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Abstract.

Motivated by the stringent reliability required by some of the future cellular use cases, we study the impact of precoding errors on the SINR outage performance for various spatial diversity techniques. The performance evaluation is carried out via system-level simulations, including the effects of multi-user and multi-cell interference, and following the 3GPP-defined simulation assumptions for a traditional macro case. It is shown that, except for feedback error probabilities larger than 1%, closed-loop microscopic diversity schemes are generally preferred over open-loop techniques as a way to achieve the SINR outage performance required for ultra-reliable communications. Macroscopic diversity, where multiple cells jointly serve the UE, provides additional robustness against precoding errors. For example, a 4x4 MIMO scheme with two orders of macroscopic diversity can achieve the 0 dB SINR outage target at the 10^{-5}-th percentile, even for a precoding error probability of 1%. Based on the obtained results, it is discussed what transmission modes are more relevant depending on the feedback error constraint.

1 Introduction

Ultra-reliable communications over wireless is an active research topic that will open the possibility of novel applications [1]. For some of the use cases, latencies of a few milliseconds must be guaranteed with reliability levels up to 99.999%. The signal to interference-and-noise ratio (SINR) outage performance is a relevant metric for ultra-reliable communications. In this context, spatial diversity techniques such as microscopic and macroscopic diversity have shown promising potential. For example, the work in [2], [3] shows that the proper combination of macroscopic and microscopic diversity techniques can provide the required SINR outage performance.

Microscopic diversity is typically used in modern cellular systems, such as the Long Term Evolution (LTE), by use of multiple-input multiple-output (MIMO) antenna techniques. In the downlink, the gains provided by microscopic diversity strongly depend on the availability and accuracy of channel state information (CSI) at the eNodeB. If the channel knowledge is precise enough, closed-loop (CL)

schemes, which are known to provide the best performance [4], can be applied. However, in cases of absence or inaccurate CSI knowledge due to e.g. imperfect channel estimation, open-loop (OL) schemes are typically more appropriate.

In frequency division duplex (FDD) modes, where channel reciprocity is not applicable, the eNodeB obtains the CSI through an uplink feedback channel. The CSI contains information about the current channel quality, and the preferred precoding matrix to be applied in downlink CL transmissions. Apart from the typically applied quantization in order to cope with the limited feedback capacity of real systems, the precoding information is prone to errors due to the intrinsic presence of fading and interference in the wireless channel. The impact of CSI feedback errors have been evaluated from a system capacity point of view. For example, the work in [5] evaluates the influence of CSI feedback errors on the throughput performance of multi-user MIMO systems, whereas [6] demonstrates the significant performance degradation when a UE intentionally reports the wrong CSI to the eNodeB. Previous reliability analyses [2], [3] have not considered these types of imperfections. Our hypothesis is that precoding errors could have a significant impact on ultra-reliable communications, which is what we evaluate in this work.

In this paper we study the impact of CSI feedback errors on the achievable downlink SINR performance in a multi-cell multi-user environment. Our focus is on the very-low percentiles of the SINR distribution in order to quantify the impact of feedback errors on ultra-reliable communications, and determine what transmission modes (e.g. OL or CL) are more relevant depending on the feedback error probability. The complexity of our system model prevents a purely analytical evaluation without omitting important aspects influencing the performance. The evaluation is carried out following the 3GPP-defined simulation assumptions for a LTE macro cellular network that relies on commonly accepted models and methodologies. Mathematical expressions for the user-experienced SINR, when applying the different transmission schemes and related imperfections, are presented in this article and used in the simulations. Long simulations are run to ensure statistical reliable performance results with high level of confidence

The rest of the paper is outlined as follows: Section 2 describes our system model. The simulation assumptions are outlined in Section 3. Performance results are presented in Section 4, followed by concluding remarks in Section 5.

2   System Model

The network consists of a set of $\mathcal{N} = \{1, ..., N\}$ cells, each equipped with T transmit antennas, and a set of $\mathcal{K} = \{1, ..., K\}$ UEs with R receive antennas. Each downlink connection between UE $k \in \mathcal{K}$ and its serving cell $j \in \mathcal{N}$ is represented by a TxR CL MIMO system as shown in Fig. 1. As our focus is on reliable communications, only single-stream transmission cases are considered [7]. First, each UE estimates the RxT-dimensional channel $\mathbf{H}_{jk}$, whose (m,n)-th element represents the complex channel gain from transmit antenna n at cell j, to receive antenna m at UE k. As a second step, the vector $\mathbf{u}_j$ corresponding to
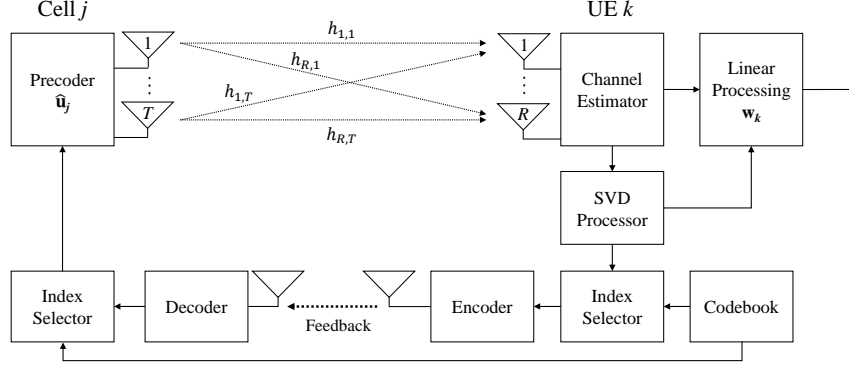
Fig. 1. Transmitter-Receiver Architecture.

the largest eigenvalue of the $\mathbf{H}_{jk}^H\mathbf{H}_{jk}$ matrix is calculated through singular value decomposition (SVD), i.e. $\mathbf{u}_j = \text{EIG}_{max}(\mathbf{H}_{jk}^H\mathbf{H}_{jk})$. Next, an index selector selects from a pre-defined codebook the precoding vector that matches best with $\mathbf{u}_j$. We refer to this quantized version as $\hat{\mathbf{u}}_j$. The index to the precoder, i.e. precoding matrix indicator (PMI), is transmitted to the cell through the uplink feedback channel.

The cell uses the received PMI to obtain $\hat{\mathbf{u}}_j$, which is then applied in the data transmission. Within each cell, the UEs are served on orthogonal resources, i.e. there is no intra-cell interference as it is also the case for LTE assuming single-stream and single-user MIMO transmission modes [4]. In a frequency-flat fading case, the R-dimensional received signal $\mathbf{r}_j$ by a user (for simplicity, we omit the user-specific index) served in cell $j \in \mathcal{N}$ is given as follows,

$$\mathbf{r}_j = \mathbf{H}_j\sqrt{\Omega_j}\hat{\mathbf{u}}_j s_j + \sum_{i\in\mathcal{N}\setminus j}\mathbf{H}_i\sqrt{\Omega_i}\hat{\mathbf{u}}_i s_i + \mathbf{n} \ , \tag{1}$$

where Ω_i represents the averaged received power from the i-th cell, including the effect of the antenna gain and pattern, distance-dependent attenuation and shadowing; s_i represents the transmitted symbol (for simplicity, $\|s_i\| = 1$) and $\mathbf{n}$ is a Rx1 zero mean Gaussian vector with variance σ^2 representing the noise power at each receiving antenna.

In order to maximize the received signal power at the receiver, the R received signals are combined by applying a weight vector $\mathbf{w} = \mathbf{H}_j\hat{\mathbf{u}}_j$. The resulting post-detection SINR expression is given by,

$$SINR_j = \frac{\Omega_j\|\hat{\mathbf{u}}_j^H\mathbf{H}_j^H\mathbf{H}_j\hat{\mathbf{u}}_j\|^2}{\sum_{i\in\mathcal{N}\setminus j}\Omega_i\|\hat{\mathbf{u}}_j^H\mathbf{H}_j^H\mathbf{H}_i\mathbf{u}_i\|^2 + \sigma^2\|\hat{\mathbf{u}}_j^H\mathbf{H}_j^H\|^2} \ , \tag{2}$$

where $[\,\cdot\,]^H$ denotes the Hermitian transpose.

The presented microscopic scheme corresponds to transmission mode 6 (TM6) in LTE terminology. TM6 is a special case of CL spatial multiplexing (TM4) where the transmission rank is limited to one. The UE utilizes the downlink

cell-specific reference signals (RS) to perform the channel estimation, and select the preferred PMI (from a common codebook). The eNodeB signals the applied precoding to the UE in the downlink grant [4].

TM6 allows operation with 2 or 4 transmit antennas. For the former case, the LTE Release 8 codebook contains 4 precoding vectors, whereas there are 16 different entries for four transmit antennas [8]. The number of entries have been selected as a tradeoff between the uplink signalling overhead and downlink performance.

In cases where channel information is missing at the eNodeB, spatial diversity gain can be obtained with open-loop transmission modes. LTE transmission mode 3 (TM3) supports OL spatial diversity by use of space-frequency block coding (SFBC) techniques [9], which are based on the space-time block coding initially proposed by Alamouti [10]. SFBC achieves similar diversity order to CL, but with a reduced received power since the transmit beamforming gain is not obtained [10]. The post-detection SINR of a TxR OL MIMO scheme is simply modelled by adding a $10 \log_{10} T$ SINR penalty to the performance obtained with a TxR MIMO system assuming full channel knowledge at the transmitter (i.e. without quantized precoding) [10].

As a method to further improve the SINR outage performance, we also consider macroscopic diversity transmissions from M cells to a certain UE [2]. We assume a simple soft-combining approach as known from Universal Mobile Telecommunications System (UMTS), where the received signal from each macroscopic branch is independently detected and combined at the UE [11]. As this scheme rely on non-coherent transmissions, each of the M macroscopic links can be modelled as shown in Fig. 1. The SINR after combining M ($1 \leq M \leq N$) macroscopic branches is expressed as follows,

$$SINR = \sum_{j=1}^{M} SINR_j \, , \tag{3}$$

where $SINR_j$ is the SINR calculated according to (2), assuming the UE is connected to cell j.

2.1   Precoding Errors

The gains provided by spatial diversity techniques depends on the accuracy of the CSI at the transmitter [4]. Since the CSI is estimated at the UE and transmitted to the eNodeB through an uplink feedback channel, it is vulnerable to multiple sources of delay and other imperfections. The delays are a consequence of the constrained CSI reporting periodicity and processing time, meaning that the optimal precoding will not be immediately applied at the transmitter. Additionally, errors in the channel estimation could lead to a sub-optimal PMI selection. Another source of degradation is errors in the uplink transmission of the CSI due to the inevitable presence of fading and interference in the wireless channel.

We focus uniquely on the effect of precoding feedback errors. We assume that errors in the feedback channel can occur with a given error probability P_e. In

such cases, the PMI decoded by the eNodeB will be different to the reported by the UE, which will lead to a erroneous precoder selection. The errors in the feedback channel are assumed to be i.i.d for each UE-eNodeB connection.

Since the eNodeB signals the applied precoding in the scheduling grant, the UE can still apply a proper combining weight vector to improve the signal quality at the receiver. In other words, the benefits of transmit diversity are lost but the receive diversity gain is maintained. As a more pessimistic case, errors could alter the applied-PMI related signalling in the downlink grant, resulting in loss of both the transmit and receive diversity gain.

3   Simulation Assumptions

The evaluation is carried out by analysing the downlink SINR distribution for different antenna schemes, transmission methods, and feedback error probabilities. A snapshot-based simulation approach is applied and the respective assumptions are summarized in Table 1. A large macro-cellular network composed of three-sector sites with inter-site distance of 500 m is assumed, where UEs are uniformly distributed [12]. Cells are transmitting at full power (full load conditions) at a 2 GHz carrier frequency. The simulation procedure is as follows: Each UE selects M serving cells according to the average received power. Effects of user mobility and handovers are not explicitly included in the simulations. However, the effect of handover hysteresis margin is implicitly modelled in the active set selection algorithm: each UE identifies the strongest received cells that are within a certain *handover window*, as compared to the strongest cell. A serving cell for the UE is then randomly selected from the cells within the handover window. This method models the effect where not all UEs are served by their strongest cell due to the use of handover hysteresis margins in reality.

The experienced instantaneous post-detection SINR is calculated for each UE following the models in Section 2. For each snapshot, the fast fading is independent and identically distributed for each transmit-receive antenna pair, following a complex Gaussian distribution (i.e. the envelope is Rayleigh distributed). Additive white Gaussian noise with a power spectral density of -174 dBm/Hz is considered. It is assumed that UEs are scheduled with 10 MHz bandwidth, resulting in a noise power of -96 dBm when including a 8 dB noise figure at the UE.

A large number of snapshots are simulated and the generated SINR samples are used to form empirical cumulative distribution functions (CDF). Our target is to study the impact of different feedback error probabilities on the SINR outage performance. In line with [1], the key performance indicator (KPI) is the SINR at the 10^{-5}-th percentile. At this percentile, we consider a 0 dB SINR as an appropriate target to have error-free downlink reception, and therefore fulfil the low latency requirements of ultra-reliability use cases (we refer to [2] for more details).

Table 1. Simulation assumptions

Parameter	Value
Network layout	3GPP Macro case 1
UE distribution	Uniformly distributed in outdoor locations
Macro cell transmit power	46 dBm
Carrier frequency	2.0 GHz
Propagation	$128.1 + 37.6 \log10(R[\text{km}])$ dB
Antenna gain	BS: 14 dBi. UE: 0 dBi
Antenna pattern	BS: 3D with $12°$ downtilt UE: omnidirectional
Shadowing distribution	Log-normal with $\sigma = 8$ db
Shadowing correlation	Intra-site: 1.0 ; Inter-site: 0.0
Noise power spectral density	-174 dBm/Hz
Noise figure	8 dB
Noise power	-96 dBm @10 MHz
Handover window	3 dB
Fast fading	Rayleigh distributed; Uncorrelated among the different antenna branches
Feedback error probability P_e	10^{-1}, 10^{-2}, 10^{-3}
SINR outage target	0 dB at the 10^{-5}-th percentile

4 Results

The first set of results correspond to the relatively pessimistic case where the PMI applied by the eNodeB is unknown by the UE, thus the UE assumes that the applied precoding is the one that it has previously signalled. Fig. 2 shows the empirical CDF of the SINR distribution for 2x2 and 4x4 schemes, OL and CL transmission modes, and different feedback error probabilities. Obviously, the 4x4 schemes offer superior performance as compared to 2x2 MIMO schemes. The benefits of CL transmissions over OL schemes are also observable: 4.6 dB and 2.2 dB SINR gain for 2x2 and 4x4 schemes, respectively, at the 10^{-5}-th percentile.

When including the effects of feedback errors, a significant degradation of the performance is observed. For example, even for $P_e = 10^{-3}$, the experienced SINR degradation at the 10^{-5}-th percentile is as high as 8.9 dB and 3.2 dB for 2x2 and 4x4 antenna schemes. The reason is that, when this type of errors occur, the benefits of both transmit and receive diversity are not obtained, i.e. the instantaneously experienced diversity order is equivalent to a 1x1 MIMO system. Under such circumstances, it is shown how OL schemes, which do not require any uplink CSI feedback, offer better performance.

Next, we consider the case where the eNodeB applies an erroneous precoding vector, but the applied PMI is known at the receiver. Fig. 3 and 4 shows the SINR distribution with 2x2 and 4x4 antenna schemes, respectively. Cases with second order of macroscopic diversity and $P_e = 10^{-1}$ are also shown. As compared to
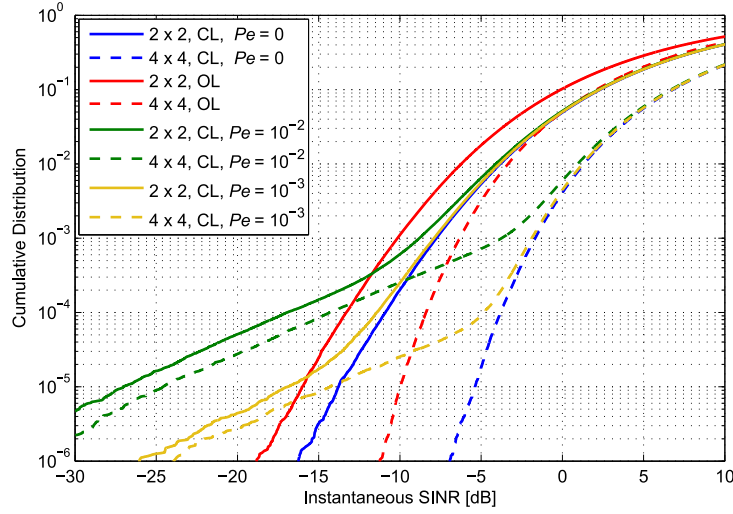
Fig. 2. SINR outage performance with 2x2 and 4x4 antenna schemes, different transmission modes and precoding error probabilities (P_e). $M = 1$.

the performance results in Fig. 2, errors in the uplink feedback have less impact on the SINR performance. For example, CL configurations with $P_e = 10^{-3}$ and $M = 1$ experience a performance degradation of only 0.3 dB. In this case, the receiver has knowledge of the applied precoding, which allows to fully harvest the receive diversity gain. It is observed that for $P_e \leq 10^{-2}$, the performance of CL schemes is better than OL.

As also observed in previous studies [2], macroscopic diversity provides additional protection against fast and slow fading hence providing significantly better SINR performance. Even for $P_e = 10^{-1}$, only a 1.3 dB performance degradation is observed for 2x2 and 4x4 MIMO schemes. With macroscopic diversity, the probability of experiencing feedback error across the M links is reduced. Note that compared to the intra-cell MIMO schemes, the considered macroscopic diversity technique relies on non-coherent transmissions and soft-combining of the multiple received signals at the UE, therefore it is only required to report traditional CSI feedback to each of the M eNodeBs.

Fig. 5 summarizes the achieved 10^{-5}-th percentile SINR performance under different transmission schemes and feedback error probabilities. The 0 dB SINR target is represented with a horizontal dashed line. As also concluded in [2], a 4x4 CL MIMO scheme with $M = 2$ allows to fulfil the 0 dB SINR target. However, it is observed that this is only achievable under certain feedback error probabilities. For instance, if the feedback error probability is $P_e \geq 10^{-1}$, 4x4 MIMO with $M = 2$ no longer fulfils the 0 dB SINR target. The SINR degradation due to feedback errors is much more severe for configurations with low diversity order. For example, 4x4 CL MIMO with $M = 1$ achieves similar performance as 4x4 OL
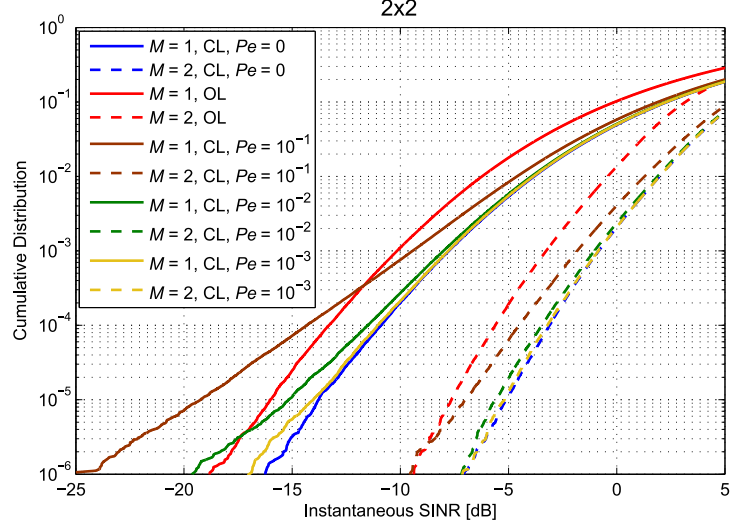
Fig. 3. SINR outage performance with a 2x2 antenna scheme, different transmission modes and precoding error probabilities (P_e). It is assumed that the applied PMI is known at the UE.
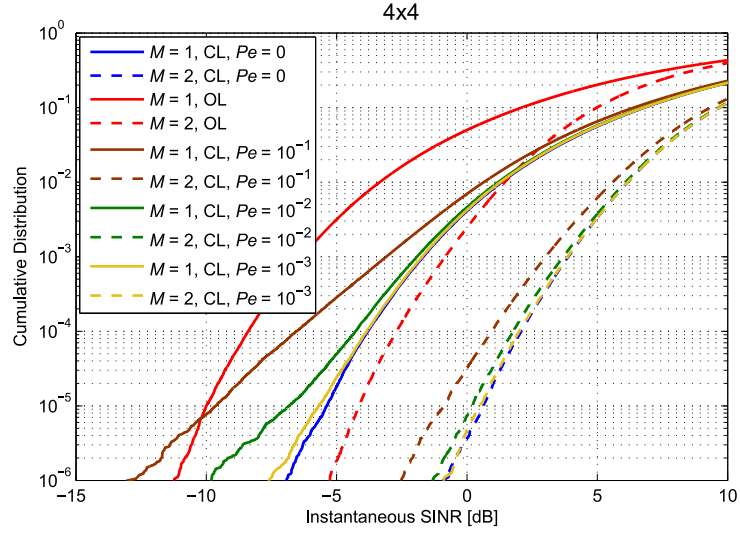

Fig. 4. SINR outage performance with a 4x4 antenna scheme, different transmission modes and precoding error probabilities (P_e). It is assumed that the applied PMI is known at the UE.

for $P_e = 10^{-1}$; whereas, under the same error probability, 2x2 CL with $M = 1$ is 3.2 dB worse than OL.
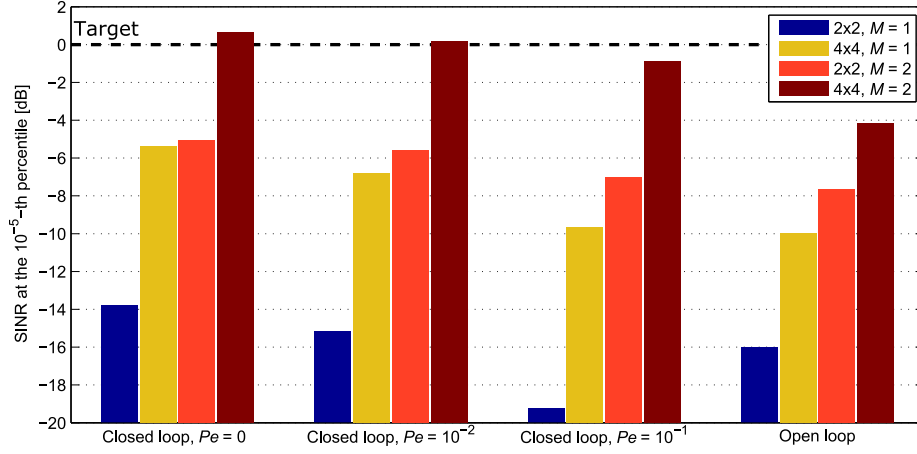
Fig. 5. Achieved SINR at the 10^{-5}-th percentile for several transmission schemes and precoding error probabilities (P_e).

5   Conclusions

In this paper we have evaluated the SINR outage performance under different CSI feedback error constraints in order to quantify its impact on ultra-reliable communications. It have been shown that even for feedback error probabilities as high as 10^{-2} (i.e. three orders of magnitude larger than the required reliability), there is a benefit of using closed-loop MIMO schemes over open-loop schemes. The performance degradation due to errors in the feedback can be reduced by applying macroscopic diversity, as the considered scheme relies on non-coherent independent transmissions from the different macroscopic branches. For instance, a 4x4 MIMO scheme with two orders of macroscopic diversity can achieve the 0 dB SINR outage target at the 10^{-5}-th percentile, even with a 1% error probability in the CSI feedback. For configurations with low diversity order, a larger performance impact has been observed. For example, closed-loop 2x2 MIMO without macroscopic diversity, performs 3.2 dB worse than open-loop transmissions for a 10% feedback error probability. Future work must also consider other sources of imperfections in the channel information. For instance, as a consequence of non-ideal channel estimation at the UE, or due to delays in the CSI report. This will allow to fully assess the reliability performance in a practical setting.

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