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Hybrid Massive MIMO for Urban V2I: Sub-6 GHz vs mmWave Performance Assessment

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Abstract—The relevance of vehicle communications in next-generation networks entails the necessity of studying their performance in the framework of upcoming massive architectures. In this regard, a study of the wireless channel between a hybrid massive MIMO BS and a vehicular platform is proposed. Adequate metrics and methodology are provided for the assessment of such scenarios. The impact of different multi-antenna geometries and MIMO architectures in both vehicle and BS is modeled based on a numerical simulation of a realistic urban area. We compare several massive hybrid BS configurations with distinct multi-antenna vehicular rooftop solutions. This paper studies the channel eigenvalues and capacities for sub-6 GHz (3.6 GHz) and millimeter-wave (mmWave) (26 GHz) bands under different propagation conditions. The results suggest that the use of hybrid massive configurations increase the channel capacity by subdividing the massive BS into two or four logical radio channels. It is also shown that the greater available bandwidth at mmWave band can compensate the larger attenuation of radio channels in small size cells. The use of adequate metrics to measure the temporal coherence of the channel is also discussed for the beam switching update.

Index Terms—MIMO systems, antenna arrays, urban propagation, vehicles.

I. INTRODUCTION

AUTOMOTIVE and telecommunications industries have joined efforts on vehicle communications over the last decade. Indeed, there is an increasing interest of users and manufacturers in connecting vehicles to the high-speed network aiming to provide multimedia services and driving assistance. To respond to these demands with limited spectrum availability, multiple input multiple output (MIMO) in general, and massive MIMO (mMIMO) in particular, may introduce significant improvements. The throughput of the system can be significantly enhanced [1], and multi-user interference reduced [2]. Given their higher directivity, massive architectures are worthwhile if the user location is known and the update of the steered

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Fig. 1. Generic model of a downlink V2I scenario.

beam is fast enough. In that regard, hybrid beamforming is assumed to be the key technology to make massive geometries cost-efficient. Molisch *et al* [3] classify and analyze several hybrid structures according to the channel state information (CSI) available at the base station (BS) and their complexity. In [3], a reduced-complexity hybrid architecture is proposed, in which each RF chain is connected to a subset of antennas. Initial system-level studies of beamforming at millimeter-wave (mmWave) frequencies reveal the potential benefits of hybrid beamforming in terms of performance and energy efficiency [4].

Fig. 1 illustrates a generic model of the downlink communication in a vehicle-to-infrastructure (V2I) system. In a first step, the user sends a pilot signal that allows the BS to identify and locate it spatially. With this information, the BS radiates into the coverage area with a focusing strategy depending on the specific antenna configuration. Due to the distribution of the BS radiated field, some other regions may be reached by the signal. Other users might perceive this as an interference, degrading the performance of their communication channel. In general, massive architectures intend to reduce this effect and improve the overall performance of the network. Additionally, the subdivision of the massive geometry allows to concentrate power in different regions corresponding to several users or to apply conventional MIMO strategies for capacity enhancement. Note that in the presented paper we investigate different configurations for one user only.

II. SCOPE OF THE STUDY

This paper proposes a methodology and metrics to assess massive architectures in vehicular environments. The main contributions can be summarized as follows:

- comparison of S-band (3.6 GHz) and K-band (26 GHz) with their full available bandwidth, i.e., up to 100 MHz and 400 MHz, respectively, according to their propagation characteristics and channel capacities;
- investigation of vehicular channels in terms of their eigenvalues and spatial distribution of the radiated fields,
- study of the coherence time in both bands as a metric to update the beamforming pattern, and
- assessment of distinct hybrid beamforming BS architectures and vehicular antenna setups based on the achievable channel capacity.

Given the complexity to perform experimental measurements in vehicular scenarios, there is an interest in using appropriate numerical models that give a preliminary assessment for the definition of a proper set of experimental validations. Other works provide empirical and probabilistic channel propagation models, as in [5]. The goal of the present analysis is centered on the physical layer modeling of the propagation environment with different antenna configurations at both the BS and the car for an urban scenario by means of electromagnetic simulation tools. In particular, the choices in defining realistic and comparable scenarios are presented and proper metrics to assess the performance of the different alternatives are introduced. We compare the system for two bands in order to evaluate different MIMO configurations as a function of the frequency under several propagation conditions. Previous studies in [6] already investigated the correlation of vehicle-to-everything (V2X) channels for sub-6 GHz and mmWave bands when omnidirectional antennas are used. In [7], analytical expressions are derived to analyze the impact of beamforming strategies on the temporal variation of vehicular channels. The concept of beam coherence time is also introduced, which allows a more relaxed realignment of the beams and it is able to provide higher spectral efficiency for very narrow beams compared to the typical definition of channel coherence time. This is the case of mmWave systems in which very directive arrays are typically used to compensate the additional attenuation.

Regulation entities have allocated parts of the spectrum to support the development of new technologies and standards. The 3.4–3.8 GHz band has been chosen by the mobile industry in many countries to roll out the fifth generation of mobile communications (5G) in the sub-6 GHz region. These frequencies have also been proposed by the 3GPP Release 15 for vehicle-to-vehicle (V2V) communications. On the other hand, one of the greatest revolutions in 5G networks is the use of mmWave frequencies. In the WRC-15, the ITU already defined some candidate bands and the national regulatory bodies have chosen a preliminary allocation. The most promising band, specially in Europe, is found at 24.25–27.5 GHz. In this paper, we study 3.6 and 26 GHz as operating frequencies and the different bandwidth options available for each band. The largest standardized bandwidth for sub-6 GHz (FR1) and mmWave (FR2) frequencies, i.e., $B_1=100$ MHz and $B_2=400$ MHz, respectively [8], are compared in terms of the achievable capacity.

In order to make a fair comparison between antenna configurations and frequency bands, we must take into consideration several factors. One of the main interests when dealing with

TABLE I
OVERVIEW OF MIMO CONFIGURATIONS WITH x_i AS THE BS INPUT, y_j AS THE VEHICLE OUTPUT, AND H THE WIRELESS CHANNEL

Conventional Configurations	Massive Configurations
SISO	mSISO

MIMO $N_T \times N_R$	mMIMO $N_T \times N_R$

massive architectures concerns the power consumption. Given the increase in propagation losses with frequency, there are two ways to obtain comparable values of signal to noise ratio (SNR) at the receiver for different bands. First, one may think on directly increase the power at the transmitter, but this is far from a realistic scenario. A second solution is to use more directive antenna geometries. A great benefit of working with higher frequencies is the possibility to fit more antennas in the same physical space to obtain larger gain values with similar physical dimensions. In this way, the number of elements can be enlarged to overcome the additional propagation losses.

On the user side, there is a trend to increase the number of elements as well. In particular, modern cars include many sensors and antennas, not only for communication, but for safety and driving assistance purposes. In the new paradigm of 5G, connected vehicles are one of the most promising areas and they are less constrained in terms of energy consumption and space compared to mobile handsets. Regarding the vehicular receiving system, the straightforward approach is to use as many RF chains as in the BS, since the minimum of both determines the upper bound of MIMO data streams. In this case, only a single radiating element is connected to each transceiver. The use of beamforming strategies at the receiver side is not investigated in the present study. Finally, the noise figure is fixed to be equal for both sub-6 GHz and mmWave bands. Current mmWave chips are already providing performances comparable to lower frequencies and fixing the noise figure allows to directly relate the noise level to the operating bandwidth and obtain a reasonable trade-off between bandwidth and SNR, which finally impacts the achievable capacity.

Table I shows the antenna configuration on both transmitter and receiver, with N_T and N_R elements respectively, for conventional and massive MIMO configurations. In the first case, single input single output (SISO) is referred to the single antenna case, at both transmitter and receiver, and $N_T \times N_R$ MIMO considers a multi-antenna geometry in which each antenna is fed by a different RF chain, being N_T the number of BS transmitting antennas and N_R are the vehicle receiving ones. In the case of massive configurations, the BS is composed by Q elements and each RF port delivers the signal to several of them. In massive

SISO (mSISO), a single port is used for the entire geometry, whereas in mMIMO the BS is organized in a set of NT modules of N_T modules of $M \times P$ elements each, $Q = N_T \times (M \times P)$. What is usually called mMIMO in literature [2] differs from the common nomenclature in the sense that the definition of mSISO is based on a single-beam radio channel and our hybrid mMIMO, on several simultaneous radio channels (N_T). Therefore, the channel matrix $\mathbf{H}$ always consists of $N_R \times N_T$ entries. More details about single-user and multiuser MIMO and mMIMO systems can be found in [9] by R.W. Heath and A. Lozano.

III. THE MIMO CHANNEL

The channel matrix $\mathbf{H}$ describes the relation between the BS (considered as the transmitter) input vector $\mathbf{x}$ and the vehicle (considered as the receiver) output vector $\mathbf{y}$:

$$\mathbf{y} = \mathbf{H} \mathbf{x} + \mathbf{v}, \quad (1)$$

where $\mathbf{v}$ is additive noise and $\mathbf{H}$ is an $N_R \times N_T$ matrix for a MIMO system.

The channel transfer function for i -th receiver and j -th transmitter, corresponding to the i -th row and j -th column of the channel matrix $\mathbf{H}$, is obtained as the addition of all multipath contributions and can be expressed as follows:

$$h_{ij}(\mathbf{r}) = \sum_{t=1}^T \Gamma(\mathbf{r}_t) e^{-jk\mathbf{r}_t}, \quad (2)$$

where $\Gamma(\mathbf{r}_t)$ is the complex envelope of the channel transfer function, including the effect of all elements in the scenario, the gain and the weight of the transmitter and receiver antennas, for the $\mathbf{r}_t$ radio path distance vector and $k = 2\pi/\lambda$ is the wave number.

The capacity of a MIMO system may be obtained as [10]:

$$C = \log_2 \left(\det \left[\mathbf{I} + \frac{P_T \mathbf{H} \mathbf{H}^*}{\sigma^2} \right] \right), \quad (3)$$

where P_T and σ^2 are transmit and noise power, respectively, $\mathbf{I}$ is the identity matrix, and $(\cdot)^*$ denotes the transpose conjugate.

The channel matrix can be normalized with the Frobenius norm. Then, the channel capacity is defined as a function of the Frobenius normalized eigenvalues λ_i [10]:

$$C = \sum_{i=1}^N \log_2 \left(1 + \frac{P_R \lambda_i}{\sigma^2} \right), \quad (4)$$

where P_R denotes the received power.

IV. SYSTEM MODEL

The system model consists of three main parts described below: the urban environment, the BS geometry, and the multi-antenna vehicle setup. In addition, some details about the numerical modeling of the propagation are given.

A. Urban Environment

A portion of a real city is chosen to simulate the V2I environment. Fig. 2 depicts two crossing streets in the city of

Fig. 2. The scenario of the intersection in Barcelona.

Barcelona, corresponding to the district of *L'Eixample*, which is characterized by its rectangular shapes and almost 90 degrees corners. The environment is composed of a ground plane made of asphalt, five buildings, three of them with courtyards, traffic and street lights and trees. Realistic object materials are considered in the model. Therefore, we model buildings as concrete and trees with a wooden trunk and vegetation on top. The latter lets rays pass through at the cost of additional attenuation. We consider street and traffic lights made of metal. The height of all the buildings is 18 m and the BS is placed on the top of one of them at a height of 21 m from the ground, i.e., 3 m above the rooftop.

Fig. 2 depicts the investigated vehicular trajectories, A and B, sampled every 0.1 m. The total lengths of A and B are 140 and 55 m, respectively. The main difference between both trajectories is the blockage of the direct path from the transmitter to the receiver (non line of sight (NLOS)) in the case of trajectory B. Trajectory A is mainly in obstructed line of sight (OLOS), due to the trees, with a line of sight (LOS) region after the corner. In trajectory A, two reference points are selected: P_1 (at 45 m in the trajectory, at 106.5 m distance from the BS) and P_2 (80 m along the trajectory, 84 m from the BS). A third point, P_3 , is placed at 30 m in trajectory B. The distance from P_3 to the BS is 77 m on a line, but the focusing strategy uses the radio path to the opposite wall, with a total distance of 150.5 m.

Each of the focusing points presents different visibility characteristics and is used to evaluate the system performance under different conditions. In summary:

- P_1 is in trajectory A in OLOS
- P_2 is in trajectory A in LOS
- P_3 is in trajectory B in NLOS

B. Base Station Multi-Antenna Geometry

We investigate a potential 5 G massive MIMO geometry with Q patch-antenna elements, as proposed by Shintaro Shinjo *et al.* in [11]. Fig. 3 shows three BS configurations:

- 1) a single $M \times N$ module,
- 2) two modules of $M \times N/2$ elements and half of the power each, and

Fig. 3. Massive BS with $M \times N$ patch antennas and the sub-array divisions into distinct mMIMO configurations.

3) four modules of $M \times N/4$ elements and a quarter of the power each.

In this study, two different frequency bands are compared in terms of their electromagnetic properties. Given the propagation loss increase with frequency, larger gain is required to partially compensate this effect. In this regard, two BS geometries are considered for the two frequencies of interest, aiming to maintain similar values of the total physical area. At 3.6 GHz, the geometry is composed of 4 elements in elevation and 16 in the azimuth plane ($4 \times 16 = 64$ in total), whereas, at 26 GHz, the antennas are scaled to fit 16 patches in elevation and 128 in azimuth ($16 \times 128 = 2048$ in total). Each element is considered to have continuous phase shifting capabilities and they are arranged according to the particular mMIMO configuration into different digital inputs. For both frequencies, the available power is fixed to 0 dBm.

In each module, a beam is produced with uniform amplitude weights and phase shifting. Phased arrays are the most extended beamforming architectures given their lower power consumption compared to other more complex strategies. Perfect knowledge of the vehicle position is assumed. Therefore, it is possible to calculate the appropriate phases to steer each of the sub-array beams towards the vehicle position. In the case of trajectory A, the beam is steered directly towards the focusing area. For trajectory B the beam is steered towards the opposite wall in order to reflect towards the focusing area.

Fig. 4 represents the gain pattern of the mSISO BS pointing towards P_2 . Due to the particular arrangement of the antennas, the beamwidth of the main lobe is wider in elevation than in azimuth and it provides poorer spatial resolution in the longitudinal axis. In Fig. 4, a gain difference of about 15 dB can be seen between the two geometries. The larger number of elements at the mmWave frequency implies a more directive pattern which is used to obtain a similar received power level at the user using the same source available power.

Fig. 5 shows the horizontal power distribution at sub-6 GHz (3.6 GHz) and near mmWave (26 GHz) for a massive BS focusing towards P_2 . For a given antenna physical size, the focusing capabilities are tightly related to the operating frequency, which also affects the scattering effects.

C. Vehicle Multi-Antenna Geometry

Fig. 6 depicts the vehicle with one, two, or four independent monopole antennas. They are aligned into a shark-fin like

Fig. 4. Gain polar patterns of the massive BS when pointing towards P_2 in free space at 3.6 and 26 GHz. (a) Azimuth pattern for $\theta = 101^\circ$. (b) Elevation pattern for $\phi = 71^\circ$.

structure on the car rooftop, at 1.42 m from the ground. The antennas are designed to resonate at each of the operating frequencies.

Pursuing low antenna correlation [12], an inter-element distance of half wavelength ($\lambda/2$) is considered [13]. The radiation pattern of the different elements is calculated taking into account the presence of the whole car, and it is assumed that it is not significantly modified by the environment.

D. Numerical Propagation Model

The propagation simulation approach is based on ray-tracing techniques in which transmitter and receiver antenna far-field patterns are used to set the angular weight of the outgoing and incoming rays. Each ray suffers different reflection and diffraction processes. In this way, the transmitter is properly modeled as long as any object intercepting a launched ray is located beyond the far field region of the antenna. The receiving antennas are modeled in presence of the vehicle platform. We use the electromagnetic solver *FEKO* to obtain the angular radiation of the individual radiation elements [14]. In order to obtain the channel matrix, the former angular distribution is introduced into the ray-tracing tool *WinProp*, see also [14]. From the obtained channel matrix, the eigenvalues and the resulting

Fig. 5. Power distribution of mSISO BS placed at 21 m height and focusing with 0 dBm power towards P_2 at both frequencies, where the receiver is placed at 1.42 m. (a) 3.6 GHz. (b) 26 GHz.

Fig. 6. Three different vehicle antenna setups with one, two, and four monopoles at 1.42 m and radiation pattern of the single antenna on top at 26 GHz.

capacity can be calculated to compare the performance of the mMIMO configurations.

The ray tracing approach used in the propagation software in which the study is based has already been validated by experimental measurements, for instance in [15], where good agreement between simulation and measurements is found. In order to provide an adequate trade-off between computation complexity and accuracy the following scenario interactions are considered: a maximum of one transmission (through an object), three reflections and two diffractions per ray. In case of the higher frequency (26 GHz), the transmissions through the objects are neglected given the large attenuation in concrete walls and tree trunks.

TABLE II
SIMULATION PARAMETERS

Parameter	Notation	Values	Unit
Transmit power	P_T	0	dBm
Carrier frequency (S-band)	f_{c1}	3.6	GHz
Carrier frequency (K-band)	f_{c2}	26	GHz
Antenna elements BS (S-band)	Q_1	64	-
Antenna elements BS (K-band)	Q_2	2048	-
Maximum bandwidth (S-band)	B_1	100	MHz
Maximum bandwidth (K-band)	B_2	400	MHz
RX noise figure	NF	4	dB
Distance BS to reference point P_1	d_1	106.5	m
Distance BS to reference point P_2	d_2	85.4	m
Distance BS to reference point P_3	d_3	150.5	m

The work in [6] details the angular and temporal profile of multipath components in a vehicular scenario. The authors investigate the number of paths to be considered under LOS and NLOS conditions according to different thresholds (power level below the most dominant path) in sub-6 GHz and mmWave frequencies. The number of interactions chosen in the simulations has been agreed to reach the minimum number of relevant multipaths above the noise. In particular, up to 20 different paths are calculated, what is enough for dominant components of 30 dB greater than the noise level when omnidirectional radiators are used both in the transmitter and the receiver. The use of directive beams also attenuates some components and even less relevant paths could be considered.

V. SIMULATION RESULTS AND DISCUSSION

In this section, the performance of the different mSISO and mMIMO configurations are analyzed for the previously defined simulation environment. Channel capacity and eigenvalues are computed along the trajectories (see Fig. 2). A massive BS is set as the transmitter with an overall available power of 0 dBm. The focusing capabilities of these geometries allow to concentrate the radiated fields around the user at different positions. The physical dimensions of the BS are comparable for the two investigated frequencies: 64 patch antennas at 3.6 GHz, which are translated to an area of 0.11 m²; and 2048 antennas at 26 GHz, equivalent to a physical area of 0.07 m². The ratio of surface areas corresponds to $10 \log(\frac{S_{3.6}}{S_{26}}) = 1.9 \text{ dB}$, where S_f corresponds to the total physical area of the array at the frequency f . According to the description in section IV-B, the larger number of elements of the mmWave array leads to a more directive pattern (about 15 dB more). The higher gain partially compensates the additional free space losses due to the frequency increment, which are $20 \log 26/3.6 = 17.2 \text{ dB}$. Table II lists the main parameters used in the numerical analysis.

When the receiver (vehicle) is considered, each trajectory may be divided in two regions. First, the focusing area corresponds to the main beam footprint, where the user vehicle is located and the received power is higher. For the area outside this region of interest, the radiated power should be kept as small as possible to reduce the inter-user interference and improve the system efficiency. The focusing area is defined according to the scenario conditions and the -3 dB beamwidth for the mSISO case at both

frequencies in the most restrictive dimension. At 3.6 GHz, it is translated to an interval of 30 m centered at each reference point, whereas at 26 GHz the interval is reduced to 8 m. The noise figure in the receiving chain is assumed to be 4 dB, which corresponds to a noise level of -90 dBm for $B_1 = 100$ MHz and -84 dBm for $B_2 = 400$ MHz.

The figure of merit for each reference case is defined as the average channel capacity for all points in the focusing area:

$$C_{av.} = \frac{1}{N_S} \sum_{i=1}^{N_S} C_i \quad (5)$$

being N_S the number of sampled receiver positions.

A. Beam Pointing and Received Power

Fig. 7 represents the received power along the two trajectories when the beam is focused towards the three reference points. In this case, the BS is using all the Q antennas as an array, i.e., MIMO is not used. The focusing capability is higher for the mmWave frequency due to the larger number of elements, but the final performance (capacity) also depends on the scattering properties of the environment. The focusing area at the three reference points is highlighted in grey for the 3.6 GHz geometry and blue for 26 GHz.

In trajectory A, the LOS path is used for the steering due to the availability of a direct view to the car, even though it may be attenuated by the foliage. The BS perfectly concentrates the power around the two points P_1 and P_2 (Fig. 7a and 7b) for the two frequencies. The main difference between 3.6 GHz and 26 GHz is the width of the focusing area and the depth of the fast fading notches. It implies that a faster beam switching is required for the higher frequency.

Regarding trajectory B (Fig. 7c), it is completely in NLOS. The beam is focused to the strongest reflection, corresponding to a wall. In this case, the focusing is degraded and the attenuation due to the reflected ray and the trees present in the radio path reduce the received power between 10 and 20 dB when an obstacle crosses the radio path.

B. Analysis of the MIMO Eigenvalues

In a MIMO system, the channel diversity determines the final improvement in terms of capacity with respect to the use of a single radio channel. The eigenvalues are analyzed for the two trajectories when the BS is horizontally divided in modules. The beamwidth is increased with the number of modules, since less elements are used to create each beam. A trade-off between focusing (more received power and, hence, SNR) and number of channels is also a matter of interest. In order to evaluate the channel eigenvalues, the case of mMIMO 4×4 is used.

Fig. 8 shows the eigenvalues for LOS and OLOS corresponding to trajectory A. The BS beam is switched from P_1 to P_2 at the intermediate point between them. Both systems perform clearly different at the two frequencies as can be seen in the figures. At 3.6 GHz, the first normalized eigenvalue is always below 0.9 and sometimes comparable to the second one, or even the third value. At 26 GHz, one single usable radio path is evident. A

Fig. 7. Received power for mSISO BS at 3.6 and 26 GHz. (a) BS focusing towards P_1 . (b) BS focusing towards P_2 . (c) BS focusing towards P_3 .

relevant eigenvalue over 0.9 is present within the focusing areas of both reference points. The distribution and attenuation of the multipath components at both frequencies justify this difference. An example is shown in Fig. 9. The angle of arrival (AoA) of all the rays in the simulation environment for P_2 is shown when

(a)

(b)

Fig. 8. Normalized eigenvalues for mMIMO 4x4 at each position on trajectory A, in (O)LOS. The beam is switched from P_1 to P_2 in the intermediate point between them. (a) Eigenvalues at 3.6 GHz. (b) Eigenvalues at 26 GHz.

the system performs in mMIMO 4 $\times$ 4 configuration at 3.6 and 26 GHz. The larger directivity of the BS and the attenuation of the reflected and diffracted paths at the higher frequency leads to narrower distribution of the multipaths. On the other hand, the arrival of rays is more uniformly distributed at 3.6 GHz.

Fig. 10 depicts the eigenvalues of trajectory B. The entire trajectory is in NLOS condition but the particular beamforming strategy focuses the power towards the strongest reflection. The distribution of the eigenvalues is then conditioned, especially for the mmWave frequency due to the more directive pattern. In this sense, a single relevant eigenvalue can be seen within the focusing area at 26 GHz. The wide beam used at 3.6 GHz allows to include several objects intercepting the rays in the focusing area (much wider compared to 26 GHz). The interaction with those objects produces a strong variation of the eigenvalues. When the car approaches the corner in the last meters, outside the focusing area for both frequencies, two different results are obtained depending on the frequency. At 3.6 GHz, the diffraction effect of the main lobe represents the strongest contribution and a single relevant eigenvalue is obtained. At 26 GHz, the main beam is not reaching the corner and the diffraction of rays is

Fig. 9. Normalized AoA distribution at 3.6 and 26 GHz for the reference point P_2 in mMIMO 4 $\times$ 4 configuration.

weaker at high frequencies. For that reason, around the corner, the main contribution is given by the multiple reflection effects of the secondary lobes and the eigenvalues tend to equalize.

The effect of the diffracting corner has also a strong contribution even inside the focusing area. In Fig. 11, the AoA distribution at P_3 is depicted for the two frequencies. It is possible to state that the rays coming from the corner (at 0 degrees) are even stronger than the ones coming from the focusing direction (about 300 degrees). This particular focusing strategy is not working properly in NLOS since most of the power is received from a different direction. When a mMIMO configuration is used, the wider beamwidth leads to a stronger power of those diffracted rays, whereas the focusing direction is penalized.

C. Average Capacity

The overall performance of the system for the different geometries is finally evaluated in terms of the average capacity over the focusing area for each reference point. The average capacity is obtained by (5). It is compared for the two frequencies used in this study and as a function of the number of radio channels: mSISO, mMIMO 2 $\times$ 2, and mMIMO 4 $\times$ 4. We use a bandwidth $B_1=100$ MHz for both frequencies and a second larger bandwidth $B_2=400$ MHz only in K-band. The transmitter power of 0 dBm is equally split into the different modules, which implies a 3 dB or 6 dB power reduction at each sub-array for mMIMO 2 $\times$ 2 and 4 $\times$ 4, respectively.

Fig. 12 shows the average capacity for OLOS, LOS, and NLOS. When comparing the case of both frequencies using $B_1=100$ MHz (blue and red bars), it is seen that the lower frequency performs better in all cases, for which the use of mMIMO configurations outperforms the mSISO significantly as well. The use of a single beam direction takes advantage of the directive nature of the propagation environment at mmWave frequencies as seen in the eigenvalue analysis. In addition, the high SNR achieved in LOS (Fig. 12b) makes the hybrid division of the massive geometry a good strategy to improve the achievable capacity, despite the directivity loss at each sub-array. Considering the larger bandwidth available at 26 GHz, it is shown that, by increasing it to $B_2=400$ MHz, the achievable

Fig. 10. Normalized eigenvalues for mMIMO 4x4 at each position on trajectory B with beam pointing towards P_3 (NLOS case). (a) Eigenvalues at 3.6 GHz. (b) Eigenvalues at 26 GHz.

channel capacity is comparable, or higher, with respect to the sub-6 GHz band.

Fig. 13 shows the evolution of the average capacity for different values of bandwidth when the BS is focusing towards the three reference positions. The evolution follows the expected performance and similar capacity is obtained at mmWave frequencies to the cost of larger bandwidth compared to the 3.6 GHz band. For NLOS cases, the increment is less noticeable and other focusing strategies could be applied to improve the SNR perceived by the user.

D. High-Mobility Environments

The use of massive architectures and directive beams require more accurate and faster systems to manage the resources and steer the radiation diagram towards the right direction. This is particularly challenging when we are dealing with users moving at high velocities. In [7], Va *et al.* investigate the impact of those beamforming geometries in vehicular channels. They discuss the use of the channel coherence time as refreshing period for the beams and introduce the concept of beam coherence

Fig. 11. Normalized AoA distribution at 3.6 and 26 GHz for the reference point P_3 in mMIMO 4x4 configuration.

time, which allows a slower update with better performance when the alignment overhead is considered. Given the particular distribution of rays, as seen in previous section, the Clarke-Jakes assumption of uniform angular spread is no longer valid and the channel coherence time cannot be approximated by the inverse of the Doppler frequency, $T_C \simeq \frac{1}{f_D}$, in beamforming situations.

The authors in [7] define the channel coherence time in LOS and NLOS for vehicular scenarios with very directive beams as:

$$T_{C,LOS}(\theta) = \frac{D_\lambda}{f_D \sin(\alpha_{LOS})} \cos^{-1}(2\theta^2 \log R + 1) \quad (6)$$

$$T_{C,NLOS}(\theta) = \frac{1}{2\pi f_D} \sqrt{\frac{1}{\theta^2} \log \frac{1}{R^2} - (\log R)^2} \quad (7)$$

In (6) and (7), $f_D = \frac{v}{c} f_0$ is the Doppler frequency shift, θ is the BS beamwidth, α_{LOS} is the AoA of the LOS path, $D_\lambda = D/\lambda$ is the TX-RX LOS distance in wavelength units and R is the correlation threshold for which the channel is considered uncorrelated. The LOS distance is set to $D = 96$ m, as it is the mean value between P_1 and P_2 LOS distance. Typical values of R range from 0.3 to 0.9 [16]. In this case, a value of $R = 0.5$ is used. Previous expressions assume that the scatterers and the transmitter are very far from the receiver in terms of the wavelength, the beam is perpendicular to the traveling direction (fastest fading) and the pointing error due to the movement is ignored. The beamwidth at 3.6 GHz is 15° and it reduces to 3° at 26 GHz. The LOS path is assumed to be perpendicular to the car, equal to the beam direction, $\alpha_{LOS} = 90^\circ$.

The concept of beam coherence time is defined as:

$$T_{B,LOS}(\theta) = \frac{D_\lambda}{f_D \sin \mu_r} \cos^{-1}(\theta^2 \log \zeta + 1) \quad (8)$$

$$T_{B,NLOS}(\theta) = E_\beta \left[\frac{D_{r,\lambda}}{f_D \sin \mu_r} \cos^{-1}((\beta^2 + \theta^2) \log \zeta + 1) \right] \quad (9)$$

In (8) and (9), μ_r is the pointing direction with respect to the direction of movement (90° as in (6) and (7) is considered), $D_{r,\lambda} = D_r/\lambda$ is the distance to the scatterers in terms of wavelength of the one-ring model and ζ is ratio that the received power has to fall to consider the beam misaligned. The values used in this analysis are $D_r = 10$ m, corresponding to the road

Fig. 12. Average channel capacity in the three focusing areas. (a) P1 (OLOS). (b) P2 (LOS). (c) P3 (NLOS).

Fig. 13. Average capacity versus bandwidth for massive architectures at 3.6 and 26 GHz when single beam focusing is used. (a) P1 (OLOS). (b) P2 (LOS). (c) P3 (NLOS).

width, and the misalignment threshold is set to $\zeta = -3$ dB. Finally, $\beta \sim \mathcal{N}(m_{AS}, \sigma_{AS}^2)$ is an empirical model of the angular spread lobe width based on a Gaussian distribution [17]. The measurements performed in [17] in an urban area revealed a value of $\sigma_{AS} = 25.7^\circ$. The mean, m_{AS} , is chosen to be 62.7° at 3.6 GHz and 31.4° at 26 GHz [18], [19]. $E_\beta[\cdot]$ is the expected value over the angular spread parameter, β .

These metrics allow us to define reasonable bounds for the beam switching times. Fig. 14 shows the channel and beam

coherence times for some typical velocities in urban environments (assuming a static transmitter like the cellular BS) given the mSISO radiation patterns used in this study.

In the case of the channel coherence time (Fig. 14a), the range of values is very diverse when the speed is modified. In the NLOS case, velocities close to 100 km/h present uncorrelated channels

Fig. 14. Channel and beam coherence time for the mSISO geometries at 3.6 and 26 GHz. (a) Channel coherence time. (b) Beam coherence time.

almost every millisecond, near the expected duration of a slot in next-generation 5G networks [20]. This case is particularly challenging when one considers cars driving in opposite directions or in highway scenarios. The use of the beam coherence time as a metric to update the steering direction implies a reduction of the switching frequency of some orders of magnitude. Despite the LOS behaves similarly to the $T_{C,LOS}$ case (perpendicular steering leads to faster change of the channel), the NLOS situation reveals slower variations even for high velocities. This new metric could relax the update of the beams and decrease the power consumption, as well as the alignment overhead, which translates to larger spectral efficiency. When comparing the two bands, sub-6 GHz and mmWave, the main difference is given in LOS due to the beamforming strategy that focuses the power towards the direct path. The narrower beam considered at the higher frequency leads to a faster change of the channel and the necessity of a more frequent update of the steering.

VI. CONCLUSION

In this paper, we have investigated the performance of different mMIMO configurations in terms of their eigenvalues, channel capacity, and focusing capabilities. The necessity of

compensating extra propagation losses proportional to the frequency lead to larger massive geometries and more accurate beamforming techniques. The eigenvalues and capacity analysis suggest that the system performance may be enhanced by subdividing the massive BS into four modules, i.e., mMIMO 4x4 for the sub-6 GHz case. In the mmWave band, the eigenvalues are significantly less uniform, but still better performance is obtained when the mMIMO configurations are used. The improvement is particularly high in LOS situations, in which high SNR regimes are obtained. The larger spectrum availability in this region allows a bandwidth increment by, at least, a factor of four, which translates to better performances of the mmWave band compared to the sub-6 GHz band.

The significant step of moving from one up to four antennas on the vehicles is mainly justified by the potentially larger capacity, but also for diversity purposes to avoid deep fading effects at higher bands. Smart antennas with beamforming capabilities on the vehicle still need to be studied given the possible increase in capacity as well. It is also shown that an accurate steering massive geometries in high-mobility environments is necessary in future radio networks. A long-term parameter as the beam coherence time is used to predict the channel variations in beamforming vehicular scenarios.

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