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Can Multi-User MIMO Measurements Be Done Using a Single Channel Sounder?

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Abstract

In this paper, we consider the question whether mobile multi-user MIMO measurements can be emulated by sequentially measuring each point-to-point link with a single channel sounder. The crucial aspect of this approach is whether it is practically feasible to keep the environment sufficiently static between sequential measurement runs.

We investigate this aspect in the context of an outdoor-to-indoor MIMO channel measurement campaign. To quantify the degree to which the surroundings can be kept static between sequential measurements, we focus on measurement *repeatability.* We performed the same fixed-outdoor to mobile-indoor measurement several times, and then compared the outcomes for different runs. As measures of similarity, we employ the collinearity between channel matrices, collinearity between spatial correlation matrices, and relative condition numbers.

Our measurements showed that the similarity regarding the channel matrices is quite high. The results also indicates a strong dependence on the accuracy of the positioning of the measurement equipment and on the exact position of the channel sampling. In terms of channel correlation matrices, we find that the similarity of the correlations at the MS is quite good, and the similarity of the correlations at the BS is very high, which leads to a sufficient similarity of the full correlation matrix.

Therefore, the best answer to the question in the title is as so often, “it depends”. Our results indicate that the single channel-sounder approach is definitely feasible when the focus is on channel statistics, i.e. the spatial correlation matrices. When channel matrices are of interest, the approach is only applicable to a limited degree.

1 Introduction

Ever since MIMO made its way into standards and commercial wireless communications products [1, 2] due their ability to increase capacity/throughput, the number of multi-antenna terminals is constantly increasing. This implies that wireless networks that employ MIMO technology will become more and more crowded, leading to higher levels of interference between terminals. Fortunately, MIMO allows for spatial interference mitigation techniques, i.e. the interfering signals can be (spatially) distinguished from the signals of interest. In order to investigate whether the channels are spatially separable, multi-user MIMO measurements are inevitable.

In multi-user (MU) MIMO sounding experiments we wish to simultaneously observe the channel from a single base station (BS) to multiple mobile stations (MS), to subsequently test multi-user coding, beamforming techniques, or space-time algorithms.

To date only a very limited number of *multi-user* MIMO measurements were undertaken to investigate real interference channels[1]. These measurements were carried out with a huge effort by using two (almost incompatible) channel sounders, which made the evaluation of the data even more

[1]All of that work is performed in the WILATI project [3].

cumbersome. However, the method using two separate sounders, resulted in the highest accuracy of measuring the characteristics of a two-user (i.e. multi-user) MIMO channel.

In our approach where only a *single channel sounder* is used, we can observe the channel from a BS to the individual MSs, at different times for different users (or locations). Subsequently, we combine these measurements as if the data from different MSs were obtained simultaneously. This concept is valid if all the BS-MS channels are completely time *in*variant. In general, this condition will not be met, since scatterers are not likely to be time invariant (e.g. because of wind and foliage movement, moving traffic, etc.).

Contribution Since already the availability of a single channel sounder is an expensive issue (let alone two of them), we validate the approach of using a single channel sounder while performing the measurements sequentially. For that we took outdoor-to-indoor measurements, where we *tried to keep the environment as invariant as possible*. During these measurements, the (indoor) receiver was moved along well-defined routes, representing the MS. Some of these routes were measured multiple times. A high similarity between the first and the second run of the measured route indicates that the *environment* is time invariant, and thus that the single-sounder approach is indeed feasible.

Organization Section 2 presents the measurements that we used for the evaluations. The similarity measures are summarized in Section 3. Section 4 discusses the results from applying the similarity measures to the data. Finally, Section 5 presents our conclusions.

2 Measurements

In this paper we used the measurements from the Stanford July 2008 Measurement Campaign [4].

2.1 Equipment

We used the RUSK Stanford channel sounder, which performs MIMO measurements based on the "switched array" principle. The transmitter sends a chirp-like signal to sound the channel, which is eventually recorded at the receiver unit. By post-processing the measured data we obtain the complex channel transfer function $\mathbf{H}(t, f)$.

The measurements were taken at a center frequency of 2.45 GHz with a bandwidth of 240 MHz, and a test signal length of 3.2 μs. Since we experienced occasional interference from WiFi equipments and microwave ovens, we decided to concentrate on the lowest 70 MHz of the measured spectrum in this evaluation, i.e. the band from 2.33 to 2.40 GHz.

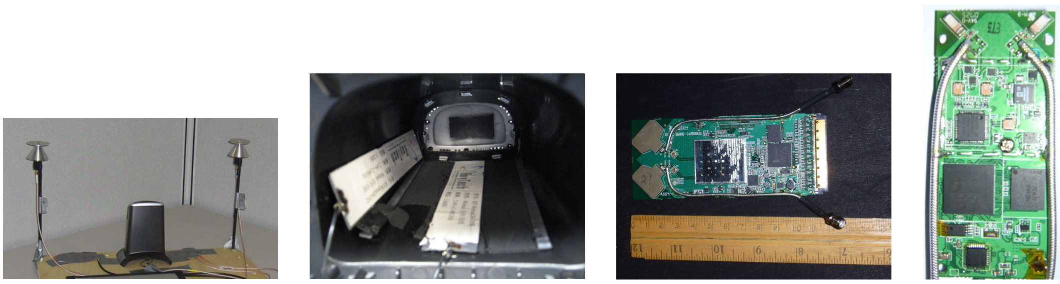
The transmitter output power was 0.5 W. A rubidium reference clock in the two units ensured accurate timing and clock synchronization.

In this campaign, we strived to measure routes multiple times, keeping the same route with very high accuracy. For this reason, we used a distance measuring wheel providing a trigger signal every 1.6 cm ($\pm 2\%$) to the sounder. So, the channel transfer function can also be formulated as a function of distance, $\mathbf{H}(d, f)$, where d is a multiple of 1.6 cm.

For the outside location, two dual-polarized WiMAX base station antennas were mounted on a scissor lift raised to a height of 10 m (see Figure 1a). The antennas were connected by long low-loss RF cables to the transmitter on the ground. Indoors, we mounted four different types of antenna arrays onto the receiver unit (see Figure 1b): (i) two omni-directional Discone antennas with a spacing of 4.6 wavelengths (Figure 2a), (ii) two patch antennas in a WiMAX customer premises equipment (CPE, see Figure 2b), (iii) an array of two planar inverted F antennas on a PC card (Figure 2c), and (iv) an array of two ceramic antennas on a USB dongle (Figure 2d).

(a) (b)

Figure 1: (a) Base station antennas at the transmitter lifted to 10m, (b) Receive arrays used for the O2I moving measurements



(a) (b) (c) (d)

Figure 2: Antennas used for the outdoor-to-indoor mobile measurements: (a) Discones and CPE mounted on the wooden board, (b) inside-view of the CPE array: two patches with orthogonally oriented main lobes, (c) broadband WiMAX PC-card antenna array, (d) narrowband WiMAX antenna array with ceramic elements

Figure 3: Outdoor measurement map (Picture: © Google Maps)

2.2 Environment

We conducted the measurements in an outdoor-to-indoor BS-to-MS environment. To validate our single-sounder approach for measuring the MU MIMO channel, we had to ensure that the environment was as invariant as possible. Two BS positions were used in the measurements, and at each position the BS was rotated in three different directions (see Figure 3). The indoor environment is a cubicle-style office environment in Santa Clara, California. For the indoor measurements we used 5 routes going along the cubicles (see Figure 4). These five routes were measured for every base station position and orientation. A few routes were even measured multiple times with the same BS configuration. We will use one of these latter measurements to discuss the applicability of using a single sounder for multi-user measurements.

To ensure comparable measurements the following precautions were taken:

- The measurement routes were marked on the floor by duct tape. The sounder was pushed along the taped route as accurately as possible.

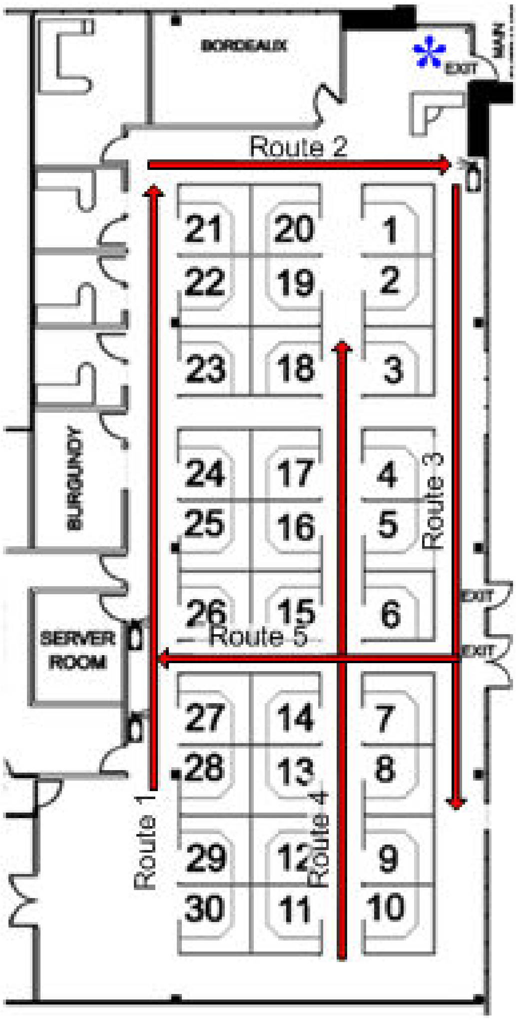


Figure 4: Indoor route map. The blue asterisk indicates the corresponding corner of the office environment in the outdoor map.

- For each specific route, all people indoors helping in the measurements stayed at the same position in the room for all different BS configurations. This was done to ensure that the radio environment was as similar as possible.

For the evaluations in this paper we chose a number of routes that were measured twice. The routes are denoted as TxpDd-Rr, where p is the transmitter position, d the transmitter direction, and r the route number, e.g. Tx1D2-R3 denotes the measurement of Route 3 (see Figure 4) with the transmitter at position 1 facing into direction 2 (see Figure 3).

3 Channel similarity measures

We concentrate on two kinds of similarity measures: (i) similarity of the channel matrices, (ii) similarity of the spatial correlation matrices (at BS, MS, and full correlation matrix)[2].

Since we are interested in the applicability of sequential channel measurements for the design and testing of MU coding, or other space-time algorithms, the similarity metrics should compare the singular value structure of two matrices. Taking this into account, we quantify similarity in two ways: by the collinearity between matrices, and by the condition number of matrices.

3.1 Matrix collinearity

The distance between two matrices of same dimensions can be quantified by the collinearity given by [5]

$$c(\mathbf{A},\mathbf{B}) = \frac{|\mathrm{tr}(\mathbf{A}\mathbf{B}^{\mathrm{H}})|}{\|\mathbf{A}\|_{\mathrm{F}}\|\mathbf{B}\|_{\mathrm{F}}}, \tag{1}$$

where $\mathbf{A}$ and $\mathbf{B}$ are the (complex-valued) matrices to be compared, $\|\cdot\|_{\mathrm{F}}$ denotes the Frobenius norm of a matrix, and $(\cdot)^{\mathrm{H}}$ is the matrix conjugate transpose operation. A helpful interpretation of this measure comes from the fact that it is a normalized inner product, and thus has a geometric meaning. For example, if $\mathbf{A}$ and $\mathbf{B}$ are real-valued, then $c(\mathbf{A},\mathbf{B}) = |\cos\angle\left(\mathrm{vec}(\mathbf{A}),\mathrm{vec}(\mathbf{B})\right)|$, where $\mathrm{vec}(\cdot)$ stacks the columns of its matrix argument on top of each other.

In general, the collinearity measure describes how similar the subspaces of the compared matrices are. This measure ranges between zero (no collinearity, i.e. matrices are orthogonal to each other) and one (full collinearity, matrices are similar).

The beauty of this measure is that it compares both the singular values and the subspaces of the matrices. A full collinearity is encountered when (i) *both* singular values and their associated singular vectors of the two matrices are equal (i.e. the matrices are exactly equal), or (ii) when both matrices individually have singular values that are all equal (in this case the singular vectors are inconsequential). This measure is invariant against fading or path loss as long as the multipath structure remains the same, i.e. $c(\mathbf{A},\beta\mathbf{B}) = c(\mathbf{A},\mathbf{B})$, and $c(\mathbf{A},\beta\mathbf{A}) = 1$ for any $\beta \neq 0$.

Note that the Correlation Matrix Distance, introduced in [6] is a special case of this measure, but is only applicable to Hermitian matrices (in the authors' case: correlation matrices). Nevertheless, the basic idea between these measures is the same. Hence, the conclusion in [6], stating that this measure is directly correlated to the performance of MIMO precoding schemes, remains valid.

[2] Note that another notion of channel similarity can be defined in terms of the multipath structure (i.e. similarity of the double-directional power spectrum), however, our antenna configuration does not allow for directional evaluations.

3.2 Condition number ratio

As second measure for similarity we compare the matrix condition numbers as

$$\chi(\mathbf{A}, \mathbf{B}) = 10 \cdot \log_{10} \left(\frac{\lambda_{\max}(\mathbf{A})}{\lambda_{\min}(\mathbf{A})} \Big/ \frac{\lambda_{\max}(\mathbf{B})}{\lambda_{\min}(\mathbf{B})} \right), \tag{2}$$

where $\lambda_{\max}(\mathbf{A})$ denotes the largest singular value of the matrix $\mathbf{A}$.

In this measure, the similarity between the condition numbers is indicated by a value of 0 dB, while other values (positive and negative) describe a mismatch of the condition number ratio in dB.

4 Results

To assess whether the single-sounder approach is feasible, we compare two data sets, collected from two measurements of the same environment. For the antennas, we used all four ports at the base station antennas (two antennas times two polarizations), and the Discone antennas at the receiver because of their omnidirectionality. However, our results look similar for all other combinations. For comparison purpose, we used the similarity measures both on the spatial correlation matrices and directly on the channel matrices.

4.1 Comparing spatial correlation matrices

We distinguish between the spatial correlation at the receiver, $\mathbf{R}_{\mathrm{Rx}} = \mathrm{E}\{\mathbf{H}\mathbf{H}^{\mathrm{H}}\}$, the spatial correlation at the transmitter, $\mathbf{R}_{\mathrm{Tx}} = \mathrm{E}\{(\mathbf{H}^{\mathrm{T}})(\mathbf{H}^{\mathrm{T}})^{\mathrm{H}}\}$, and the full correlation matrix, $\mathbf{R}_{\mathrm{full}} = \mathrm{E}\{\mathrm{vec}(\mathbf{H})\mathrm{vec}(\mathbf{H})^{\mathrm{H}}\}$, where the vec($\cdot$) operation stacks the columns of a matrix into a vector. By doing so, we can distinguish between the changes of the environment at the transmitter and at the receiver, separately, as well as quantify the changes of the joint correlation[3]. Using the spatial correlation matrices for comparison, we test whether the local propagation characteristics match. We obtained the correlation matrices from the measurements by replacing the expected values above by averages in time, space, and frequency, namely over a sliding window of 5 wavelengths (equal to 38 snapshots) and over all frequency samples in the interference-free band.

Figure 5 quantifies the similarity of the correlation matrices for four different environments, using the collinearity measure. We observe the following three trends:

1. The collinearity of the transmit correlation matrices is almost always above 0.98. This indicates that the characteristics at the transmitter are maintained with very high accuracy. This is because the outdoor BS transmitter stayed in the same position and the environment around it did not change significantly during the different runs of the measurement route.

2. The collinearity of the receive correlation matrices is sensitive to changes in the environment, but it is mostly above 0.9, which still represents a very good match of the scattering environment around the receiver. This comes as a pleasant surprise, since the rich indoor scattering together with the moving MS leads to a strongly changing channel. However, this does not seem to impair the close match between the two sequential measurements.

3. Note that in the case of the collinearity of the full correlation matrix we are comparing much larger matrices, therefore we would expect a worse matching from the two runs. By taking this into account and observing that in some routes, we obtain collinearity values mostly above 0.9 we can conclude that we can yet quite accurately capture the full correlation characteristics of the channel. However, the results also show that the collinearity of the full correlation matrix

[3]Note that we do *not* assume the Kronecker model, here.

is more susceptible to environment changes. Since the the full correlation matrix depends on the double-directional characteristics of the propagation environment, these may not be always fully similar.

Using the condition number ratio of the full correlation matrices (see Figure 6), we find that the outcome is somewhat correlated with the collinearity results. For condition number differences close to zero, we usually observe strong collinearity. However, the collinearity metric is more sensitive to environment changes.

4.2 Comparing channel matrices

Finally, we use the collinearity metric directly on the measured channel matrices. For the following results, we present the channel collinearity *averaged* over all frequency bins. Here, we evaluated the collinearity of two runs on the same measurement route. To demonstrate the strong impact of the position accuracy of the measurements, we compared the two runs with a certain shift, i.e. we evaluated $c(\mathbf{H}(d), \mathbf{H}(d + \Delta d))$, with Δd being an integer multiple of 1.6 cm.

Figure 7 shows the results of this evaluation. The data highlighted by the ellipse emphasizes the area of interest: Obviously, the evaluation depends very strongly on the exact starting position and on the accuracy of the spatial sampling of the channels. Already small shifts of a tenth of a wavelength result in a deterioration of the channel matrix similarity. At shifts of a quarter wavelength, the similarity is almost gone.

The collinearity in the first part (0 m to 5 m) is changing strongly, which we could attribute to a non-ideal matching of the exact position of the route together with a strong line of sight component.

5 Conclusion

We presented an approach to measure multi-user channels subsequently using a single channel sounder. To assess the accuracy of this measurement technique, we compared the channels of multiple runs of the same measurement route, using matrix-based distance measures.

Our results indicate:

- The *environment must be kept as invariant as possible*. In our outdoor-to-indoor measurements, this property was easy to ensure around the elevated outdoor base station, but also achievable indoors by taking a number of precautions.
- Hoping to measure exactly the same channel matrices in multiple measurement runs is futile since already offsets of the measurement equipment of a tenth of a wavelength lead to a deterioration in the channel similarity. However, when all measures are taken to keep the scenario (almost) identical between the measurement runs (e.g., use fixed rails to move the measurement equipment along the same path each time), one is able to measure similar channels.
- For channel correlation matrices, we distinguished between the transmit correlation, the receive correlation, and the full correlation. In our measurements, the transmit correlation was almost matched exactly, which is due to the stationarity of the outdoor scenario. The receive correlation matrix showed quite good similarity, it differed only few times. The full correlation matrix was more difficult to capture, which might indeed be due to a slightly changing scenario and larger size of the matrix.

From this we conclude that the single-sounder approach is definitely feasible when one is interested in the general trends and statistics of the multi-user MIMO channel.

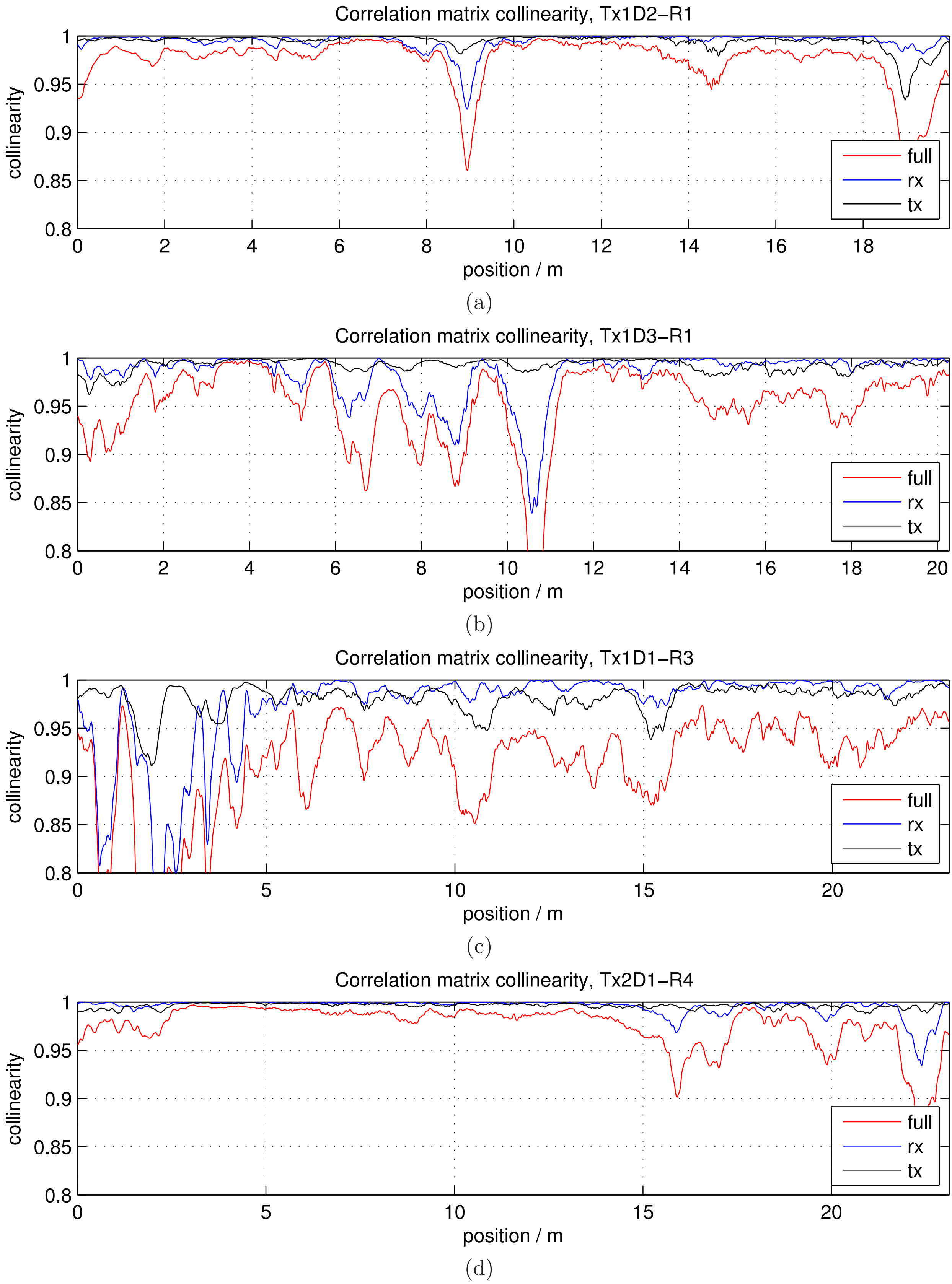


Figure 5: Collinearity of correlation matrices for four different combinations of transmitter positions and routes.

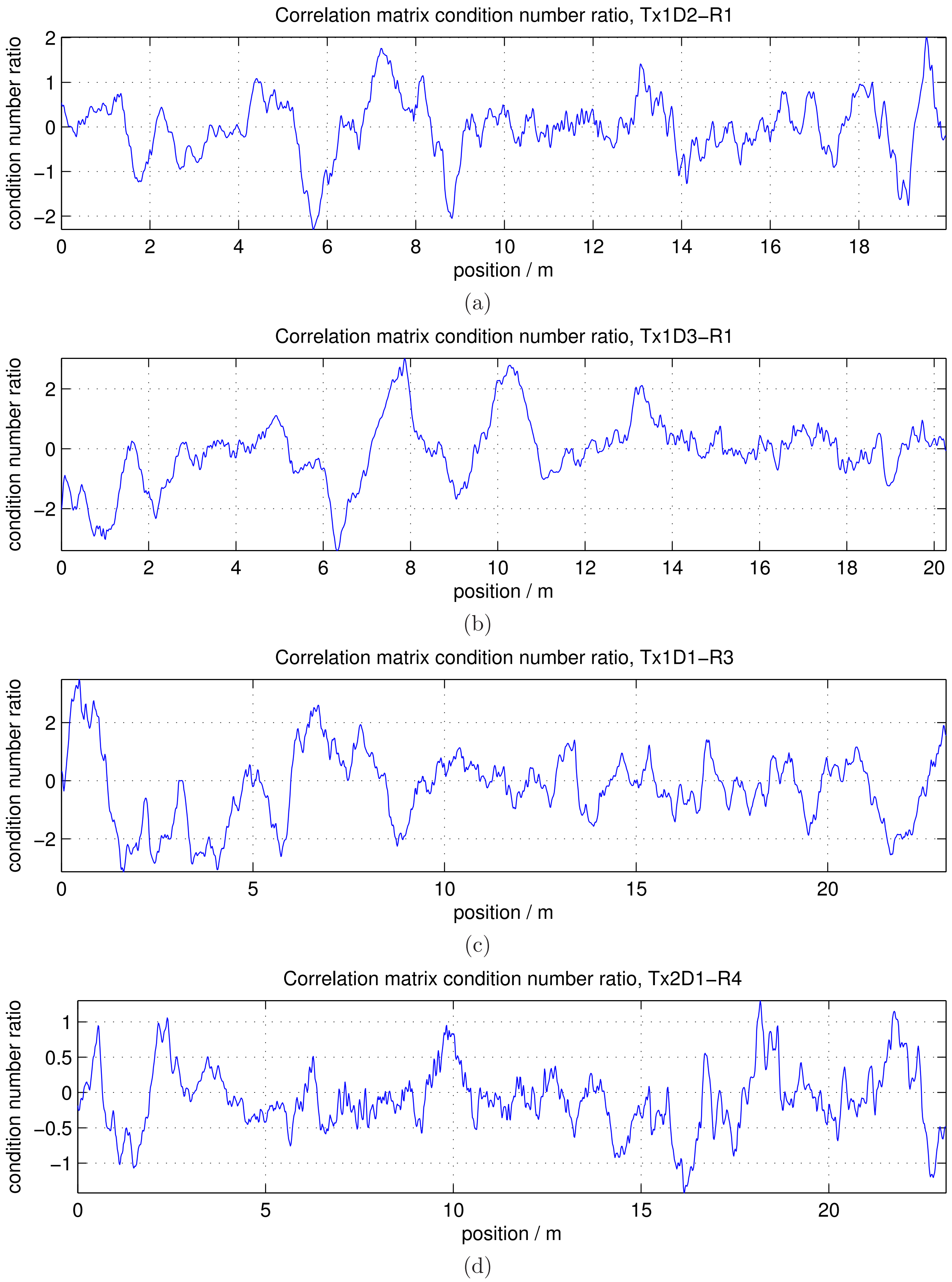


Figure 6: Condition number ratio of the full correlation matrices for four different combinations of transmitter positions and routes.

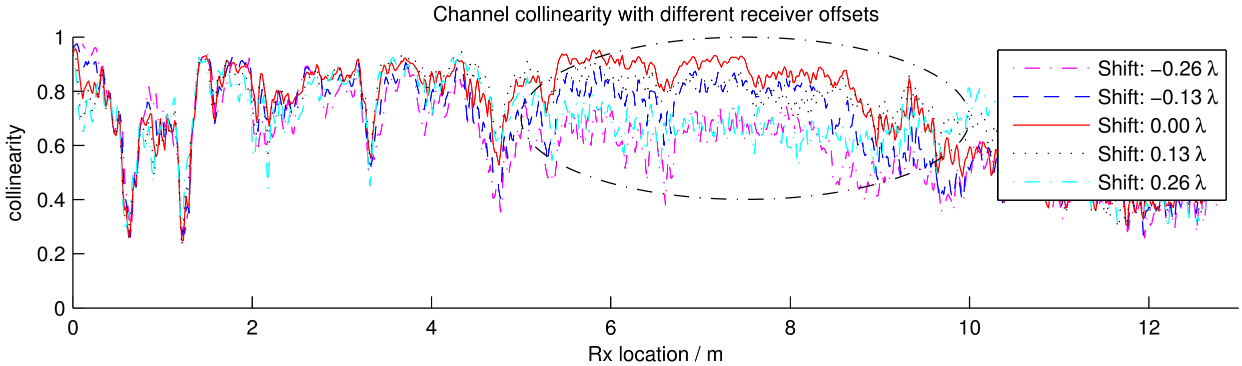


Figure 7: Collinearity of channel matrices of measurement Tx1D1-R3, when the two measured routes show a small position offset.

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