# Capacity Evaluation of Measured Vehicle-to-Vehicle Radio Channels at 5.2 GHz

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*Abstract*— **Reliability in Ricean multiple-input-multiple-output (MIMO) channels is crucial for safety related vehicle-to-vehicle (V2V) applications. In Ricean channels, there is a Signal-to-Noise Ratio-dependent critical data rate below which signaling with zero outage is possible. The link will be more reliable the higher this critical data rate is. We present results of spectral efficiency and outage probability from channel sounder measurements of V2V 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 critical data rate. Nevertheless, 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.**

## I. Introduction

Cooperative systems can lead to improved driving safety. Today, usually these systems rely on a wireless local area network (WLAN) standard for automotive use, called IEEE 802.11p, which is under development in order to implement Wireless Access in Vehicular Environments (WAVE) [1]. Operating at 5.850–5.925 GHz, WAVE systems adopt orthogonal frequency-division multiplexing (OFDM) and achieve data rates of 3 to 27 Mbps. Vehicular communications has been an active research field in the recent years. The multiple-input multiple-output (MIMO) technology has become the most popular transmission technique, as it provides an improved transmission quality and achieves higher data rates for wireless communications in multipath environments [2].

Theoretical studies such as [3] show the importance of capacity and outage performance in Ricean MIMO channels.

The development of efficient vehicle-to-vehicle (V2V) communications systems requires an understanding of the underlying radio propagation channels in order to analyze the real impact of real-world propagation conditions. Therefore, measurements campaigns, such as the one carried out in [4, 5], provide very valuable information on real propagation environments.

From one of the first measurement campaigns [6], which only took into account cars driving in the same direction until the most recent wideband V2V channel measurements [7], all the results have shown channel characteristics such as power delay profile (PDP), doppler profile which have been useful, in order to generate vehicular channel models such as in [8] or [9]. But to the authors' knowledge there has not been any measurement data analysis on spectral efficiency and outage performance in Ricean MIMO channels in the field of vehicular communications.

This contribution presents the first results on this area based on the data acquired during the radio channel measurement campaign, 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 high bandwidth leads to high temporal resolution.

The antenna system used was a 4x4 MIMO circular antenna array with vertically polarized patch antenna elements and the measurement vehicles were two similar transporters of the type VW LT35. A more detailed description of the antennas and the radio channel measurement campaign is presented in [2].

*Contributions of the paper:* We apply the ergodic capacity introduced in [10] and critical data rate measures introduced in [11] to real V2V measurement data. Both parameters are evaluated for different signal-to-noise ratio (SNR) values. Moreover the temporal evolution of both parameters is evaluated and discussed. Outage performance is also evaluated.

*Organization of the paper:* In *Section II* a brief overview of the theory behind Ricean MIMO channels is presented. Furthermore the ergodic capacity and outage probability concepts are discussed as main characterization criteria for radio channel capacity evaluation. Evaluation results on the spectral efficiency and outage probability are presented in *Section III* and finally the paper is concluded in *Section IV*.

## II. Spectral Efficiency and Outage Performance in Ricean Vehicular Communication Channels

### A. Ricean MIMO Channel for Vehicular Environments

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

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

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 single column vectors

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

with length $L = M_{\mathrm{TX}} \times M_{\mathrm{RX}}$. Defining $\tilde{\boldsymbol{h}}[n,k] = vec(\tilde{\boldsymbol{H}}[n,k])$, the statistics of $\tilde{\boldsymbol{H}}$ are characterized by the correlation matrix $\boldsymbol{\mathcal{R}} = \mathcal{E}\{\tilde{\boldsymbol{h}}\tilde{\boldsymbol{h}}^H\}$ with singular value decomposition $\boldsymbol{\mathcal{R}} = \boldsymbol{U\Sigma V}^H$ [11]. Note that $\bar{\boldsymbol{h}}$ and $\boldsymbol{\mathcal{R}}$ completely characterize the statistics of the MIMO channel.

As it is mentioned in [11], it is important to quantify the impact of the propagation conditions on the error probability of the transmission. In our case, we 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 L-dimensional vector $\boldsymbol{h} = \bar{\boldsymbol{h}} + \tilde{\boldsymbol{h}}$ generates a subspace $\boldsymbol{\mathcal{R}}$ which depends on $\bar{\boldsymbol{h}}$ and the subspace generated by the realizations of $\tilde{\boldsymbol{h}}$.

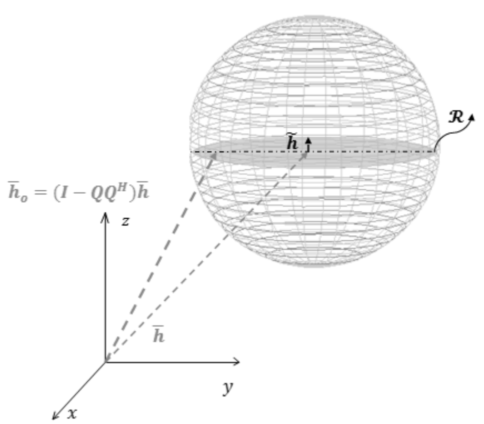


**Fig. 1: Three dimensional illustration of Ricean MIMO Channel**

Fig. 1 also shows $\bar{\boldsymbol{h}}_{\boldsymbol{o}}$ the projection of $\bar{\boldsymbol{h}}$ onto the range space of $\boldsymbol{\mathcal{R}}$. If $\bar{\boldsymbol{h}}_{\boldsymbol{o}}$ exists, this means that the projection of $\bar{\boldsymbol{h}}$ lies on the nullspace of $\boldsymbol{\mathcal{R}}$, we have at least one dimension which is purely additive white Gaussian noise (AWGN). On the other hand, if $\bar{\boldsymbol{h}}$ lies entirely in the range space of $\boldsymbol{\mathcal{R}}$ all the dimensions "excited" by $\boldsymbol{h}$ will have a Rayleigh fading component.

Geometrically speaking, considering the Hermitian angle between $\bar{\boldsymbol{h}}$ and $\bar{\boldsymbol{h}}_{\boldsymbol{o}}$ as $0 \le \gamma \le \pi/2$, we can conclude that $0 < \gamma \le \pi/2$ implies that there will be a certain signal-to-noise (SNR) ratio dependent so-called "critical data rate" [11], below which transmission with zero outage probability is possible.

Whereas, if $\gamma = 0$, there will not be such a zero outage transmission channel. The larger $\gamma$ is, the higher the critical data rate will be and the lower the outage probability gets.

One of the goals of this paper is to evaluate how this critical data rate varies for different SNR values. In order to perform this evaluation, the variation of $\gamma$ should be monitored for different time instants of the measurement run. The angle $\gamma$ is calculated from the expression given by [11]

$$\gamma = \angle(\bar{\boldsymbol{h}}, \bar{\boldsymbol{h}}_{\boldsymbol{o}}) = \boldsymbol{cos^{-1}}\left(\left|\frac{\bar{\boldsymbol{h}}^{\boldsymbol{H}}\bar{\boldsymbol{h}}_{\boldsymbol{o}}}{\|\bar{\boldsymbol{h}}\|\|\bar{\boldsymbol{h}}_{\boldsymbol{o}}\|}\right|\right) \quad (3)$$

where the projection of $\bar{\boldsymbol{h}}$ onto the range space of $\boldsymbol{\mathcal{R}}$ ($\bar{\boldsymbol{h}}_o$) is created from the covariance matrix of the channel. The covariance between the channel matrix elements is described by the covariance matrix

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

where $\boldsymbol{\mu_h}[n,k]$ is the mean vector of $\bar{\boldsymbol{h}}[n,k]$. Note that in measurements since there is a phase variation of the dominating component, a phase shift has to be done in order to have a correct mean value of the LoS contribution [12]. We estimate the sample covariance matrix at time $n_o$

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

where the mean vector is defined as

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

The $\bar{\boldsymbol{h}}_o$ is obtained by applying the singular value decomposition to the estimated covariance matrix

$$\hat{\boldsymbol{\phi}}[n_o,k] = \boldsymbol{U\Sigma V}^H \quad (7)$$

and selecting the column vector in $\boldsymbol{U}$ (which contains the eigenvectors of $\boldsymbol{\mathcal{R}}$) the largest covariance elements in $\boldsymbol{\Sigma}$ above the noise threshold. With this filtered diagonal matrix a new covariance is calculated, named $\boldsymbol{Q}$. Subtracting the two vectors, $\bar{\boldsymbol{h}}_{\boldsymbol{o}}$ is obtained as:

$$\bar{\boldsymbol{h}}_o = (\boldsymbol{I} - \boldsymbol{QQ^H})\bar{\boldsymbol{h}} \quad (8)$$

The angle $\gamma$ will vary with the length of $\|\bar{\boldsymbol{h}}_o\|^2$. So when $\|\bar{\boldsymbol{h}}_o\|^2$ is zero, $\gamma$ 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 $\|\bar{\boldsymbol{h}}_o\|^2$ is greater than zero, there will be a reliable zero outage transmission channel. The critical data rate will be calculated after converting the $\bar{\boldsymbol{h}}_{\boldsymbol{o}}$ vector into a $16 \times 16$ matrix ($\bar{\boldsymbol{H}}_o$), and the capacity of this matrix be the critical data rate. [14].

In this scenario the two pick-up trucks were driving in opposite directions, towards each other. At 2.5 s both cars entered their own lane in the highway where they had LoS. At this moment they were approximately 280 meters from each other. At 7.5 s they crossed and 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 estimates, (4) and (5) valid.

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 100 km/h and corresponds well with the stationarity time for similar highway scenario in [13].

### *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

$$C[n,k] = \mathbb{E}_H\left\{log_2\left[\det\left(\boldsymbol{I}_{M_R} + \frac{\rho}{M_T}\boldsymbol{H}[n,k]\boldsymbol{H}[n,k]^H\right)\right]\right\} \quad (9)$$

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 unit matrix of size $M_T$, $\rho = \frac{P_T}{\sigma^2}$ and $\frac{\rho}{M_T}$ is the average SNR at each receiver branch. $C[n,k]$ depends on time, $n$, and frequency bin, $k$ since capacity is calculated for the channel defined within $n_0$ and $n_0 + 20$ ms and for each frequency bin $k$. The time-variant channel does not have any effect on the calculation of ergodic capacity, and thus no matrix rotation will be required.

Another measure of channel capacity that is frequently used is *outage capacity*; the probability that the capacity is less than the outage capacity denoted by $C_{outage}$ is $q$. This can be expressed in mathematical terms by [11]

$$Prb\left\{C[n,k] \leq C_{outage}[n,k]\right\} = q \quad (10)$$

As it has been mentioned in Section *II.A,* outage probability varies with the Hermitian angle $\gamma$.

## III. Measurement Results

For the evaluation we use a measurement where the transmitter and receiver cars are driving in opposite directions at 100 km/h.

### *A. Spectral Efficiency Evaluation*

As mentioned before, the ergodic (mean) capacity is defined for every time bin, indexed by *n*, and frequency bin, indexed by *k*. The snapshot time range to be analyzed is defined by the channel stationarity time.

The time instants chosen in order to show the ergodic capacity and critical data rate results are 2.5 s, when both cars are driving at the highway in opposite directions with LoS, and 7.5 s, when both cars are passing by each other. Regarding the frequency bin selection, $k$ = 628 has been randomly chosen, out from the 769 frequency bins. Fig. 2 shows the ergodic capacity and critical data rate versus SNR for $n$ = 2.5 s. The blue line denotes the ergodic (mean) capacity calculated out from the 64 snapshots while the red line is the critical data rate of the reliable channel $\overline{\boldsymbol{H}}_o$.

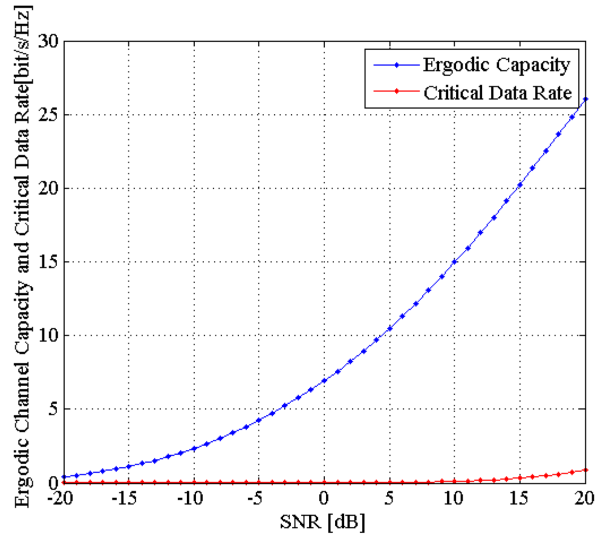


**Fig. 2: Ergodic capacity and critical data rate for *n* = 2.5 s and *k* = 628 (5.275 GHz)**

Fig. 3 shows the same capacity and critical data rate, but for the time instant when the cars are passing each other. Compared to Fig. 2, the channel at $n$ = 7.5 s has got a lower ergodic capacity and critical data rate. This means that at $n$ = 7.5 s in a perfect power control scenario, there will be less number of reliable channels able to transmit below this critical data rate with zero outage probability.

As seen in both figures, the critical data rate is very small in contrast to ergodic capacity. This is why critical data rate is used for signaling purposes.

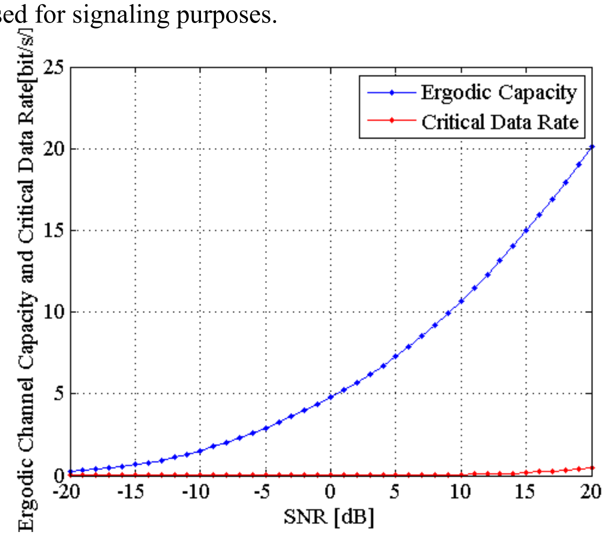


**Fig. 3: Ergodic capacity and critical data rate for *n* = 7.5 s and *k* = 628 (5.275 GHz)**

In order to evaluate the temporal progress of both ergodic capacity and critical data rate a third time instant has been selected: $n$ = 10 s. Taking a fixed SNR of 20 dB, the instant ergodic capacity and critical data rate of the three instants are compared.

Table 1 shows the critical data rate and ergodic capacity for the three timestamps. We observe that both are lower when the cars are closed and higher, when the cars are more separate from each other.

TABLE 1: ERGODIC CAPACITY AND CRITICAL DATA RATE VS. TIME FOR A CONSTANT SNR = 20 dB

| | n = 2.5 s | n = 7.5 s | n = 10 s |
|---|---|---|---|
| Critical Data Rate (bit/s/Hz) | 0.85 | 0.51 | 2.45 |
| Ergodic Capacity bit/s/Hz | 26.05 | 20.10 | 35.20 |

This is because at the beginning of the measurement run, when cars are far from each other, the MIMO channels are less correlated (see upper Fig.4) and therefore the ergodic capacity will be higher. The partial LoS channels in this example are 6, 7, 11 and 14. Regarding Rician *K*-factor analysis, as it was presented in [12], these 4 LOS channels have got the highest *K*-factors.

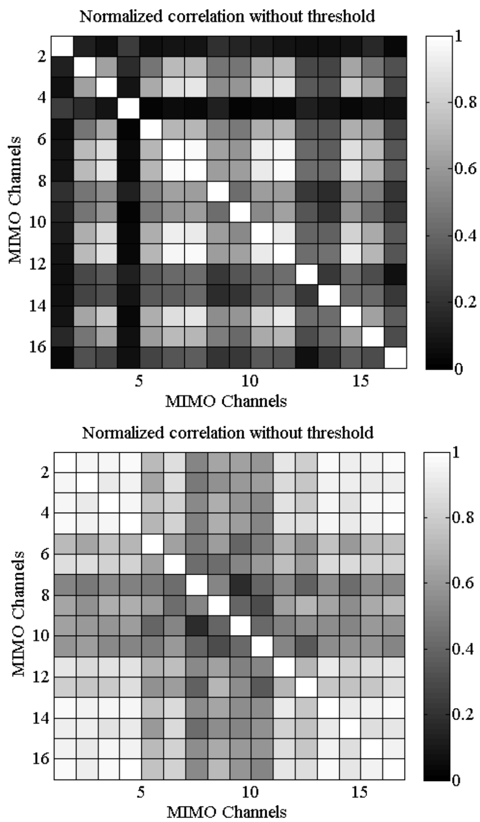


**Fig. 4: Normalized correlation matrixes of the measured data for *n* = 2.5 s (upper graph) and *n* = 7.5 s (lower graph)**

For the same SNR value, as both cars are closer, the correlation between the individual SISO channels compounding the MIMO channel will be higher (see lower Fig.4) and this will make the 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. And finally when the cars drive apart, both parameters increase, because the more distant they are from each other, the less correlated the MIMO channel is. This ergodic capacity and critical data rate evaluations were calculated for a perfect power control scenario, hence having a constant SNR.

The question that arises at this point is why the capacity is lower at 7.5 s, when the cars are crossing and as at 10 s, when cars are driving away from each other. The propagation needs to be studied in order to find the explanation for this effect. The channel with the strongest LoS component is the one that maximizes capacity.

The channel at 7.5 s turns not to be the one with the strongest LoS, and it is not indeed, because due to the structure of the cars there is strong scattering on the metallic structure. However at 10 s, the cars receive from back-to-back where no metallic scatterers are deployed. There we find a maximum LoS channel.This supports the results shown in Table 1 at 10 s, where the ergodic capacity and the critical data rate reach their maximums at 35.20 bit/s/Hz and 2.45 bit/s/Hz. respectively. Fig. 5 shows the scenarios at each time.


**Fig. 5: General highway scenario and individual screenshots from the video of the measurement run: The Rx car passing by the Tx car and The Rx driving away from the Tx car (From LEFT to RIGHT)**

## B. *Outage Performance Evaluation*

Regarding capacity distribution, a symmetrical distribution leads to lower outage probabilities. For lower SNR values a symmetric distribution can be seen for reliable channels, whereas less reliable channels have non-symmetrical capacity distribution.

In order to compare the outage probability at two different time instants, the cumulative distribution function (cdf) of the capacity should be analyzed.

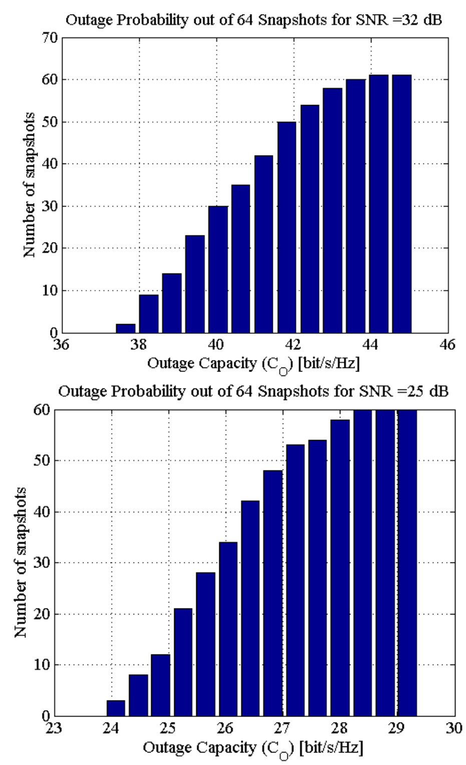


**Fig. 6: Outage probabilities of the measured data for *n* = 2.5 s (upper graph) and *n* = 7.5 s (lower graph)**

Fig. 7 shows how evaluating the measured data and taking into account the instantaneous SNR for each instant time for the same outage capacity values the upper bar diagram has got less outage probability than the one for $n$ = 7.5 s. For example, for an outage capacity of 30 bit/s/Hz, the channel at $n$ = 2.5 s. has got 0% outage probability (there are no snapshots within that range of outage probability). On the other hand the channel at $n$ = 7.5 s will have a 100% outage probability.

Monitoring the Hermitian angle $\gamma$ generated by the LoS channel vector $\bar{\boldsymbol{h}}$ and the auxiliary vector $\bar{\boldsymbol{h}}_o$, we can see that the bigger $\gamma$ is, the larger $\|\bar{\boldsymbol{h}}_o\|^2$ is, which implies a higher data rate and therefore lower outage probabilities

## 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.

*Spectral efficiency* evaluation results have shown that the higher is the critical data rate the higher ergodic capacity is. A higher ergodic capacity means a higher spectral efficiency for a certain SNR value. A higher critical data rate allows for more reliable transmission. Our results also show that for constant transmission power the capacity decreases as the MIMO channel correlation increases. Finally, the highest capacity is reached at the strongest LoS component. This situation occurs in our experiment at time 10 s. For a constant SNR of 20 dB the maximum values for ergodic capacity and critical data rate are at 35.20 bit/s/Hz and 2.45 bit/s/Hz. respectively.

Regarding *outage performance*, less reliable channels have got higher outage probabilities at lower outage capacities.

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