# Non-stationarity Characterization for Vehicle-to-vehicle Channels Using Correlation Matrix Distance and Shadow Fading Correlation

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**Abstract**— Vehicle-to-Vehicle (V2V) radio channels have been considered as non-stationary due to the dynamic scatterers in V2V environments. To characterize its stationarity is of great importance as it determines the time-variant V2V channel statistics. Therefore, we analyze the non-stationarity of V2V radio channels using two metrics: the correlation matrix distance (CMD) and the shadow fading correlation. The analysis is based on the measurements conducted in a suburban area of Finland at 5.3 GHz. We use the Aalto channel sounder and a $30 \times 4$ MIMO system. The power delay profile (PDP), CMD, and shadowing are estimated from the measured channel impulse responses. The equivalent stationarity distance is found to be around 6 m, and it is observed that regions with large delay spreads correspond to smaller stationarity regions. The shadow fading auto-correlation coefficient is found to follow an exponential decay model and the decorrelation distance is considered as the shadowing-based equivalent stationarity distance. Based on the comparison of the equivalent stationarity distances estimated by the two metrics, it is found that the CMD metric is more sensitive to the changes of direction-of-arrival/departure, whereas the shadowing metric takes only into account the power variations over time. We also note that the estimation of shadowing metric is close to the results from CMD. This shows that the shadow correlation can also be used to characterize the non-stationarity of radio channels.

## 1. INTRODUCTION

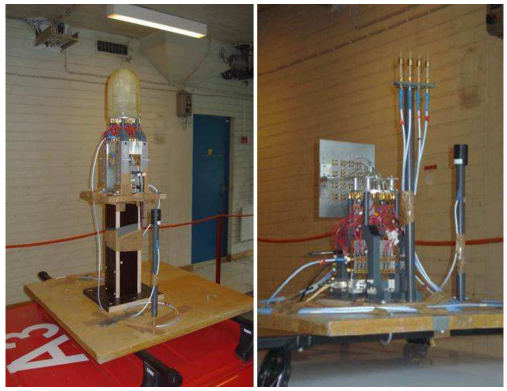
Vehicle-to-vehicle (V2V) communication networks will potentially improve the efficiency and safety of Intelligent Transportation Systems (ITS). Since ITS applications imply strict packet delay constraints, a dependable connectivity is crucial. Accurate V2V radio channel models are therefore required. Owing to the rapidly changing environment when both link ends move, vehicular radio channels have been found to be non-stationary. Characterizing the non-stationary is therefore important for V2V channel modeling.

A number of papers have already investigated the non-stationarity of V2V channels. In [1] and [2], the correlation matrix distance (CMD) was employed to characterize the non-stationarity of V2V MIMO channels. In [3], the spectral divergence was used to analyze the non-stationarity of vehicular channels, and in [4], the complexity of spectral divergence was investigated based on V2V measurements.

A more traditional measure of the changes in channel statistics is the shadow fading correlation [5], which was so far not considered for V2V channels. Shadowing represents the variability of the received power around its expected value. The spatial autocorrelation function of shadowing is a measure of how fast the local shadowing evolves as the two mobile terminals (i.e., V2V) move along a certain route: the decorrelation distance of shadowing dictates how rapidly the environment changes, and can thus be considered as an equivalent stationarity distance.

Summarizing, the existing works have several limitations. In particular, a comparison of the stationarity evaluations from the CMD and shadowing correlation is currently lacking. It is still unclear whether the two metrics lead to similar evaluations or not. Therefore, we conduct the V2V channel measurements in suburban environments and introduce a shadowing-correlation based stationarity distance to characterize the non-stationarity of V2V channels. The estimated stationarity distances using the two metrics are compared.

The remainder of the paper is organized as follows. Section 2 shows the measurement campaign. Section 3 introduces the two metrics to investigate the non-stationarity of channels. Section 4 presents the results. Finally, Section 5 concludes the paper.



(a) (b)

Figure 1: Antenna arrays. (a) Semi-spherical antenna array of Rx. (b) Uniform linear array of Tx.

## 2. MEASUREMENTS

The Aalto channel sounder [6], which is based on the switched-array principle, was used in the measurements. The measurements were conducted at 5.3 GHz, with a bandwidth of 60 MHz. The snapshot time (i.e., the time required to measure all antenna pair channels) was set at 1.632 ms, whereas the snapshot repetition rate was set at 66.7 Hz. The transmit power was 36 dBm. A dual-polarized semi-spherical antenna array was used at the receive (Rx) side. The antenna arrays consist of 15 dual-polarized (horizontal and vertical) elements (i.e., 30 feeds), which are arranged in a spherical geometry. A Uniform Linear Array (ULA) with 4 vertically polarized antenna elements was used at the transmit (Tx) side. The antenna arrays are shown in Fig. 1. In the measurements, the Tx car was always traveling ahead of the Rx car. We thus cluster the antenna elements at Rx by defining the "front" and "back" elements. The "front" case has pure line-of-sight (LOS), whereas the LOS path is blocked by the Rx array for the "back" case (since these elements are hidden from the Tx side, owing to the geometry of the Rx antenna array). This grouping enables us to evaluate the impacts of different array configurations on the channel stationarity.

The measurement campaign was conducted in suburban (Tapiola) area, which mostly consist of small detached houses, parking lots, and an average tree density of roughly 5 m high. There are large sidewalks and road signs sparsely distributed on both sides of the two-lane road. In the measurements the cars were driving in the same direction (convoy), mainly under LOS conditions. 6800 snapshots were recorded. The inter-vehicle distance varied between 10 and 500 m, due to the medium traffic conditions.

## 3. METRICS

We use two metrics to analyze the stationarity: CMD and shadowing correlation. The CMD between the two correlation matrices $\mathbf{R}(it_{\text{rep}})$ and $\mathbf{R}(jt_{\text{rep}})$ measured at times $it_{\text{rep}}$ and $jt_{\text{rep}}$ is defined by

$$d_{\text{corr}}(i,j) = 1 - \frac{\text{tr}\left\{\mathbf{R}(it_{\text{rep}}) \cdot \mathbf{R}(jt_{\text{rep}})\right\}}{\left\|\mathbf{R}(it_{\text{rep}})\right\|_f \cdot \left\|\mathbf{R}(jt_{\text{rep}})\right\|_f}, \tag{1}$$

where $i$ and $j$ are the time indices, $t_{\text{rep}} = 15\,\text{ms}$ is the snapshot time interval and $\text{tr}\left\{\cdot\right\}$ and $\left\|\cdot\right\|_f$ denotes the trace and Frobenius norm of a matrix. The CMD is zero if the correlation matrices are equal up to a scaling factor and one if they are completely uncorrelated. In this paper, the CMD is computed with full channel correlation matrix, defined as

$$\mathbf{R}_{\text{Full}}(it_{\text{rep}}) = \frac{1}{W}\sum_{k=i}^{i+W-1} \text{vec}\left[\mathbf{G}(kt_{\text{rep}})\right] \cdot \text{vec}[\mathbf{G}(kt_{\text{rep}})]^{\text{H}} \;, \tag{2}$$

where $W$ is the averaging interval to remove the impact of the small-scale fading, $(\cdot)^{\text{H}}$ denotes hermitian transpose, and $\text{vec}\left[\cdot\right]$ operator stacks a matrix into a vector columnwise. The complex MIMO channel matrices $\mathbf{G}(kt_{\text{rep}})$ are obtained from the $N_{\text{Rx}} \times N_{\text{Tx}}$ impulse response matrices $\mathbf{H}(\tau, kt_{\text{rep}})$, as

$$\mathbf{G}(kt_{\text{rep}}) = \sum_{\tau} \mathbf{H}(\tau, kt_{\text{rep}}), \tag{3}$$

where $\tau$ denotes delay. $W$ was set to 54, which corresponds to a 40 wavelengths window at 5.3 GHz with an average speed of 10 km/h in the measurements.

For the shadowing metric, the auto-correlation coefficient of shadow fading is employed, expressed as

$$\rho(\Delta k t_{\mathrm{rep}}) = \left| \frac{E\left\{X(kt_{\mathrm{rep}})X(kt_{\mathrm{rep}} + \Delta k t_{\mathrm{rep}})\right\}}{\sigma} \right|, \quad (4)$$

where $E\{\cdot\}$ denotes the expected value of $\{\cdot\}$. $X(kt_{\mathrm{rep}})$ is the shadow fading component measured at time index $k$, and $\sigma$ is the standard deviation of shadow fading. The procedure for obtaining $X(kt_{\mathrm{rep}})$ is as follows: i) we first estimate the path gain $P_G(kt_{\mathrm{rep}})$ from the channel impulse response, averaged over Tx/Rx and the 40 wavelengths window; ii) then we use the delay of the LOS component in power delay profile (PDP) to estimate the Tx-Rx distance, and conduct least-square (LS) fit to get the distance-dependent path gain; iii) finally we remove the distance-dependent path gain out of the corresponding $P_G(kt_{\mathrm{rep}})$ to get $X(kt_{\mathrm{rep}})$. The decorrelation time, which depends on the scenario, is defined to be the time at which the auto-correlation coefficient drops to $1/e$. By multiplying it by the speed, we obtain the decorrelation distance, which is considered as the shadowing-based equivalent stationarity distance.

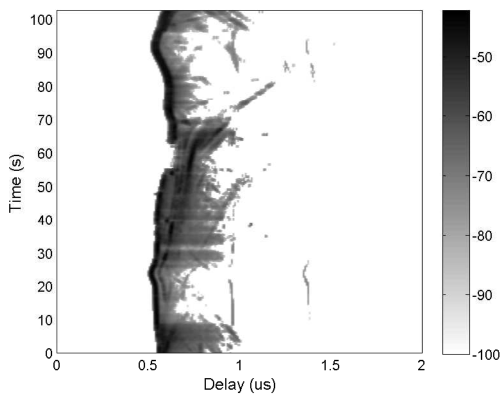



Figure 2: APDPs of the measurements in suburban.

## 4. RESULTS

The averaged PDPs (APDPs) (over the 40 wavelengths window) of the measurement route are presented in Fig. 2. We can see that in APDPs there are two regions (10–25 s and 70–95 s) with a small number of scattering components after the LOS component. These two regions correspond to the open areas in the beginning and the end of the route. For the other regions of APDPs, there are relatively rich scattering components after the LOS path, which are mostly caused by the surrounding large tree densities and heavy traffic conditions. For the two regions with few scattering components, the corresponding RMS delay spreads are very small with a mean value of 25.41 ns; while the mean value of the RMS delay spreads in other regions is 51.64 ns.

Figure 3 shows the plot of the estimated CMD between arbitrary times of the example route for the "front" case. It is observed that there are generally two stationarity regions in CMD plots, corresponding to the regions of 10–25 s and 70–95 s. This means that the region with a large delay spread corresponds to a reduced stationarity of channels. For the CMD, the time-variant stationarity time is defined as the maximum period over which the CMD remains below a certain threshold, and the stationarity distance is the product of the stationarity time and average speed. In our analysis, the threshold for CMD was set at 0.2, as suggested by [1] for V2V channels.

The estimated auto-correlation coefficient of shadowing is found to follow an exponential decay [5]

$$\rho(\Delta d) = \exp\left(-\frac{\Delta d}{d_{\mathrm{cor}}}\right), \quad (5)$$

where $\Delta d$ denotes the equivalent distance difference, and $d_{\mathrm{cor}}$ denotes the equivalent decorrelation distance (also the shadowing-based equivalent stationarity distance). Fig. 4 shows the estimated auto-correlation coefficient and the exponential decay model. It is found that Eq. (5) offers a good fit to the measurements.

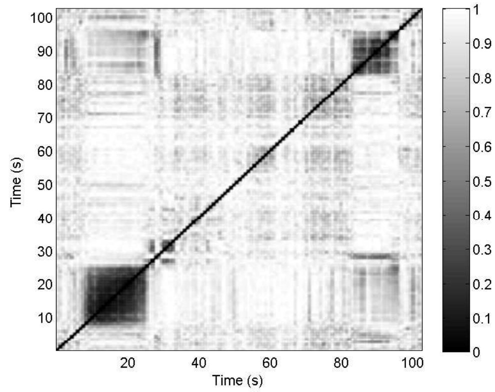



Figure 3: Estimated CMD for the "front" case in the measurements.

The results of CMD and shadowing correlation are summarized in Table 1. From the CMD metric we find that the "front" case has a larger stationarity distance than the "back" case. This is because the "front" array has a strong and stable LOS component that dominates the radio wave propagation. While for the "back" case, the broadside of most antenna elements points towards opposite direction to the Tx, and there is no LOS so that weaker components have more importance in the radio wave propagation. Since these components are likely to appear/disappear rapidly on small time scales, the structure of the MIMO channel will change faster than in the "front" case. From shadowing metric, it is found that the "front" and "back" cases are relatively close to each other. This is because the shadowing correlation takes only into account the power variations over time. Hence, if the power of the LOS and of the roadside components vary both similarly over time, then same shadowing correlation can be obtained. On the other hand, the direction-of-arrival/departure of the LOS component are more or less constant over time (as long as the relative orientation of the Tx and Rx vehicles doesn't change), while it is obviously not the case for the roadside scatterers.

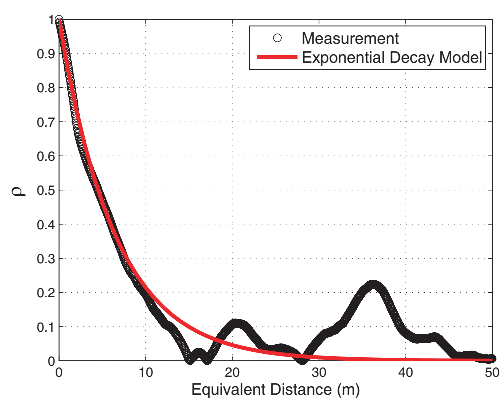



Figure 4: Exponential decay model of the shadow fading correlation.

The estimated stationarity distances using the shadowing metric is generally close to the estimations of CMD using full channel correlation matrix. This shows that the shadowing metric can be used for characterization of the non-stationarity of V2V channels. As the estimation of shadow fading does not require MIMO measurements, it thus has a more wide application range.

Table 1: Estimated equivalent stationarity distance.

| CMD, Front | Shadowing, Front | CMD, Back | Shadowing, Back |
|---|---|---|---|
| 6.03 (m) | 6.50 (m) | 3.21 (m) | 6.84 (m) |

## 5. CONCLUSION

In this paper, we employed two metrics, correlation matrix distance (CMD) and shadow fading correlation, to characterize the non-stationarity of V2V radio channels based on data measured with a $30 \times 4$ MIMO sounder at 5.3 GHz in suburban environment. The equivalent stationarity distance is found to be around 6 m. It is found that: i) the region with a large delay spread leads to a reduced size of stationarity region; ii) CMD metric is more sensitive to the changes of direction-of-arrival/direction-of-departure; and iii) the shadowing metric offers a good performance for the non-stationarity characterization. As the measurements of shadowing do not require MIMO system and are easier to be conducted, the shadowing correlation metric might have a wider application range in the analysis of channel non-stationarity.

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