Vehicular Channel Characterization and Modeling

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***Abstract*—Vehicle-to-vehicle transmissions have emerged as a key component of future communication standards, whose design and testing critically depends upon the understanding of propagation mechanisms. An important and specific aspect of vehicular communication channels lies in the fact that these are essentially non-stationary. Hence, this communication addresses two recent contributions in the field of non-stationary vehicular propagation, based on extensive measurements conducted at 5.3 GHz in suburban, urban, and underground parking areas. First, the estimation of quasi-stationarity regions is addressed by means of various metrics. It is found that the size of quasi-stationarity regions ranges from 3 to 80 m and is strongly affected by bandwidth and array configurations. A second contribution consists in proposing a dynamic wideband directional channel model. This model incorporates both angular and delay domain properties as well as the dynamic evolution of multipath components, relying on a birth-survival-death process between successive stationarity regions.**

I. Introduction

VEHICULAR wireless channel modeling has received significant attention in the last decade in the context of Intelligent Transportation Systems (ITS). In addition to multimedia communications, ITS should further enable all vehicles to collect traffic data and road state information and share information for safety improvements thereby preventing road accidents by periodically monitoring the locations of surrounding vehicles [1]. Naturally, this should be paired with a dependable connectivity, as such applications imply strict packet delay constraints. The system performance is ultimately fixed by the propagation channel, which must therefore be modeled accurately.

However, because both transmit and receive terminals are possibly moving, sometimes at high speeds, vehicular propagation is characterized by non-stationary conditions [2]–[5], making classical cellular models inadequate on this point of view [6]. The first issue to be addressed is thus to define the so-called *quasi-stationarity* region introduced by [7]–[9], i.e. the finite region in time or space over which the channel statistics remain *similar enough* (note that this is not a rigorous definition of strict or wide-sense stationarity, hence the term "*quasi-stationarity*"). of course, appropriate similarity measures are required to substantiate what "*similar enough*" means [10].

Once stationarity regions have been identified, the second issue is to model the wireless channel, taking into account the non-stationarity aspects, in particular the transitions between successive stationarity regions. Both issues will be addressed in this communication, based on recent measurement campaigns and modeling efforts.

The paper is organized as follows. Section II reviews recent results in the literature and points out at the remaining gaps and open questions. Section III briefly summarizes the measurement campaign upon which our results are based. Section IV aims at answering the following question: what metric should be used when estimating the quasi-stationarity region, as a function of the measurement system available ? Section V proposes an advanced stochastic vehicular channel model that can be used in view of simulating system performance.

II. Literature Overview

A. Quasi-Stationarity Metrics

A number of similarity measures have been proposed to define the size of quasi-stationarity regions.

- The correlation matrix distance (CMD) [11]–[13] enables to evaluate the changes in the spatial structure of the channel and has been applied to vehicular channels in [9], [10], [14]–[16]. It requires multi-antenna data and its values is strongly related to the size of employed arrays, as illustrated in Section IV.
- The spectral divergence (SD) [17] measures the distance between strictly positive, non-normalized spectral densities, e.g. power-delay profiles [18] and local scattering functions [19] measured at different times [20], [21]. It naturally requires broadband data.
- The shadow fading correlation (SFC) [22] is a more traditional measure of the changes in channel statistics. The shadowing autocorrelation function measures how fast local shadowing evolves as both mobile terminals move: hence, the decorrelation distance can thus be considered as an equivalent possible measure of quasi-stationarity distance when only narrowband channel gains are available.
- Other metrics have also been used over the years. In [9], an algorithm-specific approach from a system perspective is proposed and compared with the CMD, and the impact of polarization configuration of MIMO array is discussed. In [23], a modified mean square error metric is proposed and found to behave analogous to the CMD. In [24], it is suggested to identify the intervals of WSS by analyzing changes in the wavenumber spectrum estimated at different locations. In [25], stationarity intervals are identified by comparing the delay power spectral density estimated at different time instances.

B. Vehicular Channel Models

Given the time-varying nature of vehicular propagation, statistical models have been widely adopted [26]–[28]. However, most models currently lack a detailed characterization of dynamic channel parameters, in particular the appearance and disappearance of multipath components (MPCs) and the variation of their properties during their lifetime. Even though some recent papers have investigated the time-variant vehicular channels, these papers either focus on the characterization of the size of local WSS region and do not present the dynamic channel modeling [14], [21], or consider the MPC properties to remain constant within the lifetime and do not analyze the angular domain variations [29], [30].

Naturally, one way to implicitly address this issue is to resort to deterministic models, such as ray-tracing [31]. However, ray-based models remain environment-specific and their accuracy depends upon the description of the environment. While they are clearly a part of the answer, they can hardly embrace the full stochastic nature of vehicular propagation.

III. Experimental Setup

The measurement campaign used the Aalto MIMO channel sounder [32] at 5.3 GHz and a bandwidth of 60 MHz and a transmit power of 36 dBm. The receive (Rx) terminal was equipped with a dual-polarized semi-spherical antenna array comprising 15 dual-polarized patch elements (i.e. 30 feeds). A uniform linear array with 4 vertically polarized omnidirectional antenna elements was used at the transmit (Tx) side. Both antenna arrays were mounted on wooden platforms atop the roof of two cars. These cars wee driven at 5 to 40 km/h into four environments: Aalto university campus (Otaniemi), the suburbs and city center of Tapiola and an underground parking lot. The inter-vehicle distance varied between 10 and 500 m, depending on the traffic conditions, which ranged from no traffic at all (in the underground parking area) to heavy (in the urban and the NLOS suburban areas), with frequent obstructions of the line-of-sight. A detailed overview of the full setup can be found in [33], [34].

IV. Evaluation of Quasi-Stationarity Regions

When dealing with quasi-stationarity concepts, it is important to make a distinction between the *propagation level* and the *system level*. The former can be thought of as the inherent non-stationarity of the *physical* propagation channel, as determined by the dynamic multipath components. Naturally, it should be independent of the system configuration. The latter results from the combination of the channel with the system resolution in delay and angle. Hence, it depends on the bandwidth and on the antenna array size and reflects the characteristics that the system can "see". For a system with infinite bandwidth and perfect angular resolution, the quasi-stationarity on system-level tends to the propagation-level quasi-stationarity. This implies that the estimated degree of non-stationarity reduces when the bandwidth and array size become limited.

Based on the collected experimental results, stationarity regions were identified using three of the above defined metrics (CMD, SD and SFC), the ultimate goal being to characterize the quasi-stationarity on the propagation level. For the CMD, it is further possible to use the full channel correlation matrix, or the Tx/Rx correlation matrices, as well as any number of antenna in the array. This enables to analyze the impact of the array size on the estimated quasi-stationarity region, as the transmit array was only made of 4 antennas (versus 32 for the receive array).

The detailed analysis can be found in [33], but Table I illustrates the main conclusions (the stationarity distance is defined as the product of the quasi-stationarity time interval by the average speed, as it should approximately be independent from the vehicles' speed). It confirms that

- both SD and shadowing metrics are meaningful to characterize quasi-stationarity and are independent on the electrical array aperture;
- the speed has an impact, not per se, but because of the differential speed with respect to the surrounding traffic;
- the CMD is a meaningful system-level metric (i.e. for a given antenna configuration); it can be used as a propagation-level metric as long as a large electrical array aperture is used in the estimation.

As for answering the question raised in our introduction, it is suggested, when characterizing the quasi-stationarity, to use SD and shadowing metrics for a measurement system with a small electrical array aperture (typically less than 4 antennas at each side), and to use the CMD metric for arrays with large electrical apertures.

V. Advanced Non-Stationary Vehicular Channel Model

The proposed non-stationary vehicular channel model [34] is essentially a stochastic directional tap-delay line model, with smooth transitions from one stationarity region to another via a birth-survival-and-death process for the multipath components.

The MPC lifetime is modeled by means of a truncated Gaussian distribution. Distributions for the number of multipaths and their relative positions (in delay and angle) are also fitted by analytical distributions, as detailed in [34]. All these distributions are used to initialize the properties of each MPC in the first stationarity region. In addition, a Nakagami distribution is suggested to describe the small-scale fading behavior within a given stationarity region. The most important aspect of the model is the transition from one region to the next one, which rests essentially on the following iteration.

1) Death or survival: In the next stationarity region, some MPCs are pruned, depending on their lifetime. The remaining MPCs are categorized into two groups: MPCs with *long* and *short* lifetimes. MPCs with short lifetimes keep their initial amplitude, delay, and azimuth from the first to the next region. By contrast, the amplitude, delay, and azimuth of MPCs with long lifetimes are updated based on a stochastic model.

TABLE I
AVERAGE QUASI-STATIONARITY REGION SIZE (IN METERS) FOR 5 SCENARIOS

	CMD Tx	CMD Rx	CMD Full	SD	SFC
suburban LOS (5-15 km/h)	31.14	9.75	5.03	5.87	6.82
suburban NLOS (5-15 km/h)	21.29	7.84	3.70	6.78	-
suburban LOS (30-40 km/h)	68.86	16.71	10.18	16.15	36.15
urban LOS (5-15 km/h)	20.58	6.64	3.64	3.30	3.12
underground parking LOS (5-15 km/h)	17.31	4.53	2.78	4.45	3.80

2) Birth: New MPCs are generated to complement the surviving set. The initial MPC power (i.e. at birth) depends on its excess delay, and a linear polynomial function is used to model the variations within the lifetime.

As an example, Figure 1 compares simulated and measured power delay- and azimuth-profiles: it can be observed that all profiles seem to qualitatively match. To assess the matching in a more quantitative manner, second-order statistics, such as delay- and azimuth-spreads, provided by measurements and simulations, are also successfully compared in [34].

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REFERENCES

[1] C. F. Mecklenbräuker, A. F. Molisch, J. Karedal, F. Tufvesson, A. Paier, L. Bernadó, T. Zemen, O. Klemp, and N. Czink, "Vehicular channel characterization and its implications for wireless system design and performance," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1189–1212, 2011.

[2] A. Paier, J. Karedal, N. Czink, H. Hofstetter, C. Dumard, T. Zemen, F. Tufvesson, A. F. Molisch, and C. F. Mecklenbräuker, "Car-to-car radio channel measurements at 5 GHz: Pathloss, power-delay profile, and delay-Doppler spectrum," in *Proc. IEEE ISWCS'07*, 2007, pp. 224–228.

[3] A. Paier, J. Karedal, N. Czink, H. Hofstetter, C. Dumard, T. Zemen, F. Tufvesson, C. F. Mecklenbräuker, and A. F. Molisch, "First results from car-to-car and car-to-infrastructure radio channel measurements at 5.2 GHz," in *Proc. IEEE PIMRC'07*, 2007, pp. 1–5.

[4] A. F. Molisch, F. Tufvesson, J. Karedal, and C. Mecklenbräuker, "A survey on vehicle-to-vehicle propagation channels," *IEEE Wireless Communications*, vol. 16, no. 6, pp. 12–22, 2009.

[5] D. W. Matolak, "Channel modeling for vehicle-to-vehicle communications," *IEEE Communications Magazine*, vol. 46, no. 5, pp. 76–83, 2008.

[6] N. Akhtar, S. Coleri Ergen, and O. Ozkasap, "Vehicle mobility and communication channel models for realistic and efficient highway VANET simulation," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 248–262, 2015.

[7] A. Gehring, M. Steinbauer, I. Gaspard, and M. Grigat, "Empirical channel stationarity in urban environments," in *EPMCC'01*, Vienna, Austria, 2001, pp. 1–6.

[8] A. Ispas, G. Ascheid, C. Schneider, and R. Thomä, "Analysis of local quasi-stationarity regions in an urban macrocell scenario," in *Proc. IEEE VTC'10*, Taipei, 2010, pp. 1–5.

[9] A. Ispas, C. Schneider, G. Ascheid, and R. Thomä, "Analysis of the local quasi-stationarity of measured dual-polarized MIMO channels," *IEEE Transactions on Vehicular Technology*, to be published, 2014.

[10] L. Bernadó, "Non-stationarity in vehicular wireless channels," Ph.D. dissertation, Technische Universität Wien, Vienna, Austria, Apr. 2012.

[11] M. Herdin, "Non-stationary indoor MIMO radio channels," Ph.D. dissertation, Technische Universität Wien, Vienna, Austria, Aug. 2004.

[12] M. Herdin and E. Bonek, "A MIMO correlation matrix based metric for characterizing non-stationarity," in *Proceedings IST Mobile & Wireless Communications Summit*, 2004.

[13] M. Herdin, N. Czink, H. Özcelik, and E. Bonek, "Correlation matrix distance, a meaningful measure for evaluation of non-stationary MIMO channels," in *Proc. IEEE VTC'05*, vol. 1, 2005, pp. 136–140.

[14] O. Renaudin, V.-M. Kolmonen, P. Vainikainen, and C. Oestges, "Non-stationary narrowband MIMO inter-vehicle channel characterization in the 5-GHz band," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 4, pp. 2007–2015, 2010.

[15] O. Renaudin, V. Kolmonen, P. Vainikainen, and C. Oestges, "Car-to-car channel models based on wideband MIMO measurements at 5.3 GHz," in *Proc. IEEE EuCAP'09*, 2009, pp. 635–639.

[16] A. Paier, T. Zemen, L. Bernadó, G. Matz, J. Karedal, N. Czink, C. Dumard, F. Tufvesson, A. F. Molisch, and C. F. Mecklenbräuker, "Non-WSSUS vehicular channel characterization in highway and urban scenarios at 5.2 GHz using the local scattering function," in *Proc. IEEE ITG WSA'08*, Vienna, Austria, 2008, pp. 9–15.

[17] T. T. Georgiou, "Distances and Riemannian metrics for spectral density functions," *IEEE Transactions on Signal Processing*, vol. 55, no. 8, pp. 3995–4003, 2007.

[18] F. Kaltenberger, L. Bernadó, and T. Zemen, "Characterization of MU-MIMO channels using the spectral divergence measure," *COST 2100, TD (08)*, vol. 640, 2008.

[19] G. Matz, "On non-WSSUS wireless fading channels," *IEEE Transactions on Wireless Communications*, vol. 4, no. 5, pp. 2465–2478, 2005.

[20] L. Bernadó, T. Zemen, A. Paier, G. Matz, J. Karedal, N. Czink, C. Dumard, F. Tufvesson, M. Hagenauer, A. F. Molisch *et al.*, "Non-WSSUS vehicular channel characterization at 5.2 GHz-spectral divergence and time-variant coherence parameters," *XXIXth URSI General Assembly*, pp. 9–16, 2008.

[21] L. Bernadó, T. Zemen, A. Paier, and J. Karedal, "Complexity reduction for vehicular channel estimation using the filter divergence measure," in *Proc. IEEE ASILOMAR'10*, 2010, pp. 141–145.

[22] M. Gudmundson, "Correlation model for shadow fading in mobile radio systems," *Electronics letters*, vol. 27, no. 23, pp. 2145–2146, 1991.

[23] T. Jamsa, P. Kyosti, and J. Iinatti, "Correlation error metrics of simulated MIMO channels," in *Proc. IEEE VTC'07*, 2007, pp. 407–412.

[24] R. Bultitude, G. Brussaard, M. Herben, and T. Willink, "Radio channel modelling for terrestrial vehicular mobile applications," in *Proc. Millenium Conf. Antennas and Propagation*, 2000, pp. 1–5.

[25] D. Umansky and M. Pätzold, "Stationarity test for wireless communication channels," in *Proc. IEEE GLOBECOM'09*, 2009, pp. 1–6.

[26] L. Bernadó, T. Zemen, F. Tufvesson, A. F. Molisch, and C. F. Mecklenbrauker, "Time-and frequency-varying-factor of non-stationary vehicular channels for safety-relevant scenarios," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 1007–1017, 2015.

[27] S. Zhu, T. S. Ghazaany, S. M. Jones, R. Abd-Alhameed, J. M. Noras, T. Van Buren, J. Wilson, T. Suggett, and S. Marker, "Probability distribution of rician K-factor in urban, suburban and rural areas using real-world captured data," *IEEE Trans. Antennas Propag.*, vol. 62, no. 7, pp. 3835–3839, 2014.

[28] T. Abbas, L. Bernado, A. Thiel, C. Mecklenbrauker, and F. Tufvesson, "Radio channel properties for vehicular communication: Merging lanes versus urban intersections," *IEEE Veh. Technol. Mag.*, vol. 8, no. 4, pp. 27–34, 2013.

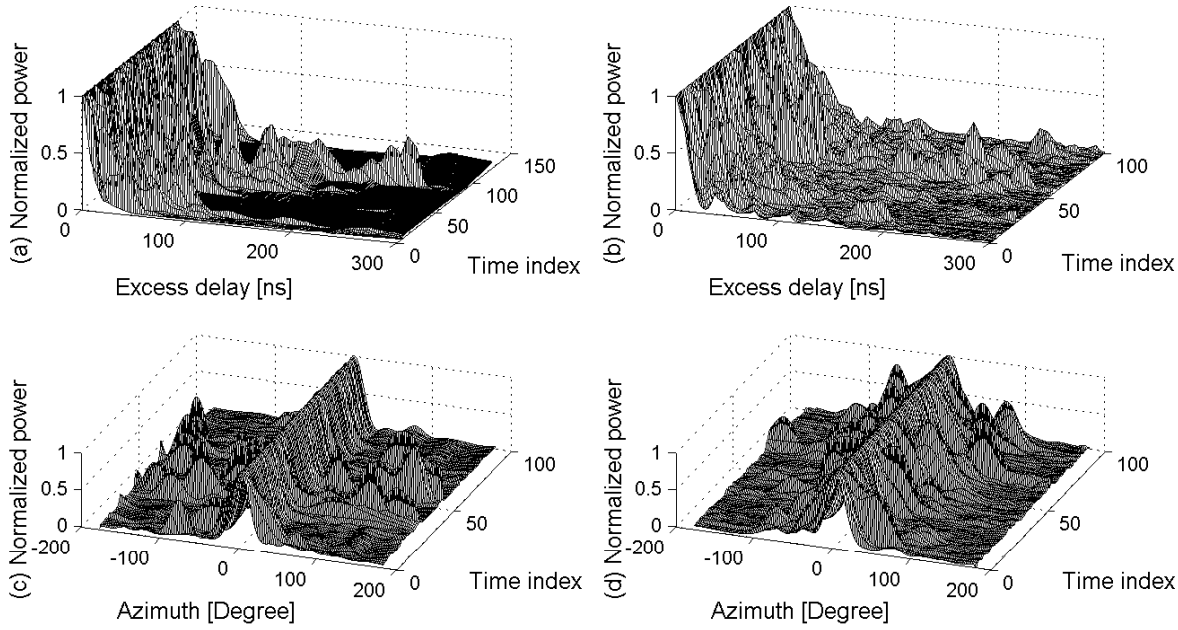

Fig. 1. Comparison of power-delay and power-angular profiles in suburban environments. (a) Measured PDP. (b) Simulated PDP. (c) Measured PAP. (d) Simulated PAP.

[29] O. Renaudin, V.-M. Kolmonen, P. Vainikainen, and C. Oestges, "Wideband measurement-based modeling of inter-vehicle channels in the 5-GHz band," *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3531–3540, 2013.

[30] J. Karedal, F. Tufvesson, N. Czink, A. Paier, C. Dumard, T. Zemen, C. F. Mecklenbrauker, and A. F. Molisch, "A geometry-based stochastic MIMO model for vehicle-to-vehicle communications," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3646–3657, 2009.

[31] M. Schack, J. Nuckelt, R. Geise, L. Thiele, and T. Kurner, "Comparison of path loss measurements and predictions at urban crossroads for C2C communications," in *Antennas and Propagation (EUCAP), Proceedings of the 5th European Conference on*. IEEE, 2011, pp. 2896–2900.

[32] V. Kolmonen, J. Kivinen, L. Vuokko, and P. Vainikainen, "5.3-GHz MIMO radio channel sounder," *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 4, pp. 1263–1269, 2006.

[33] R. He, O. Renaudin, V.-M. Kolmonen, K. Haneda, Z. Zhong, B. Ai, and C. Oestges, "Characterization of quasi-stationarity regions for vehicle-to-vehicle radio channels," *IEEE Trans. Antennas Propag.*, vol. 63, no. 5, pp. 2237–2251, 2015.

[34] ——, "A dynamic wideband directional channel model for vehicle-to-vehicle communications," *IEEE Trans. Industrial Electron.*, vol. 62, no. 12, pp. 7870–7882, 2015.