Results of a MIMO Testbed with Geosynchronous Ku-Band Satellites

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***Abstract*—If multiple-input multiple-output (MIMO) satellite communications (SATCOM) systems use spatial multiplexing instead of polarization multiplexing, the channel capacity depends on the geometrical conditions of the antenna setup. This theoretical result is proven and confirmed for the first time by a true-MIMO test campaign. We utilize two Ku-band satellites and a ground station with two antennas as a 2 $\times$ 2 MIMO SATCOM system. The channel capacity is estimated and compared to its theoretical prediction. Moreover, a MIMO data transmission scheme based on single-carrier frequency domain equalization is applied and tested.**

I. Introduction

Due to their potentially high bandwidth efficiency, multiple-input multiple-output (MIMO) systems are an integral part of today's terrestrial wireless communications standards. In SATCOM, however, the applicability of the MIMO technology is subject to contentious discussions in the scientific community. The main reason can be found in the characteristics of the SATCOM channel. The satellite channel for Fixed Satellite Services (FSS) or Mobile Satellite Services (MSS) in frequency bands above $10\,\mathrm{GHz}$ is specified by a strong Line-of-Sight (LOS) signal with no or negligible multipath components (MPC), where MPC are widely believed to be a prerequisite for high MIMO gains.

On the other hand, it has already been shown by theory that high MIMO gains in strong LOS channels are possible, if particular antenna geometries are considered. This idea has been applied to SATCOM systems in [1], and a criterion has been developed for the optimal positioning of the MIMO antenna elements on Earth and in geostationary earth orbit (GEO). It has been shown that the inter-antenna spacing is a key parameter, but comparably large separations are required either on Earth or in orbit. This leads to mainly two concepts: a) multiple antennas onboard a single-satellite, or b) multiple satellites at different orbit positions.

This paper is dedicated to prove for the first time the theoretical results provided in [1] by means of real satellite channel measurements. More precisely, we will probe the MIMO channel with an appropriate training sequence which gives us the channel capacity in return. To this end we have developed a measurement system comprising two transmitter (Tx) antennas and two receiver (Rx) antennas on Earth. A single-satellite with two antennas and overlapping service zones in up- and downlink and in the same frequency bands is not available yet. Therefore, we have developed a special setup that provides us with a MIMO channel formed by two existing satellites working in the same frequency band. We utilize the two satellites "EUTELSAT 7B" (E7B) and "EUTELSAT 10A" (E10A), which have a small frequency range in common, provide an overlapping downlink coverage, and are only 3° apart. We use small Rx antennas with a wide main lobe so that both satellites can be received simultaneously when the Rx antennas point directly between E7B and E10A. An adjustable Rx antenna separation on ground enables us to probe the influence of the antenna geometry on the channel capacity.

The conducted SATCOM measurement campaign with spatially distributed antenna elements on ground and in orbit is the first of its kind. We consider the results as a breakthrough towards future MIMO SATCOM implementations since the achievable MIMO capacity has now been practically determined and validated. The probing results will prove very impressively that carefully placed antenna elements lead to the maximum channel capacity in MIMO SATCOM applications. Thus, seven years of its original publication at the Workshop on Smart Antennas (WSA) 2008 in Darmstadt, Germany, we will now report on the practical "proof of concept" of this innovative approach.

II. Overview of the Measurement System

The MIMO satellite measurement system consists of two Tx terminals, two Rx terminals and two GEO satellites. Fig. 1 shows a graphical illustration of the setup. We have used leased capacity on the two GEO satellites E7B and E10A at 7° East and 10° East, respectively. Both satellites provide transparent payloads and share a small part of the Ku-band spectrum in up- and downlink. In particular the up- and downlink center frequencies have been $f_c^{(\mathrm{u})} = 14.005\,\mathrm{GHz}$ and $f_c^{(\mathrm{d})} = 12.505\,\mathrm{GHz}$, respectively, with an available bandwidth of $500\,\mathrm{kHz}$ on both satellites. They are equipped with linearized traveling wave tube amplifiers (TWTAs) and are operated in the linear regime. Tx and Rx are both located at 48.08° North and 11.64° East, which is on the roof top of our laboratory building in Neubiberg, Germany. A photography of the Tx and Rx antenna farm is shown in fig. 2.

The Tx antennas are $1.8\,\mathrm{m}$ dishes having a $3\,\mathrm{dB}$-beamwidth of approximately 0.8° at $14\,\mathrm{GHz}$ and a maximum equivalent isotropically radiated power (EIRP) of $55.7\,\mathrm{dBW}$ each. They act as two single-input single-output (SISO) feeder uplinks,

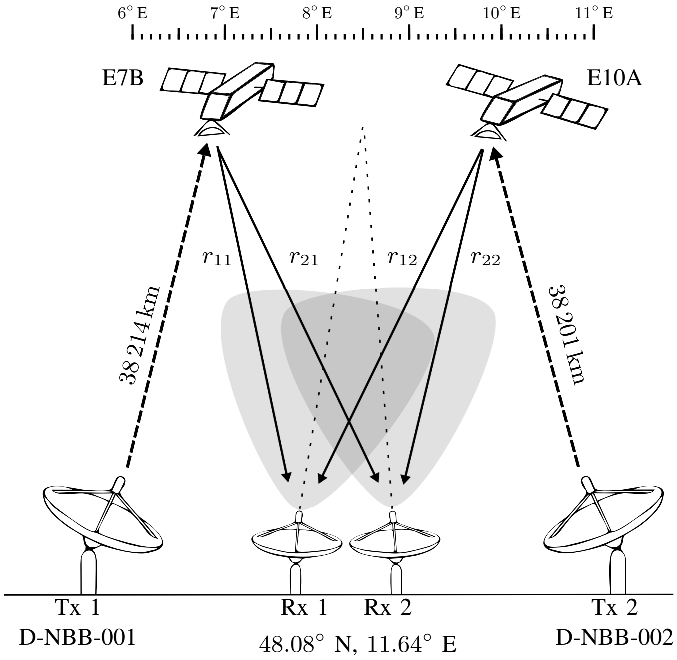

Fig. 1. Overview of the measurement system and setup.

one for each satellite, i.e. Tx antenna 1 points towards E7B, and Tx antenna 2 points towards E10A.

The downlink forms a 2×2 MIMO channel with two elliptical aperture dishes with $0.75\,\mathrm{m}$ equivalent diameter, having a $3\,\mathrm{dB}$-beamwidth of approximately $2.0°$ at $12\,\mathrm{GHz}$ each. Both Rx dishes point at the geostationary arc at longitude $8.5°$ East, i.e. exactly between E7B and E10A so that both downlink signals can be received by each Rx antenna simultaneously via the edges of the main lobe. As a consequence we have to cope with a gain fall out of approximately $-12\,(1.5°/2.0°)^2 = -6.8\,\mathrm{dB}$[1]. The resulting effective figure of merit (G/T) towards each satellite is approximately $17.3\,\mathrm{dB/K} - 6.8\,\mathrm{dB} = 10.5\,\mathrm{dB/K}$. Moreover, to estimate the MIMO capacity as a function of the antenna geometry, Rx antenna 2 is moveable on a bar (please see fig. 2). Thus, the inter-antenna distance d between both Rx antennas can be adjusted along a fine grid within a range of $1.4\,\mathrm{m}$ to $3.7\,\mathrm{m}$.

All ground components run with a common $10\,\mathrm{MHz}$ reference clock from one Rubidium oscillator and are, thus, perfectly synchronized in frequency and time. Due to free running oscillators in the satellites and independent movements of both satellites within their station keeping box, a carrier frequency offset between both receive signals at Rx 1 and Rx 2 needs to be considered. This carrier frequency offset has been estimated before each channel access by comparison of the center frequencies at Rx 1 and Rx 2. Through individual and appropriate tuning of each uplink center frequency at Tx 1 and Tx 2 this carrier offset has been compensated successfully.

[1]Please note, that this calculation is only valid for sufficiently small off-axis angles, i.e. typically smaller than half the $3\,\mathrm{dB}$-beamwidth. Although this is not fulfilled in our scenario this value is sufficient to get a rough estimate for the link budget. The estimate is sufficient for the analysis presented in this paper.

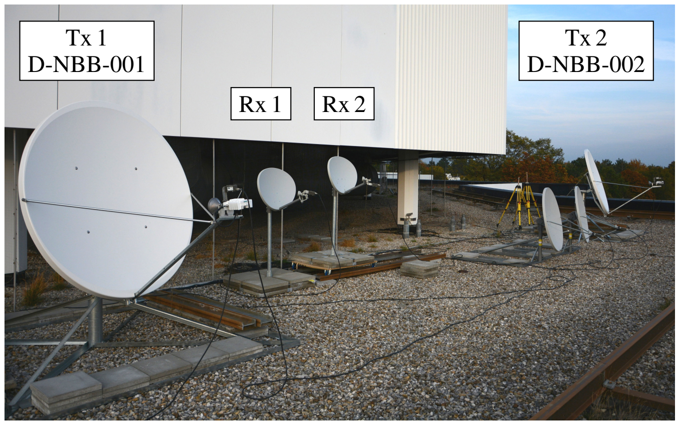

Fig. 2. Photography of the antenna farm showing the Tx and Rx antennas of the MIMO SATCOM measurement system.

III. MIMO Satellite Channel

We consider a system bandwidth $B_w = 100\,\mathrm{kHz}$ much smaller than the carrier frequencies $f_c^{(\mathrm{u})} = 14\,\mathrm{GHz}$ and $f_c^{(\mathrm{d})} = 12.5\,\mathrm{GHz}$ of the up- and downlink, respectively. In that case the satellite channel is a frequency flat fading LOS channel, which has been proven through channel measurements in [2]. The LOS channel coefficient H_{mn} between the n-th Tx and the m-th Rx antenna can be modeled in complex baseband as[2]

$$H_{mn} = a_{mn} \exp\{-\mathrm{j}\,\vartheta_{mn}\}. \qquad (1)$$

The magnitude a_{mn} incorporates all gains and losses of the respective uplink, downlink, and payload, and ϑ_{mn} is the phase shift resulting from the propagation delay and the transmission delay of the payload, respectively. Taking the downlink as an example and neglecting all atmospheric effects, the LOS channel coefficient can be modeled according to the free space wave propagation

$$H_{mz}^{(\mathrm{d})} = \frac{\lambda_c^{(\mathrm{d})}}{4\pi r_{mz}} \exp\left\{-\mathrm{j}\,\frac{2\pi}{\lambda_c^{(\mathrm{d})}} r_{mz}\right\}, \qquad (2)$$

Here, $\lambda_c^{(\mathrm{d})}$ is the wavelength at the downlink center frequency, i.e. $\lambda_c^{(\mathrm{d})} = c_0/f_c^{(\mathrm{d})}$ with c_0 being the speed of light in free space. r_{mz} is the path length between the m-th Rx antenna on the ground and the z-th satellite. We denote the 2×2 MIMO channel transfer matrix (CTM) as $\boldsymbol{H}$ that contains the four LOS channel coefficients H_{mn} in the case of a narrowband LOS channel. Furthermore, we introduce the normalization of the CTM as follows:

$$[\boldsymbol{H}_{\mathrm{norm}}]_{m,n} = H_{mn}/\,|H_{mn}| = \exp\{-\mathrm{j}\,\vartheta_{mn}\} \qquad (3)$$

This normalization reduces the CTM to its phase entries.

[2]In this paper the following mathematical notations are applied: $\mathrm{E}\{.\}$ is the expectation operator over all possible realizations of a random variable. $\det(.)$ is the determinant of a matrix. $(.)^{\mathrm{H}}$ and $(.)^{\mathrm{T}}$ is the conjugate transpose and the transpose of a matrix or a vector, respectively, and $\sqrt{\mathrm{j}} = -1$. $\boldsymbol{I}$ is the identity matrix of appropriate dimension.

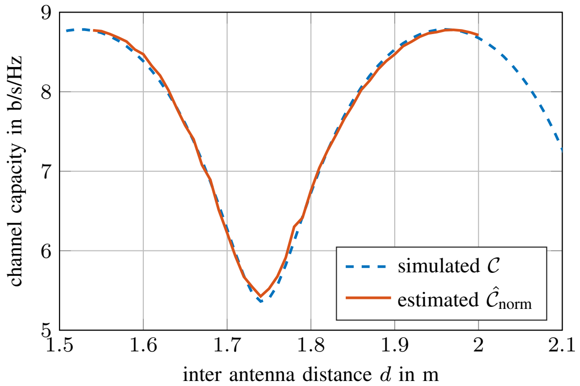

Fig. 3. Capacity estimation of the measured MIMO SATCOM channel and comparison with simulation results, assumed $\rho^{(\text{ref})}$ of $10\,\text{dB}$.

IV. MIMO Channel Capacity Calculation

A. Capacity using the Theoretical Channel

The MIMO spectral efficiency with arbitrary and equally probable transmit symbols as channel inputs, and in case of additive white Gaussian noise (AWGN) is calculated according to [3]

$$\mathcal{C} = \log_2 \left(\det \left(\boldsymbol{I} + \rho^{(\text{ref})} \cdot \boldsymbol{H}_{\text{norm}} \boldsymbol{H}^{\text{H}}_{\text{norm}} \right) \right), \tag{4}$$

where $\rho^{(\text{ref})}$ is any reference signal-to-noise ratio (SNR) at the receiver input.

It has been shown by theory that in strong LOS channels distinct geometrical arrangements between the Rx and Tx antenna elements are the key to obtain orthogonal channels with maximum capacity. This has been applied in [1] to derive a general optimization criterion for orthogonal LOS MIMO channels. For the 2×2 downlink case analyzed in this paper, the geometrical criterion is

$$r_{21} - r_{22} + r_{12} - r_{11} = v \frac{\lambda_c^{(\text{d})}}{2}, v \in \mathbb{Z}, v \nmid 2. \tag{5}$$

v is an integer and can be chosen arbitrarily in $\mathbb{Z}$ but must be indivisible by 2, i.e. $v \nmid 2$. Applying the geographical parameters of our measurement setup from fig. 1, condition (5) delivers an optimal spacing of the Rx antennas of[3]

$$d_{\text{opt}} = v \cdot 21.7\,\text{cm}. \tag{6}$$

Odd multiples of this optimal inter-antenna spacing on Earth result in an orthogonal MIMO downlink channel as the measurement results will show in the following section.

B. Probing Results

Using $\hat{\boldsymbol{H}}_{\text{norm}}$, the estimated channel capacity writes

$$\hat{\mathcal{C}}_{\text{norm}} = \log_2 \left(\det \left(\boldsymbol{I} + \rho^{(\text{ref})} \cdot \hat{\boldsymbol{H}}_{\text{norm}} \hat{\boldsymbol{H}}^{\text{H}}_{\text{norm}} \right) \right). \tag{7}$$

To verify the dependence of the capacity on the antenna geometry we measured the MIMO SATCOM channel for different Rx antenna separations. The result is given in fig. 3 showing the estimated capacity $\hat{\mathcal{C}}_{\text{norm}}$ according to (7) as a function of d. The inter-antenna spacing d has been adjusted in steps of $1\,\text{cm}$ by hand, starting with approximately $d_{\text{opt}} = 7 \cdot 21.7\,\text{cm} = 1.52\,\text{m}$. To compare $\hat{\mathcal{C}}_{\text{norm}}$ derived from measurements with our theoretical predictions, the theoretical LOS MIMO channel $\boldsymbol{H}_{\text{norm}}$ has been simulated. Using $\boldsymbol{H}_{\text{norm}}$ the exact capacity $\mathcal{C}$ according to (4) has also been calculated and is shown in the figure.

The probing results match very well the theoretical simulations. The curves in fig. 3 prove the predicted dependence of the channel capacity on the antenna geometry very exactly.

[3] To calculate this value eq. (22) in [1] has been applied.

V. Content of the Final Paper

The final paper will provide the following analysis and results:

- Derivation of the MIMO channel capacity for the distinct application case
- Description of the applied Maximum-Likelihood channel estimator, derivation of the measurement accuracy, and provision of an error analysis for the channel capacity estimation
- First test results of a MIMO transmission as published in [4]
- Extensive discussion of the measurement results

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