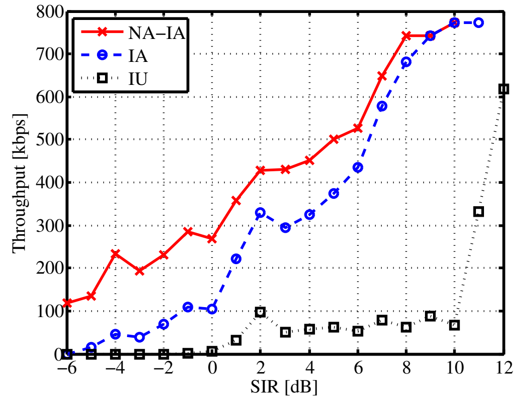

Fig. 4. Throughput vs. SIR for $\mathrm{MCS}_1 = 16$.

measurement environment with the UE in the foreground and the eNB on the roof in the background. The UE is moved at low speeds to avoid a strong Doppler effect but to allow for an averaging of the performance over sufficiently different channel realizations. The mean signal-to-noise ratio (SNR) is 21 dB.

E. Measurement Results

Figure 3 depicts the measurement results for all MCS and for all three receivers. Note that the throughput plots are based on one scheduled subframe per frame. It can be observed that the IU, IA, and NA-IA receiver achieve maximum throughput for $\mathrm{MCS}_1 = 9$, $\mathrm{MCS}_1 = 21$ and $\mathrm{MCS}_1 = 20$, respectively. Although the maximum throughput of IA and NA-IA receiver are almost identical, the NA-IA achieves a significantly higher throughput for $\mathrm{MCS}_1 > 16$, for 64QAM modulation.

Figure 4 shows the throughput of the three receivers vs. the received SIR for a fixed MCS of 16 for the case when scheduling is based on sub-band PMI feedback combined with the case when the scheduler uses a fixed wide-band PMI. The SIR was estimated directly from the channels. It can be seen that the IA receiver and especially the NA-IA receiver work already reasonably well even for very low SIR. The IU receiver needs a much higher SIR to work properly. This means that the IA receivers are also able to cope with situations, where the scheduling and the PMI selection are not optimal, which is often the case.

IV. Conclusion

This paper evaluated the potential performance improvements of IA receiver designs over an IU receiver in LTE MU-MIMO through real-time field measurements conducted with the OpenAirInterface experimental platform.

The measurements revealed that the NA-IA receiver significantly outperforms the IA receiver. This is especially true for higher order modulations such as 64QAM (which are more sensitive to interference) or when the MU interference is very strong. In these cases signaling of the interfering modulation order can greatly improve performance.

For lower order modulations and low MU interference the simplified IA receiver without knowledge of the interfering modulation order performs equally well as the NA-IA. The IU receiver on the other hand needs a very low level of MU interference to achieve a comparable performance to the IA receivers, which is almost impossible to achieve within the LTE specifications.

References

[1] S. Wagner and F. Kaltenberger, "Interference-aware receiver design for MU-MIMO in LTE: Real-time performance measurements," *Intel Technology Journal (special issue on 4G communications)*, vol. 18, no. 1, pp. 154–171, 2014.

[2] 3GPP, "Physical channels and modulation," 3GPP, Technical Specification 36.211-V8.6.0, Sep. 2009.

[3] S. Sesia, I. Toufik, and M. Baker, Eds., *UMTS Long Term Evolution: From Theory to Practice*. Wiley and Sons, 2009.

[4] J. Duplicy, B. Badic, R. Balraj, R. Ghaffar, P. Horvath, F. Kaltenberger, R. Knopp, I. Kovacs, H. Nguyen, D. Tandur, and G. Vivier, "MU-MIMO in LTE systems," *EURASIP Journal on Wireless Communications and Networking*, 2011.

[5] Z. Bai, S. Iwelski, G. Bruck, P. Jung, B. Badic, T. Scholand, and R. Balraj, "Receiver performance-complexity tradeoff in LTE MU-MIMO transmission," in *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, 2011, pp. 1–7.

[6] R. Ghaffar and R. Knopp, "Interference-aware receiver structure for Multi-User MIMO and LTE," *EURASIP Journal on Wireless Communications and Networking*, 2011.

[7] J. H. Bae, S. Kim, J. Lee, and I. Kang, "Advanced downlink MU-MIMO receiver for 3GPP LTE-A," in *IEEE International Conference on Communications (ICC)*, Ottowa, Canada, Jun. 2012, pp. 7004–7008.

[8] Eurecom, "The openairinterface website," 2013. [Online]. Available: http://www.openairinterface.org

[9] 3GPP, "Network-assisted interference cancellation and suppression for LTE (release 12)," 3GPP, Technical Report 36.866-V1.0.0, Dec. 2013.

[10] B. Badic, A. F. Cattoni, M. Diedonne, J. Duplicy, P. Fazekas, F. Kaltenberger, I. Z. Kovács, and G. Vivier, "Advances in Carrier Aggregation and Multi-User MIMO for LTE-Advanced: Outcomes from SAMURAI project," White paper, 2012.

[11] A. Cattoni, H. Nguyen, J. Duplicy, D. Tandur, B. Badic, R. Balraj, F. Kaltenberger, I. Latif, A. Bhamri, G. Vivier, I. Kovacsk, and P. Horvat, "Multi-user MIMO and carrier aggregation in 4G systems: the SAMURAI approach," in *WCNC 2012, IEEE Wireless Communications and Networking Conference*, Paris, FRANCE, Apr. 2012.