Temporal Evolution of Channel Capacity in Vehicular MIMO Channels in the 5 GHz Band

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Abstract— **Reliability in Ricean multiple-input-multiple-output (MIMO) channels is crucial for safety related vehicle-to-vehicle (V2V) applications. Due to the time variability of vehicular communication channel, it is very significant to study the temporal evolution of channel characterization criteria. We present evaluation results of the temporal evolution of the spectral efficiency from channel sounder measurements of vehicle-to-vehicle MIMO radio channels in the 5.2 GHz band. Our results show that MIMO channels with higher spatial correlation lead to lower ergodic capacity and a reduced signal-to-noise ratio-dependent critical data rate. The temporal evolution of the ergodic capacity and critical data rate shows that the channel with the strongest line of sight (LoS) component also has the highest capacity. We also present a detailed analysis of the environmental factors affecting the capacity pattern throughout the measurement run. Dynamic scatterers introduce capacity bursts instantaneously; the trend stays congruent with the theory.**

I. INTRODUCTION

In wireless communication systems the time variation of the communication channel is caused by Doppler effects due to user movement and multipath propagation. One example of these time-variant communication channels are the vehicle-to-vehicle (V2V) communication channels.

The development of efficient V2V communications systems requires an understanding of the underlying radio propagation channel in order to analyze the impact of real-world propagation conditions. Channel capacity is the highest upper bound on the amount of information that can be reliable transmitted over a communication channel. Thus the temporal evolution of this parameter is a useful characterization criterion for vehicular communication channels.

Vehicular communication has been a matter of a lot of research. Not only the CVIS project [1] supported by the European Comission is developing a framework in order to develop, design and test the technologies needed to allow cars to communicate with each other and with the nearby infrastructure; but consortiums such as FREEWAY (Cooperative Communications for Scalable and Reliable real-time Vehicular Networks) in Europe and California PATH [2] (California Partners for Advanced Transit and Highways) overseas are currently working on similar research topics.

The multiple-input multiple-output (MIMO) technology has become the most popular transmission technique in wireless systems, as it provides an improved transmission quality and achieves higher data rates for wireless communications in multipath environments [4]. Theoretical studies such as [5] show the importance of capacity and outage performance in Ricean MIMO Channels. In more recent publications [6] the first evaluation results of vehicular communication channel capacity at 5.2 GHz have been presented. This work opens up the discussion on how does the temporal evolution over a whole measurement run look like. The present contribution tries to give some light into that topic providing, to the author's knowledge, the first results of temporal evolution of both, ergodic capacity and critical data rate, not only at three key time instants, but throughout the measurement run.

This paper will evaluate the radio channel measurements carried out with the RUSK LUND channel sounder by Vienna University of Technology, Lund University and FTW (Forschungszentrum Telekommunikation Wien) in 2007, at a center frequency of 5.2 GHz and a measurement bandwidth of 240 MHz. This measurement wideband leads to high temporal resolution. The antenna system used was a 4x4 Multiple-Input-Multiple-Output (MIMO) circular antenna array with vertically polarized patch antenna elements and the measurement vehicles were two similar transporters of the type VW LT35. A detailed description of this radio channel measurement campaign is presented in [7].

Contributions of the paper: This paper is a continuation of the research presented in [6] in terms of spectral efficiency analysis. Ergodic capacity and critical data rate measures are applied on the same real V2V measurement data. A global temporal evolution of both parameters is carried out and the effects of the propagation environment are discussed.

Organization of the paper: In *Section II* a brief overview of the theory behind Ricean MIMO channels is presented, as well as the ergodic capacity and critical data rate concepts as main characterization criteria for radio channel capacity evaluation. Measurement results are presented in *Section III* and finally the paper is concluded in *Section IV*.

II. Spectral Efficiency in Ricean Vehicular Communication Channel

A. Ricean MIMO Channel for Vehicular Environments

The MIMO-OFDM channel is described by its channel matrix $\boldsymbol{H}[n,k] \in \mathbb{C}^{M_{\mathrm{TX}} \times M_{\mathrm{RX}}}$ with time index *n* and frequency index *k*. The Ricean MIMO channel

$$\boldsymbol{H}[n,k] = \bar{\boldsymbol{H}}[n,k] + \tilde{\boldsymbol{H}}[n,k], \tag{1}$$

consists of both, a dominating or a line of sight (LoS) component $\bar{\boldsymbol{H}}[n,k]$ and a scattered zero-mean component $\tilde{\boldsymbol{H}}[n,k]$.

For statistical characterization, all the columns of the channel matrix are stacked into one column vectors

$$\boldsymbol{h}[n,k] = vec(\boldsymbol{H}[n,k]) \in \mathbb{C}^{L \times 1} \tag{2}$$

with length $L = M_{\mathrm{TX}} \times M_{\mathrm{RX}}$.

As it is mentioned in [8] and in order to evaluate the performance, it is important to quantify the impact of the propagation conditions on the error probability of the transmission. In our case, as we are working with channel sounding data we are going to analyze the error probability by means of outage probability. Keeping in mind that the channel we are working with is an arbitrary Ricean MIMO channel, the realizations of the N-dimensional vector $\boldsymbol{h} = \bar{\boldsymbol{h}} + \tilde{\boldsymbol{h}}$ generates a subspace $\hat{\boldsymbol{\mathcal{R}}}$ which depends on $\bar{\boldsymbol{h}}$ and the subspace generated by the realizations of $\tilde{\boldsymbol{h}}$. In the case where $\bar{\boldsymbol{h}}$ lies entirely in the range space of $\hat{\boldsymbol{\mathcal{R}}}$ all the dimensions "excited" by $\boldsymbol{h}$ will have a Rayleigh fading component. In the case where the projection of $\bar{\boldsymbol{h}}$ lies onto the nullspace $N(\hat{\boldsymbol{\mathcal{R}}})$, we have at least one dimension which is purely AWGN. Geometrically speaking, considering the Hermitian angle between $\bar{\boldsymbol{h}}$ and $R(\hat{\boldsymbol{\mathcal{R}}})$ as $0 \leq \gamma \leq \pi/2$, we can conclude that $0 < \gamma \leq \pi/2$ implies that there will be a certain so called signal-to-noise (SNR) ratio dependent critical data rate below which transmission with zero outage probability is possible. Whereas if $\gamma = 0$ there will not be such a zero outage transmission channel. The bigger γ is, the higher the critical data rate will be and the lower the outage probability.

One of the goals of this contribution is to evaluate how this critical data rate varies for different SNR values. In order to perform this evaluation, the variation of γ should be monitored for different time instants of the measurement run. The angle γ is calculated from the expression

$$\sin\gamma = \frac{\|\bar{\boldsymbol{h}}_o\|^2}{\|\bar{\boldsymbol{h}}\|^2} \tag{3}$$

where $\bar{\boldsymbol{h}}_o$ is an auxiliary vector created from the covariance matrix of the channel. The covariance between the channel matrix elements is described by the covariance matrix [11]

$$\boldsymbol{\phi}[n,k] = \mathbb{E}\{(\boldsymbol{h}[n,k] - \boldsymbol{\mu_h}[n,k])(\boldsymbol{h}[n,k] - \boldsymbol{\mu_h}[n,k])^H\} \tag{4}$$

where $\boldsymbol{\mu_h}[n,k]$ is the mean vector of $\boldsymbol{h}[n,k]$. Note that in measurements this mean is usually close to zero, since there is a phase variation of the dominating component. In order to get the sample covariance matrix of the measured data, it has to be estimated. The sample covariance matrix at time n_o is estimated by averaging over *N'* time snapshots.

$$\hat{\boldsymbol{\phi}}[n_o,k] = \frac{1}{N'} \sum_{n=n_o}^{n_o-N'} (\boldsymbol{h}[n,k] - \hat{\boldsymbol{\mu}}_{\boldsymbol{h}}[n,k])(\boldsymbol{h}[n,k] - \hat{\boldsymbol{\mu}}_{\boldsymbol{h}}[n,k])^H \tag{5}$$

The mean vector is defined as

$$\hat{\boldsymbol{\mu}}_{\boldsymbol{h}}[n,k] = \frac{1}{N'} \sum_{n=n_o}^{n_o+N'} \boldsymbol{h}[n,k] \tag{6}$$

In this scenario the two pick-up trucks were driving opposite directions, towards each other. At 2.5 s both cars entered their own lane on the highway where they had LoS. At this moment they were approximately 280 meters far from each other. At 7.5 s they crossed and they kept driving apart until the measurement run ended at 10 s.

For the estimation of the covariance matrix the proper estimation time (*N'* snapshots) has to be chosen, which has to be kept below the stationarity time, in order to make the clauses, (4) and (5) valid. In [6] the stationarity time for the same highway scenario is 23 ms. In order to stay below this stationarity time a 20 ms (*N'=64*) timeslot is chosen, which is about 20 wavelengths at a relative speed of 31 m/s.

B. Channel Capacity Evaluation in Vehicular Communication Channels

Another aim of this paper is to compare the magnitude of the previously mentioned critical data rate with the capacity of the channel. The measure of how much information can be transmitted and received with an arbitrary small probability of error is called the *channel capacity*.

Keeping in mind that the MIMO channel is described by its channel matrix $\boldsymbol{H}[n,k] \in \mathbb{C}^{M_{TX} \times M_{RX}}$, the ergodic (mean) capacity for a complex AWGN MIMO channel can then be expressed as

$$C[n,k] = \mathbb{E}_H\left\{log_2\left[\det\left(\boldsymbol{I}_{M_R} + \frac{\rho}{M_T}\boldsymbol{H}[n,k]\boldsymbol{H}[n,k]^H\right)\right]\right\} \tag{7}$$

where we assume uncorrelated noise in each receiver branch described by the covariance matrix $\sigma^2\boldsymbol{I}_{M_T}$, where $\boldsymbol{I}_{M_T}$ is the unitary matrix of M_T size, $\rho = \frac{P_T}{\sigma^2}$ is the average SNR at each receiver branch and $C[n,k]$ depends on time, n, and frequency bin, k.

On time because capacity is calculated for the channel defined within n_0 and $n_0 + 20$ ms and frequency bin k because capacity is calculated for each frequency bin k.

Another measure of channel capacity that is frequently used is *outage capacity* [5]. As it has been mentioned in Section *II.A,* outage probability varies with the Hermitian angle γ. The $\bar{\boldsymbol{h}}_o$ is obtained by applying the singular value decomposition to the estimated covariance matrix

$$\hat{\boldsymbol{\phi}}[n_o,k] = \boldsymbol{U\Sigma V}^H \tag{8}$$

and selecting the column vector in $\boldsymbol{U}$ (which contains the eigenvectors for $\hat{\boldsymbol{\mathcal{R}}}$) corresponding to $\boldsymbol{Q}$, the smallest covariance element in $\boldsymbol{\Sigma}$. Then substracting the two vectors, $\bar{\boldsymbol{h}}_o$ is obtained as:

$$\bar{\boldsymbol{h}}_o = (\boldsymbol{I} - \boldsymbol{Q}\boldsymbol{Q}^{\boldsymbol{H}})\bar{\boldsymbol{h}} \tag{9}$$

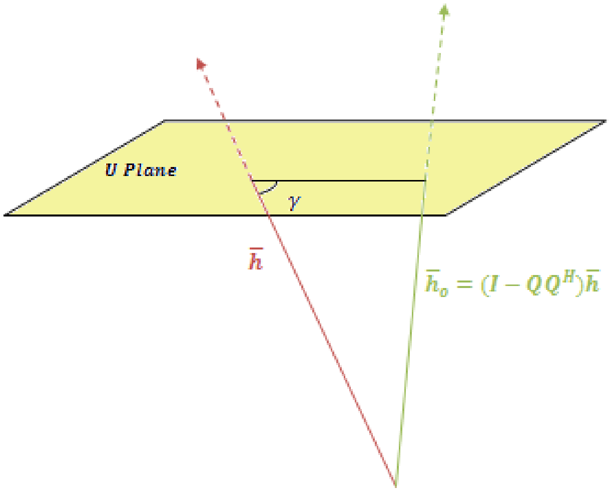

Fig. 1: Geometry of the U plane and the $\overline{h}_o$ and $\overline{h}$ vectors

The angle γ will vary with the length of $\|\overline{\boldsymbol{h}}_o\|^2$. So when $\|\overline{\boldsymbol{h}}_o\|^2$ is zero, γ will be 0º and this leads back to the situation presented in *Section II.A,* where all the dimensions "excited" by $\boldsymbol{h}$ will have a Rayleigh fading component. On the other hand, if $\|\overline{\boldsymbol{h}}_o\|^2$ is greater than zero, there will be a reliable zero outage transmission channel. The critical data rate will be calculated as the capacity of the less variant channel realization $\overline{\boldsymbol{h}}_o$.

III. MEASUREMENT RESULTS

The transmitter and receiver cars are driving opposite directions at 100 km/h. The measurement run takes 10 seconds, beginning when both cars are far but approaching each other and ending when both cars are driving away from each other.

Ergodic (mean) capacity is defined for every time bin, indexed as n, and frequency bin, indexed as k. The snapshot time range to be analyzed is defined by the channel stationarity time. The time instants chosen will be when both cars first have LoS with each other at 2.5 s and when they drive by each other at 7.5 s.

Regarding the frequency bin selection, k= 628 has been randomly chosen, out from the 769 frequency bins.

As mentioned in Section *II*, parting from the vector $\boldsymbol{U}$ the auxiliary vector $\overline{\boldsymbol{h}}_{\boldsymbol{o}}$ is defined. This will be the most reliable vector, which in terms of covariance means selecting the smallest vector in $\boldsymbol{U}$ corresponding to the smallest singular values in $\boldsymbol{\Sigma}$. Fig. 2 shows the $\boldsymbol{U}$ vectors for the sixteen channels for n = 7.5 s. The most reliable one will be in this case will be the channel number 9.

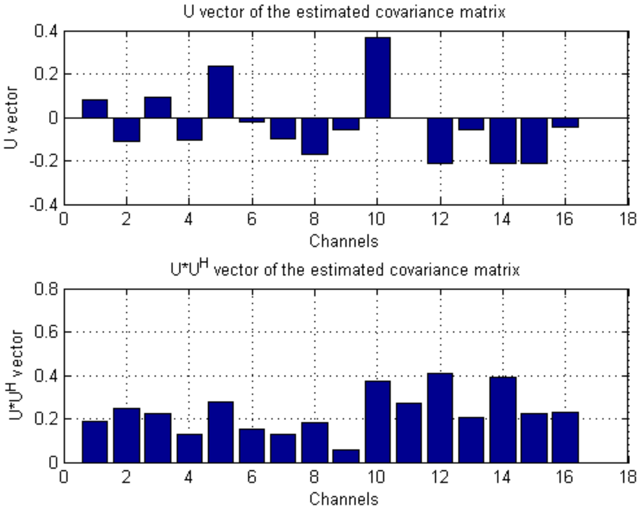

Fig. 2: U vector of the estimated covariance matrix for n = 7.5 s and k = 628

After converting this vector into a 16 × 16 matrix ($\overline{\boldsymbol{H}}_o$), the capacity of this matrix is calculated, which will be the critical data rate.

In MIMO Ricean channels there will be a critical data rate below which a zero outage transmission is possible. In order to illustrate this, Fig. 3 shows the Hermitian angle γ. We can see that for n = 7.5 s it is 67º which supports the critical data rate existence at that time instant. For 2.5 s the Hermitian angle will be bigger, 81º, hence it is a more reliable channel.

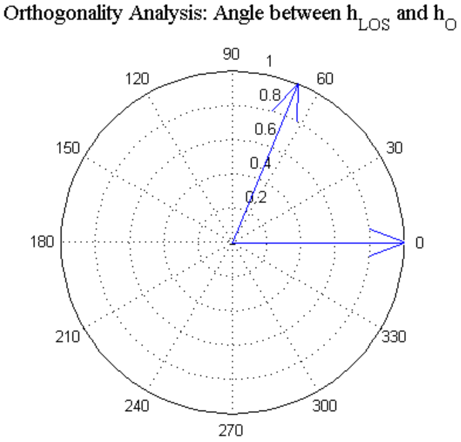

Fig. 3: Orthogonality Analysis (γ angle) for n = 7.5 s and k = 628

In order to evaluate the temporal progression of both ergodic capacity and critical data rate, they are calculated for each second of the measurement run for a constant transmit power of 27 dBm.

Early in the measurement run ergodic capacity and critical data rate decrease as the cars get closer. This is because at the beginning of the measurement run, when cars are far from each other, the MIMO channels are less correlated and therefore the ergodic (mean) capacitywill be higher.

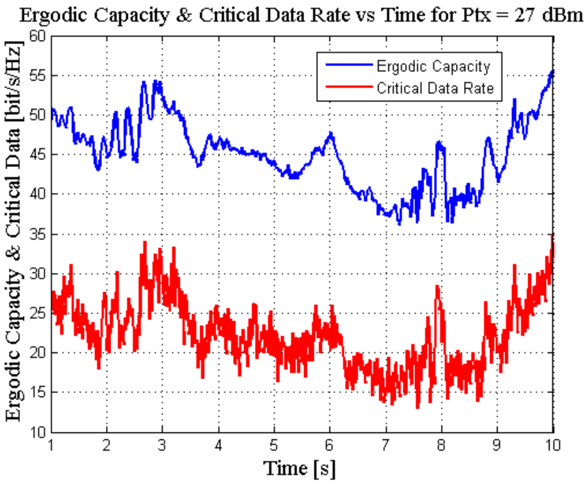

Fig. 4: Temporal evolution of ergodic capacity and critical data rate

As both cars are more proximate, the correlation between the individual SISO channels compounding the MIMO channel will be higher and this will make the ergodic (mean) capacity drop. That is why at 7.5 s the ergodic capacity and the critical data rate are lower than at 2.5 s. After passing each other both indicators increase. As it was mentioned in [6], this is due to the fact that when cars are driving away from each other at 10 s the channel is the one with the strongest LoS component. The antennas used in both link end elements were uniform circular arrays of microstrip antennas. Each array consists of a circular deployment of 16 dual-polarized elements (the Rx array consists of 4 circles) from which we selected 4 symmetrically placed, vertically polarized elements. With reference bearing 0º (as seen from the top view of the arrays) being in the direction of driving, the selected antenna elements were directed at 45º, 135º, 225º and 315º. The directions of the main lobes of these elements were the same for both measurement cars and are described in Fig. 5. Each antenna array was mounted on the top of the stack of Euro pallets, which when mounted on the car's platform, provided a total antenna height of 2.4 m above the ground.

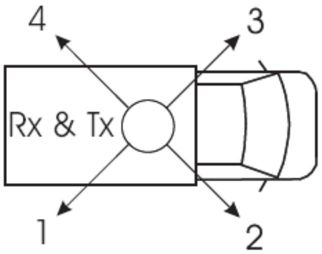

Fig. 5: Direction of the main lobes of each antenna element for receiver and transmitter.

In order to analyze the impact of the surrounding environment on the capacity of the channel, the videos, recorded from the front and the rear view of the receiver car, have been analyzed. The sudden bursts throughout the measurement run are due to mobile scatterers (surrounding traffic) as there were no sound barriers or metallic structures close to the highway. More intensive bursts are due to bigger trucks, whereas small ones are due to single cars or several cars passing by at the same time. Although the capacity increases locally, the overall tendency of both ergodic capacity and critical data rate stays coherent with the three keypoint analysis presented in [6].

IV. CONCLUSIONS

The MIMO channel has been geometrically described by its channel matrix $\boldsymbol{H}[n,k] \in \mathbb{C}^{M_{Tx} \times M_{Rx}}$ with time index n and frequency index k and also by its LoS and scattered zero-mean components.

When analyzing the *tendency of the ergodic capacity and critical data rate over time*, the highest capacity is reached at the strongest LoS component. This situation occurs in our experiment at time 10 s, when cars are driving away from each other and the Tx-Rx antennas better aligned and there are no metallic scatterers at the rear of the cars. For a constant transmit power of 27 dBm the maximum values for ergodic capacity and critical data rate are 50.54 bit/s/Hz and 28.46 bit/s/Hz, respectively. Finally about the real impact of real-world propagation conditions on channels ergodic capacity, our results have shown that dynamic scatterers generate sudden bursts that locally increase the capacity but the overall trend keeps coherent with the theory, this means higher capacity when channel are uncorrelated and lower when correlated.

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