Carrier frequency effect on the MIMO eigenvalues in an indoor environment

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ABSTRACT

The effect of the carrier frequency on the multiple-input multiple-output (MIMO) system eigenvalues is investigated experimentally in an indoor environment considering line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. The results show a reduction of the mean power gain in the MIMO system eigenvalues due to a correlation increment between the spatial subchannels when the carrier frequency increases. This effect causes a slightly reduction of the MIMO capacity.

KEYWORDS

MIMO channels, MIMO capacity, eigenvalues characterization, spatial correlation.

RESUMEN

El efecto de la frecuencia portadora sobre los valores propios de los sistemas MIMO (multiple-input multiple-output) es investigado experimentalmente en un entorno indoor, considerando condiciones de línea de vista (LOS: line-of-sight) y sin línea de vista (NLOS: non-line-of-sight). Los resultados muestran una reducción en la potencia media de los valores propios del sistema MIMO, lo cual es debido a un incremento en la correlación espacial entre los sub-canales cuando la frecuencia portadora se incrementa. Este efecto causa una reducción en la capacidad del sistema MIMO.

PALABRAS CLAVE
Canales MIMO, capacidad MIMO, caracterización de los valores propios, correlación espacial.

Clasificación Colciencias: Tipo 1

INTRODUCTION

It is well known that in wireless communications multiple-input multiple-output (MIMO) systems achieve very high data rate and high spectral efficiencies [1]. The MIMO systems are promising candidates for the deployment of future wireless networks: IEEE 802.11n, HiperLAN/2, MMAC, UWB and WiMAX are some examples. These wireless networks will use different frequencies, so that the propagation conditions observed at the radio interface will be clearly dependent on the frequency and the environment. In this sense, it is necessary to study how the properties of the MIMO channel could change with the carrier frequency. Experimental studies based on measurements campaigns have investigated the capacity reduction due to the spatial subchannels correlation [2],[3], but these works have been focused on MIMO channels characteristics at specific central frequencies in different scenarios, making the comparisons are difficult.

If, $H \in \mathbb{C}^{NxM}$, with $M \geq N$ is the MIMO channel transfer matrix, where M and N are the number of antenna elements at the transmitter and receiver, respectively, the eigenvalue decomposition (EDV) of the $H^H H \in \mathbb{C}^{MxM}$ matrix is a useful tool for MIMO system performance analysis. While the number of the non zero eigenvalues reflects the spatial multiplexing gain, the eigenvalues represent the power gain in each spatial subchannel.

A measure of the MIMO system performance is the channel capacity. Under a spatial multiplexing scheme and with equal power allocation strategy (no water-filling techniques applied [4]), the channel capacity will be obtained as the sum of the capacities supported by each spatial subchannel. Thereby, the channel capacity, C, is given by [1], [4]

$$C = \sum_{i=1}^{k} \log_2 \left(1 + li \frac{r}{M} \right) \quad (1)$$

where r is the receive signal-to-noise ratio (SNR), l_i represents the i-th eigenvalue and k is the rank of the $H^H H$ matrix.

This letter studies the effect of the carrier frequency on the eigenvalues of the $H^H H$ matrix as a measured of the MIMO system performance. The study is based on a measurement campaign of the MIMO channel carried out in an indoor environment at 2, 6 and 12 GHz, in line-of-sight (LOS) and non-line-of-sight (NLOS) conditions.

MEASUREMENT SETUP

The MIMO channel measurements were carried out at the iTEAM Research Institute - Technical University of Valencia. The outdoor walls of the building are made of glass, whereas the indoor walls are made of wood and wallboard. The ceilings and floor are built of reinforced concrete over steel plates.

The receiver array (RX) was placed in an office room. The transmitter array (TX) was placed in the same office as the RX, where the propagation was in LOS condition, and in the adjacent corridor, where the propagation was in NLOS condition. The maximum distance between the TX and the RX was 12 m to keep r>15 dB in every carrier frequency.

The full spatial correlation matrix of the MIMO radio channel, R_{MIMO}, was estimated from frequency domain samples of H, which where obtained by means of a vector network analyser (VNA); more details in [5]. Omnidirectional wideband antennas at the TX and the RX, very low attenuation cables and a wideband low noise RF amplifier at the RX were also used. The antennas were set up over a precise linear positioning robotic system emulating a virtual uniform lineal array (ULA), without coupling effects. A maximum number of 3 antenna elements at the TX and the RX was considered, in agreement with current recommendations and standards [6],[7].

One wavelength of separation between antenna elements was considered to keep the same electrical separation at each carrier frequency. Relative effects versus frequency were measured considering all band frequencies data collected consecutively at the same array elements positions over a bandwidth of 200 MHz (SPAN in the VNA) and with a frequency bin resolution of 50 kHz (4000 spectrum samples) [5]. 5 and 4 locations were measured in LOS and NLOS conditions, respectively. At each spatial position, 50 snapshots of the frequency transfer function were measured. The measurements were carried out at nights, in absence of people, guaranteeing the necessary stationary channel conditions.

RESULTS AND ANALYSIS

The entries of the measured R_{MIMO} matrix were used to derive by simulation different realisations of the MIMO channel transfer matrix, H , based on the coloring matrix of the MIMO system [8]. All realisations of H were normalised by means of the Frobenius norm, eliminating the effect of the path loss at each carrier frequency. A total of 10^5 realisations of the H matrix were considered for the results presented in this letter.

In Fig. 1 the mean power gain of the eigenvalues $l_1 > l_2 > L > l_k$ of the $H^H H$ matrix, in LOS (left) and NLOS (right) conditions, is presented. A M=N=3 MIMO configuration is considered. For comparisons, we have also plotted the mean power gain of the eigenvalues when the entries of the channel transfer matrix are independent and identically distributed (i.i.d.) complex Gaussian random variables (an uncorrelated/ideal MIMO channel). The i.i.d. case considers uncorrelated spatial subchannels.

The results show that the mean power gain associated to the largest eigenvalue, l_1, remains constant while the carrier frequency increases in LOS and NLOS conditions. Therefore, the effect of the carrier frequency on the array gain is negligible, since the expectation value of the largest eigenvalue is about $10\log E(l_1)$» 7.9dB for all carrier frequencies in LOS and NLOS. Nevertheless, the mean power gain associated to the second and third eigenvalues decreases considerably with the carrier frequency, with less proportion in NLOS conditions. The lower values, compared with the i.i.d. case, indicate an increment of the spatial correlation among the spatial subchannels, which is related with a reduction of the multipath richness. Table 1 summarises the values of the spatial correlation coefficients estimated in terms of the carrier frequency at the RX. Note

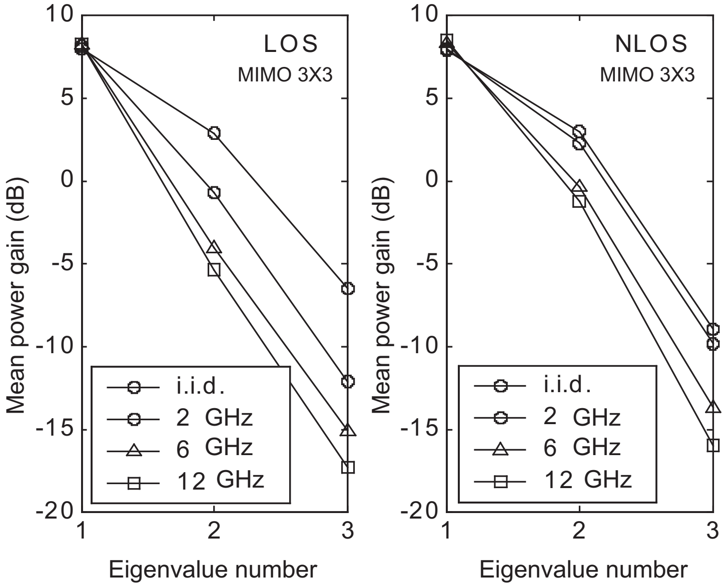

Figure. 1. Mean power gain of the MIMO system eigenvalues $l_{1,2,3}$

Table 1. Spatial correlation coefficients at the RX

f	LOS	NLOS
2 GHz	0.326	0.283
6 GHz	0.785	0.780
12 GHz	0.979	0.871

Table 2. Ergodic capactity (bits/s/Hz)

	LOS			NLOS		
f(GHz)	2	6	12	2	6	12
2x2	4.97	4.69	4.25	5.39	4.79	4.28
3x3	6.67	5.73	5.41	7.70	6.85	6.32

that the correlation among the spatial subchannels is slightly lower in NLOS conditions.

The difference in the mean power gain between the largest and the smallest eigenvalues are 20.25, 23.36 and 25.55 dB at 2, 6 and 12 GHz, respectively, in LOS condition. In NLOS condition the different is reduced to 17.74, 21.98 and 24.5 dB at 2, 6 and 12 GHz, respectively. The reduction of the mean power gain with the carrier frequency results in a reduction of the achievable ergodic capacity, as a consequence of a correlation increment among the spatial subchannels. Table 2 summarises the ergodic capacity, expressed in bits/s/Hz, for $M=N=\{2,3\}$ MIMO configurations in terms of the frequency for a SNR of 10 dB (setting in the channel simulator). Note that the ergodic capacity slightly decreases with the carrier frequency. This result agrees with results shown in [9] for an indoor environment. Nevertheless, in another study, carried out for a microcellular environment, slightly capacity increments have been reported for the higher carrier frequencies [10].

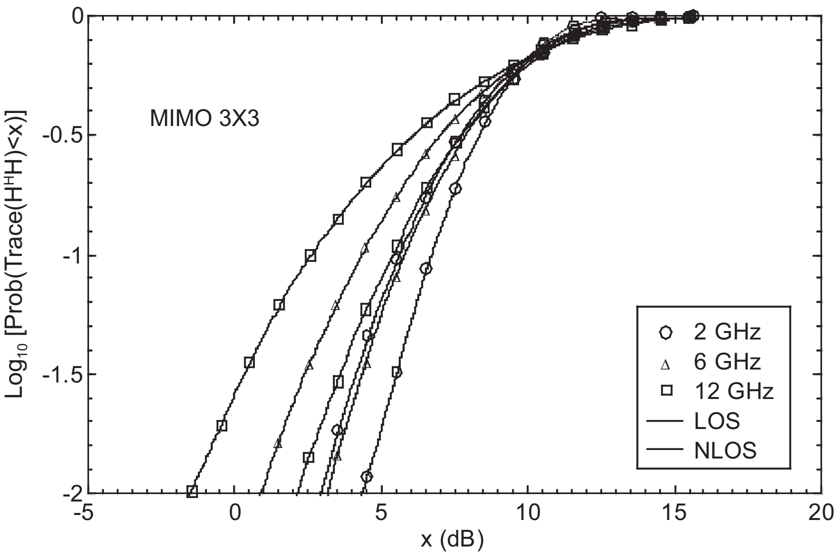

Figure. 2. Cumulative distribution function of .

Finally, Fig. 2 shows the cumulative distribution function (CDF) of the trace of the $H^H H$ matrix (Σl_i) as a measure of multipath richness. A MIMO configuration is considered. Note that the differences in terms of the carrier frequency increase for low probabilities. Smaller power gain eigenvalues dispersion means higher multipath richness, and this happens in NLOS condition.

DISCUSSION

Evidently, a complete understanding of the carrier frequency effect on the MIMO system performance requires more measurements in many different indoor environments at different carrier frequencies and bandwidths. These measurements are necessary due to the characteristics of materials are also frequency-dependent, being the multipath prejudiced for this physical characteristic.

Finally, it is worth to indicate that parallel to the measurement campaign and analysis presented in this letter, a theoretical study was performed. A new frequency-dependent (FD) MIMO channel model, based on deterministic-Gaussian-uncorrelated-scattering (DGUS) models [11], has been formulated for high carrier frequencies and wideband signals.

Due to the focus of this letter is an experimental characterization of the MIMO system eigenvalues, the results of the FD-DGUS-MIMO model will be then presented in future works.

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CONCLUSIONS

The results presented in the letter show that the mean power gain of the MIMO system eigenvalues and the multipath richness of the channel are related to the carrier frequency. In the considered indoor scenario, an increment of the carrier frequency causes a reduction in the power gain of the smaller eigenvalues, resulting in an ergodic capacity reduction.

The difference in the eigenvalues power gain in terms of the carrier frequency suggests new considerations if water-filling techniques are applied, and indicates that an equal power allocation could not be the most suitable strategy for indoor environments.

The results presented in this letter also suggest perform more frequency-dependent measurements in order to consider additional propagation scenarios with different constitutive materials.

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CURRÍCULOS

Alexis Paolo García Ariza was born in Bucaramanga, Colombia, in 1978. He received his M.S. degree in Electronic Engineering from the Industrial University of Santander (UIS), Bucaramanga, Colombia, in 2002. Now he is a Ph.D. student at the Universidad Politécnica de Valencia (UPV) since 2004, with the support of the European AlBan Programme. He was with RadioGIS research group at UIS between 2002 and 2004. He was also a Research Engineer at the iTEAM Research Institute at UPV between 2004 and 2008. He is currently a Research Assistant at the Electronic Measurement Research Lab, Institute of Information Technology, Ilmenau University of Technology, Ilmenau, Germany.

His research is focused on modelling, simulation and measurement/sounding of wireless channels, with special interest in wideband MIMO channels, ultra-wideband (UWB) channels, and millimetre-wave (MM-Wave) channels. He also developed investigations in propagation modeling applied to Andean conditions, and designing radio network planning tools based on Geographic Information Systems (GIS) for cellular and DVB-H/SH systems. He was a guest researcher at Mobile Communications Group, University of Agder, Grimstad, Norway, in 2007, where he developed investigations in perfect modelling and simulation of MIMO channels using real-world measurement data.

Gonzalo Llano R, received the M.S. degree in Technologies, Systems and Communications Networks from Technical University of Valencia (Spain) in 2007. He is currently a Ph.D. student and researcher at the Radio and Wireless Communications Group (RWCG) in the iTEAM Research Institute at the Technical University of Valencia. His research is focused on modeling and statistical characterization of UWB channels, adaptive modulation systems with multicarrier transmission for UWB (MB-OFDM UWB) and security in WPAN networks with UWB.

Lorenzo Rubio received the Telecommunication Engineering and the Ph.D degrees from the Universidad Politécnica de Valencia (UPV), Spain, in 1996 and 2004 respectively. In 1996, he joined the Communications Department of the UPV, where he is now Associate Professor of wireless communications. He is a member of the Radio and Wireless Communications Group (RWCG) of the Telecommunications and Multimedia Applications Research Institute (iTEAM).

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Juan Reig was born in Alcoy, Spain, in 1969. He received the M.S. and Ph.D. degrees in Telecommunications Engineering from the Technical University of Valencia, Spain, in 1993 and 2000, respectively. He has been a faculty member in the Department of Communications at the Technical University of Valencia, Spain since 1994, where he is now Associate Professor of Telecommunication Engineering. He is a member of the Radio and Wireless Communications Group (RWCG) of the Telecommunications and Multimedia Applications Research Institute (iTEAM). His areas of interest include fading theory, diversity, ultra-wide band systems and vehicular communications in V2V and V2I networks.