Experimental Evaluation of Relative Calibration in a MISO-TDD System

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***Abstract*—We study the transmit time reversal beamforming in a 8x1 MISO communication system at 2.68GHz. We consider the downlink time reversal transmission where a BS communicates with one user. A prototype composed by 8 antennas and designed by Orange labs acts as the BS while the user has a single antenna. The reciprocity property is destroyed by the non-symmetric characteristics of the RF electronic circuitry. We use relative calibration which is based exclusively on signal processing techniques to solve this issue. Utilizing a controlled test setup based on OpenAirInterface, the ExpressMIMO2 SDR boards, as well as a servo controlled rail, we show the feasibility of a relative calibration method through beamforming SNR measurements. We also evaluate the performance of an antenna selection scheme at the transmit side as a low-cost low-complexity alternative to capture many of the advantages of multi-antenna systems. The measurements show that the relative calibration method is performing almost optimal and that the complexity can be significantly reduced by using antenna selection.**

I. Introduction

Multi-antenna techniques can increase the link reliability, the spectral efficiency, or both. Beamforming falls in the first category and relies on the availability of channel channel state information at the transmitter (CSIT). However, the acquisition of CSIT is not trivial in systems with a large number of antennas, especially in frequency division duplex (FDD) systems that rely a bandwidth-limited feedback channel. In a Time Division Duplex (TDD) system, reciprocity between the Uplink (UL) and Downlink (DL) channels can be exploited, but care needs to be taken for the non reciprocal components in the radio frequency (RF) front-end components. In [10] and [11], authors have proved the efficacy of calibrating the destroyed channel reciprocity solely through signal processing techniques with real bi-directional channel measurements (relative calibration). In [12] a calibration method relying on mutual coupling among BS antennas is proposed, so that the mobiles are not involved in the calibration of the non-reciprocal front-end circuitry. In this paper we use the relative calibration method from [1] whose efficacy has already been demonstrated by means of real-world experiments on a 4x1 Multiple Input Single Output (MISO) system. Here, we consider a larger transmit antenna array of 8 elements and two types of reference antennas with different polarization patterns and gains, that had not been tested in [1]. We perform conjugate beamforming; the most simple form of linear precoding compared to Minimum Mean Square Error (MMSE) or zero-forcing beamforming (ZF). We compute the received beamforming Signal to Noise Ratio (SNR) over a large number of positions of the receive antenna in order to minimize the uncertainty in the mean and be as accurate as possible. Also, we examine an antenna selection scheme at the transmit side as a solution to reduce hardware complexity and cost.

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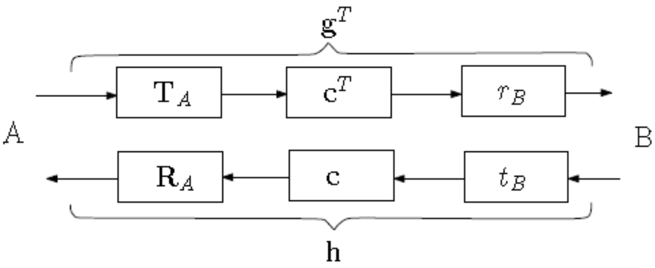

Fig. 1: Reciprocity Model

The remainder of the paper is organized as follows: Sec. II presents the system model. Sec. III describes the relative calibration method, while Sec. IV outlines the basic elements utilized in our measurement setup. Sec. V demonstrates the experimental results of the relative calibration procedure, and then conclude in Sec. VI.

II. System Model

We use the same reciprocity model introduced in [1]. We consider a point-to-point TDD communication system involving two devices A and B with M antennas and 1 antenna respectively, MISO system, as illustrated in Figure 1. The channel seen by transceivers in the digital domain (the composite channel), is comprised of the physical channel c, assumed reciprocal in both UL and DL, and filters modeling the imperfections of the transmit RF hardware (e.g., power amplifiers (PA)), ($\mathbf{T}_A$ and t_B), and the receive RF hardware (e.g, low-noise amplifiers (LNA)), ($\mathbf{R}_A$ and r_B). We note $\mathbf{T}_A$ (matrix of size MxM) as the system function in the frequency domain of the transmit block at node A from the digital-to-analog converter (DAC) to the antenna array. The diagonal elements represent the gains on each transmit chain whereas the off-diagonal elements correspond to the RF chain on-chip crosstalk and the antenna mutual coupling. We consider the ideal case, where $\mathbf{T}_A$, t_B, $\mathbf{R}_A$ and r_B are all identity filters (no crosstalk/mutual coupling) and carrier frequency at both sides is identical. Also, the filters modeling the amplifiers are assumed to remain constant over the observed time horizon. $\mathbf{R}_A$ is the system function of the receive block at node A and includes the characteristics from the antenna array to the analog-to-digital converter (ADC). t_B and r_B represent the transmit and receive chains at node B respectively. The measured UL and DL channels between nodes A and B, represented by $\mathbf{g}^T$ and $\mathbf{h}$, are thus modeled as:

$$\begin{aligned} \boldsymbol{g}^T &= r_B \boldsymbol{c}^T \boldsymbol{T}_A \\ \boldsymbol{h} &= \boldsymbol{R}_A \boldsymbol{c} t_B \end{aligned} \tag{1}$$

Eliminating c from Eq.1, we obtain:

$$\boldsymbol{g}^T = r_B(\boldsymbol{R}_A^{-1}\boldsymbol{h}t_B^{-1})^T\boldsymbol{T}_A = \boldsymbol{h}^T\frac{r_B}{t_B}\boldsymbol{R}_A^{-T}\boldsymbol{T}_A = \boldsymbol{h}^T\boldsymbol{F} \tag{2}$$

where $\boldsymbol{F} = \frac{r_B}{t_B}\boldsymbol{R}_A^{-T}\boldsymbol{T}_A$ includes all the hardware properties on both sides and is called the *calibration matrix*.

III. Relative Calibration

Let us describe how the calibration matrix is estimated. We assume here that the matrix $\boldsymbol{F}$ is diagonal. This assumption has been validated in [1], where it has been shown experimentally that the magnitude of the off-diagonal elements is at least 30dB below the one of the main diagonal and that there is thus almost no difference in beamforming perfomance.

We consider an orthogonal frequency division multiplexing (OFDM) system where for each subcarrier the channel can be regarded as flat fading. The signal model is given by:

$$\begin{aligned} y_b &= \boldsymbol{g}^T \boldsymbol{s}_a + n_a \\ \boldsymbol{y}_a &= \boldsymbol{h} s_b + \boldsymbol{n}_b \end{aligned} \tag{3}$$

where $\boldsymbol{y}_a \in \mathbb{C}^M$ and $y_b \in \mathbb{C}$ are the received signals at node A and B respectively. $\boldsymbol{s}_a \in \mathbb{C}^M$ and $s_b \in \mathbb{C}$ are the known transmit pilot sequences on the concerned subcarrier whereas the noise n_a and $\boldsymbol{n}_b$ are circularly-symmetric complex Gaussian random variables following $\mathcal{CN}(0, \sigma_n^2)$ and $\mathcal{CN}(0, \sigma_n^2\boldsymbol{I})$ respectively.

The channel responses can be estimated using received pilots. We adopt here the least square (LS) estimators as they do not require any statistical channel information, given by:

$$\begin{aligned} \hat{\boldsymbol{g}}^T &= y_b \boldsymbol{s}_a^H (\boldsymbol{s}_a \boldsymbol{s}_a^H)^{-1} \\ \hat{\boldsymbol{h}} &= \boldsymbol{y}_a \frac{s_b^*}{\|s_b\|^2} \end{aligned} \tag{4}$$

Since LS estimators are linear, the estimation errors remain circular-symmetric Gaussian variables [2] following $\mathcal{CN}(0, \sigma_n^2(\boldsymbol{s}_a^*\boldsymbol{s}_a^T)^{-1})$ and $\mathcal{CN}(0, \frac{\sigma_n^2}{\|s_b\|^2}\boldsymbol{I})$ respectively.

Substituting Eq.4 in Eq.2 we get the diagonal estimation of the calibration matrix $\boldsymbol{F}$.

IV. Measurement Setup

The implementation results were obtained using EURECOM's open-source hardware and software development platform OpenAirInterface (OAI), [3], and a rail moving with a Digital Servo Amplifier, SERVOSTAR 300, along with a Rosier servo motor controlling the movement. OAI is a wireless technology platform that offers an open-source software-based implementation of the LTE system spanning the full protocol stack of 3GPP standard both in E-UTRAN and EPC [7].

The default software radio frontend for OAI is ExpressMIMO2 PCI Express (PCIe) board, Figure 2. It consists of 4 parallel RF chains with up to 20 MHz bandwidth (4x5 MHz, 2x10 MHz, 1x20 MHz) in the range of 250-3800 MHz, while the RF equipment can be configured for both TDD or FDD operation. The LMS6002D is a fully integrated, multi-band, multi-standard RF transceiver for ExpressMIMO2. To enable full duplex operation, the LMS6002D contains two separate synthesizers (TXPLL, RXPLL) both driven from the same reference clock source PLLCLK, since this type of transceiver was initially designed to operate on FDD mode. In TDD mode, the LMS6002D transceiver alternatively turns on and off the PLLs for Tx and Rx, resulting in a random phase modulation independently for each RF chain each time the transciever is switched from TX to RX or vice versa. This makes it impossible to perform Multiple Input Multiple Output (MIMO) precoding, since the RF chains are no longer phase synchronized. However, we can deal with this issue by setting the card to FDD mode with the TX and RX frequencies shifted slightly to avoid interfering inter-modulation products, and then shifting the signal back in the digital domain. We choose to shift the TX frequency by $\frac{1}{4}f_s$ wrt the RX frequency, where f_s is the sampling frequency.

The measurements were carried out inside a controlled laboratory environment. Figure 3 represents the measurement setup. Two ExpressMIMO2 boards acting as node A and one acting as node B were connected with cables for both time and frequency synchronization. The antennas used at node A are the prototype shown in Figure 4. This prototype is designed by the team in Orange labs. Emerging technologies such as 3D printing [5] and plastronic, offering new degrees of freedom and more flexibility, are used. The antennas are printed directly on the side of a plastic box made by polycarbonate using Laser Direct Structuring (LDS) [6]. This method is highly promising for optimizing the volume in small devices such as femtocells. The prototype is of a plastronic gateway with 8 dual-band antennas (2.5GHz & 5GHz) for Wi-Fi and LTE technologies. Four out of the eight antennas from the prototype are connected to card 0 and the rest are connected to card 1. To card 2 we have connected a single antenna which was attached upon the rail. We have used two different types of antennas for this purpose:

- An LTE magnet foot antenna-SMAm.
- A smartphone-like antenna [4].

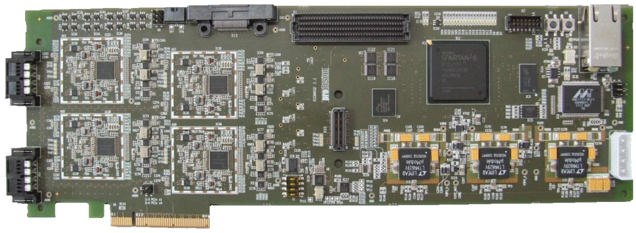

Fig. 2: ExpressMIMO2 Board

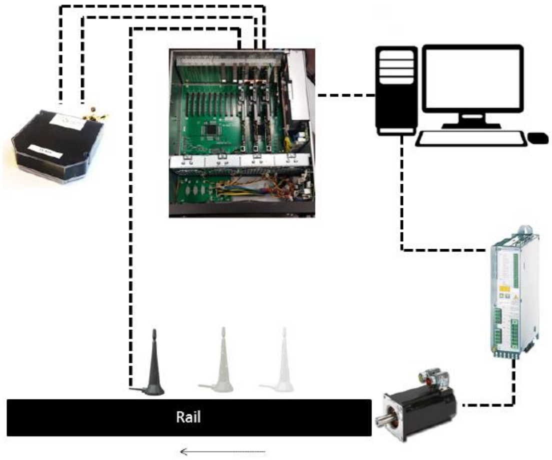

Fig. 3: Measurement Setup

V. Experimental Results

The experiments were carried out using LTE-like OFDM frames. Each OFDM symbol consists of 512 carriers, out of which 300 are filled with random QPSK symbols and the rest are set to zero. An extended cyclic prefix (ECP) of 128 samples is added to each OFDM symbol after the 512-point Inverse Fast Fourier Transform (IFFT). The sampling rate is 7.68MSPS, resulting in an effective bandwidth of 4.5MHz. Ten subframes each with 12 ECP-OFDM symbols compose the TDD OFDM frame. When one antenna of node A is on transmission, other antennas of the same side keep silent so that orthogonality in the time domain is achieved. The carrier frequency is 2.68GHz and the transmission power is of around 10dBm. Both transmit and receive gains on all the RF chains are set to 15dB.

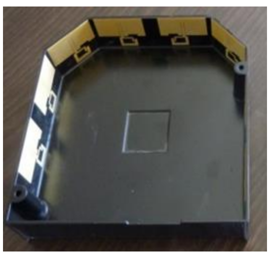

Fig. 4: Prototype

We perform the measurements for a 8x1 MISO system. Ten TDD ECP-OFDM frames are sent from node A to have a better estimation result of the diagonal elements in the calibration matrix $\boldsymbol{F}$. Therefore, we assume no RF chain crosstalk and the antenna mutual coupling effect is ignored. At the end of each bidirectional transmission we compute the diagonal $\boldsymbol{F}$ according to Eq.2 and we average.

A. Beamforming Performance

We compare the beamforming performance based on different CSIT acquisition methods. When the calibration matrix $\boldsymbol{F}$ is obtained, it can be used in the transmission. Hence, we estimate the relative DL CSI by using only UL pilots and $\boldsymbol{F}$, Eq.2, without any feedback. Thus, we can use relative downlink channel estimation to calculate the beam weights and then send the beamformed data. Let us consider the signal received by B as:

$$y = \boldsymbol{g}^T \boldsymbol{s} + n \tag{5}$$

We adopt the conjugate beamforming which consists in using the conjugate-transpose of the relative channel estimates as a linear precoder on the forward link. Thus, the precoded transmitted symbol $\boldsymbol{s}$ is given by:

$$\boldsymbol{s} = \frac{(\hat{\boldsymbol{g}}^T)^H}{\|\hat{\boldsymbol{g}}\|} x = \frac{\hat{\boldsymbol{g}}^*}{\|\hat{\boldsymbol{g}}\|} x \tag{6}$$

We compare the beamforming SNR noted by γ under 3 different assumptions.

- Ideal
  We assume node A knows $\hat{\boldsymbol{g}}$ measured by node B. The beamforming SNR is given by:
  $$\gamma_{ideal} = \frac{\|\boldsymbol{g}^T \hat{\boldsymbol{g}}^*\|^2}{\|\hat{\boldsymbol{g}}\|^2} \frac{\sigma_x^2}{\sigma_n^2} \tag{7}$$
- No calibration
  Under this assumption, the transceiver hardware is considered totally reciprocal and $\boldsymbol{h}$ is considered to be equal to $\boldsymbol{g}$, thus no calibration is needed. The SNR is:
  $$\gamma_{no\,calib} = \frac{\|\boldsymbol{g}^T \hat{\boldsymbol{h}}^*\|^2}{\|\hat{\boldsymbol{h}}\|^2} \frac{\sigma_x^2}{\sigma_n^2} \tag{8}$$
- Diagonal $\boldsymbol{F}$ estimation
  The RF chain crosstalk and the antenna mutual coupling are ignored and the calibration matrix is assumed to be diagonal, noted by $\hat{\boldsymbol{F}}$. The beamformming SNR is:
  $$\gamma_{diag} = \frac{\|\boldsymbol{g}^T (\hat{\boldsymbol{h}}^T \hat{\boldsymbol{F}})^H\|^2}{\|\hat{\boldsymbol{h}}^T \hat{\boldsymbol{F}}\|^2} \frac{\sigma_x^2}{\sigma_n^2} \tag{9}$$

We compare the 3 different beamforming SNRs shown above with the the average received SNR over all the transmit antennas.

$$\gamma_{SISO,mean} = \frac{\sum |\hat{\boldsymbol{g}}_i^*|^2}{N} \frac{\sigma_x^2}{\sigma_n^2} = \frac{\|\hat{\boldsymbol{g}}^*\|^2}{N} \frac{\sigma_x^2}{\sigma_n^2} \tag{10}$$

Node A transmits ten TDD ECP-OFDM frames after conjugate precoding under these three assumptions. We then average

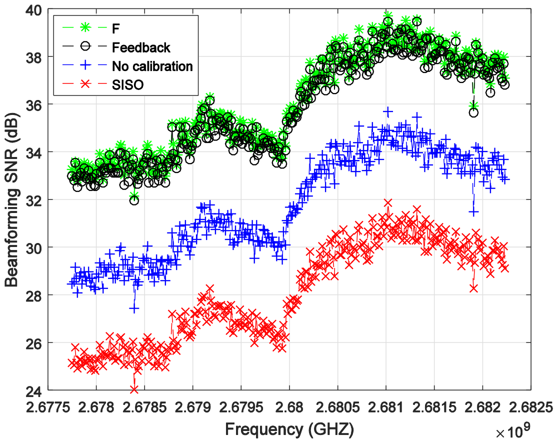

Fig. 5: Beamforming SNRs (mean SISO)

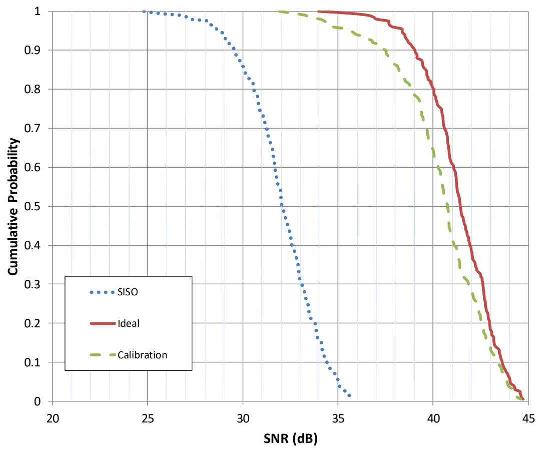

Fig. 6: CDF of SNR (magnetic Rx)

the measured SNR and compare with that of a SISO system, where only one RF chain in node A is activated, thus obtain the beamforming SNRs as illustrated in Figure 5. We observe that the beamforming SNR of the diagonal estimation is very similar to that of the ideal case, being around 34dB, which means that the channel reciprocity is fully achieved using relative calibration and ignoring the off-diagonal elements in $\boldsymbol{F}$ is reasonable in a small-scale MISO system. Also, we notice that when no calibration is used, there is some beamforming performance degradation. Afterwards, we implement another experiment where we:

- Move the receive antenna to the middle of the rail.
- Execute the calibration phase and save the calibration matrix.
- Move the receive antenna to the start position (one of the 2 edges) and begin the transmission phase which is repeated for 200 positions.
- For each position compute the beamforming SNR under the ideal and the diagonal $\boldsymbol{F}$ estimation assumptions.
- Average spatially and obtain the final beamforming SNR values.
- Compute the cdf by averaging the received SNR over the 300 subcarriers.

Figures 6 and 7 illustrate the beamforming SNR from the magnet foot antenna and the smartphone one, respectively. The total transmit power is fixed for both SISO and MISO cases. As we can see the expected beamforming gain of 9dB[1] compared to its corresponding SISO case is achieved. We observe a degradation in the performance of the system when the smartphone antenna acts as node B. This happens due to lower efficiency and gain of the smartphone antenna. Also, the omnidirectional radiation pattern of the magnetic antenna matches better to this measurement setup. However, the deviation between the two curves representing the beamforming

[1]In a NxM MIMO system the array gain is 10*log(M) dB on receive side and 10*log(N) dB on transmit side if transmit channel is known.

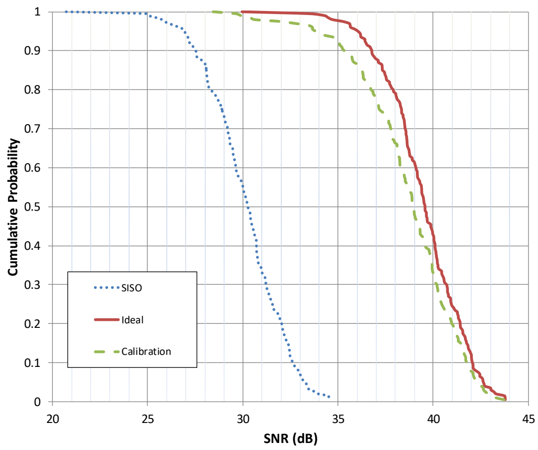

Fig. 7: CDF of SNR (Smartphone Rx)

SNR under the ideal assumption and the diagonal $\boldsymbol{F}$ estimation one for both receive antennas is the same meaning that our calibration method works perfectly regardless the different radiation patterns and gains.

B. Adaptive Beamforming

Beamforming is the method used to create the radiation pattern of the antenna array by adding constructively the phases of the signals in the direction of the mobiles desired. Geometric corrections are easy, but instrumental corrections must be found. Beamforming can severely degrade in the presence of some signal steering vector errors. These errors can be caused by a number of reasons such as array calibration imperfections, non-linearities in amplifiers, A/D converters and other hardware. All the measures that have to be taken to protect against the aforementioned imperfections require extra signal processing time and more power consumption. Thus, we decided to check if by selecting two or four out of the eight antennas existing in a prototype, we could get similar

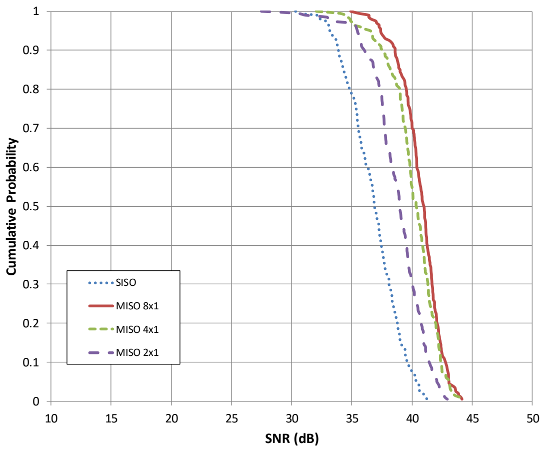

Fig. 8: Beamforming SNRs (adaptive scheme)

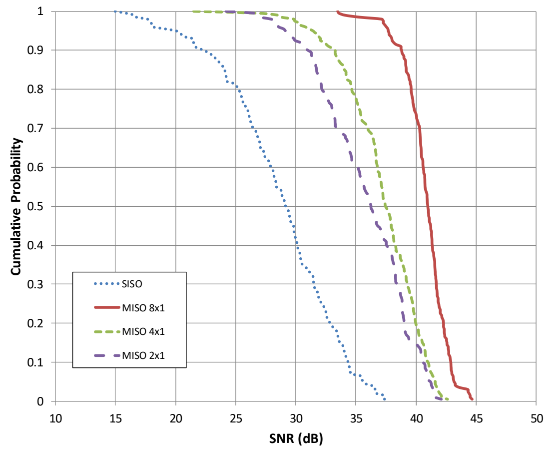

Fig. 9: Beamforming SNRs (fixed scheme)

beamforming gains. Such that, if the circumstances allow it, in terms of coverage, we may decrease the number of antennas used for transmission to a single user.

The measurement setup is the same as the one shown in Figure 3. The prototype with the antennas printed on the side of the box acts as node A and the simple magnet foot antenna acts as node B. We performed beamforming techniques using the diagonal $\boldsymbol{F}$ estimation for 200 different positions of the single receive antenna under two different scenarios:

1) *Adaptive antenna selection*. Having performed 8 SISO transmissions for each antenna element on the prototype and having measured the received SNR at node B for each SISO case, we form a vector in descending order from the identities of the antennas having the strongest signal to the antennas providing low SNR performance. Node A acquires this information through reciprocity channel and uses it to perform beamforming using the 2 or 4 high-performance antennas.
2) *Fixed antenna selection*. In this scenario we pick each time the front 2 or 4 elements from the antenna array.

The results we get after the implementation of those two scenarios are illustrated in Figure 8 and Figure 9. We observe that by selecting two or four "best" antennas we get quite similar beamforming gains compared to transmitting from all the available antennas. So, we can exploit it to save power and signal processing resources.

VI. Conclusion

In this paper, we studied the beamforming performance under different CSIT acquisition methods for a 8x1 MISO system. Our experimental results prove that the relative calibration method works in a real environment and over a long time period. Finally, we implemented an antenna selection scheme at the transmit side as a low-cost low-complexity alternative to capture many of the advantages of multi-antenna systems.

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