IEEE Sensors Letters Volume () ()
Microwave/millimeter wave sensors

Dual-Band Dual-Polarized Massive MIMO Array for Maritime Applications

Jiahao Zhang [1], Kun Yang [2], Jin Meng [1], Wei Li [1], Egil Eide [3], and Guy A. E. Vandenbosch [4*]

[1] *National Key Laboratory of Science and Technology on Vessel Integrated Power System, Naval University of Engineering, Wuhan 430033, China*
[2] *Super Radio AS, Toftes Gate 2, 0556 Oslo, Norway*
[3] *Department of Electronic Systems, NTNU, O.S. Bragstads plass 2b, 7491 Trondheim, Norway*
[4] *ESAT-WAVECORE Research Division, Department of Electrical Engineering, KU Leuven, 3001 Leuven, Belgium*
** Fellow, IEEE*

Received 24 Jun 2020

Abstract—A dual-band dual-polarized massive MIMO antenna array is presented for maritime communications and sensing applications in the 5.1 and 5.9 GHz bands. Passive elements are introduced in the array to achieve a low gain pattern variation in both bands. The optimal element spacing is studied, relying on the impact of mutual coupling and the radiation performance of the embedded elements. The topology of the MIMO array is also studied based on the system-level performance. The array was prototyped, validating the proposed concept.

Index Terms—Massive MIMO, dual-band antenna, dual-polarized antenna, antenna array, element spacing.

I. INTRODUCTION

Massive Multiple-Input Multiple-Output (MIMO) is believed to be a promising candidate technology in future wireless communication and sensing systems [1]. Equipped with a large number of antenna elements, massive MIMO provides orders of magnitude improvement in both spectral and transmitted energy efficiencies, and offers a great capacity increase. Modern wireless systems usually have to combine multiple standards and protocols [2]. This means that massive MIMO arrays with multiple functions are highly desired.

In this work, a multi-functional dual-band dual-polarized massive MIMO antenna array is proposed, aiming at dedicated 5G solutions for maritime applications, especially for land-to-boat and boat-to-boat communications. The solution has the potential of extending the radio coverage, and also providing more reliable and much higher data-rate services. To the best knowledge of the authors, the presented design is the first dedicated 5G solution worldwide for maritime applications.

A multi-functional antenna array is always beneficiary for modern communication systems. In this paper this is especially considered for maritime applications, i.e. a dual-band and dual-polarized operation is needed to support more reliable communications, and a wide scanning range is required to offer a larger communication coverage. It is quite a challenge to design a multi-functional massive MIMO array. Many designs in literature consider single band operation [3], [4]. But when the antenna array operates in two different bands, it is impossible to have an element spacing of half a wavelength in both bands. A tradeoff thus has to be made between the two operating bands. Moreover, in many previous designs, the mutual coupling between the elements was neglected [5], [6], and the antenna radiation pattern was considered constant [7], [8]. However, in realistic situations, when the antenna element spacing alters, the mutual coupling will change. What is more, the ground size of the antenna elements will also change (a larger element spacing means a larger ground), which will affect the radiation pattern. In the proposed design, the variation of the mutual coupling and the embedded radiation pattern were considered when analyzing the optimal element spacing.

Ref.	Freq. band (GHz)	Element Spacing	Pol.	No. of Elements.	Designed by
[3]	3.5	0.7 λ @ 3.5 GHz	Linear	128	Southeast Univ.
[4]	3.7	0.5 λ @ 3.7 GHz	Alternating H&V	160	Lund Univ.
[9]	2.4-2.62/ 3.4-3.6	0.62 λ @ 2.62 GHz	Linear	32	KUL
[10]	4.9-6	0.6 λ @ 6 GHz	Dual ±45°	4*4	SDSU
[11]	3.5-5.2	0.9 λ @ 5.2 GHz	Dual ±45°	4*4	CETC54
This work	4.94-5.23/ 5.79-6.15	0.55 λ @ 5.1 GHz	Dual ±90°	96	KUL/ NTNU

KUL: Katholieke Universiteit Leuven
SDSU: San Diego State University
CETC54: The 54th Research Institute of China Electronics Technology Group Corporation.
NTNU: Norwegian University of Science and Technology

Table 1. Comparison of realized massive MIMO antenna array.

By employing the aforementioned design process, a complex massive MIMO antenna array for maritime applications was developed with dual-band and dual-polarization operation. Some

Corresponding author: J. Zhang (jiahao.z@hotmail.com).
Digital Object Identifier: 10.1109/LSEN.XXXX.XXXXXXX.
1949-307X © 2016 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications standards/publications/rights/index.html for more information. (Inserted by IEEE)

realized massive MIMO antenna arrays are compared in Table 1. Realized massive MIMO arrays with linear polarization were discussed in [3], [4], [9], including a massive performance analysis from the antenna level to the system level. The proof-of-concept of massive MIMO array designs with dual-polarization was presented in [10] and [11]. However, all these references do not focus on the design strategy, and especially on the topology selection for these complex arrays. What is more, as we can see from Table I, the proposed massive MIMO array is the only one realizing dual band and dual polarization operation.

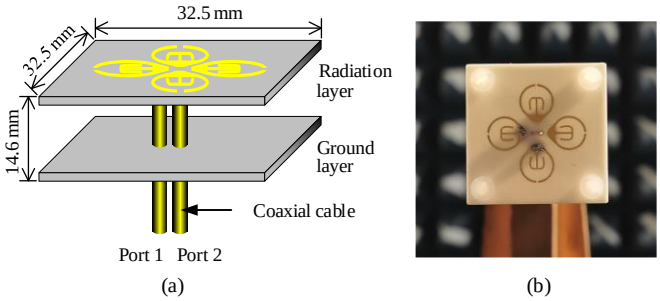


Fig. 1. (a) Schematic view of the antenna element. (b) Prototype of the element.

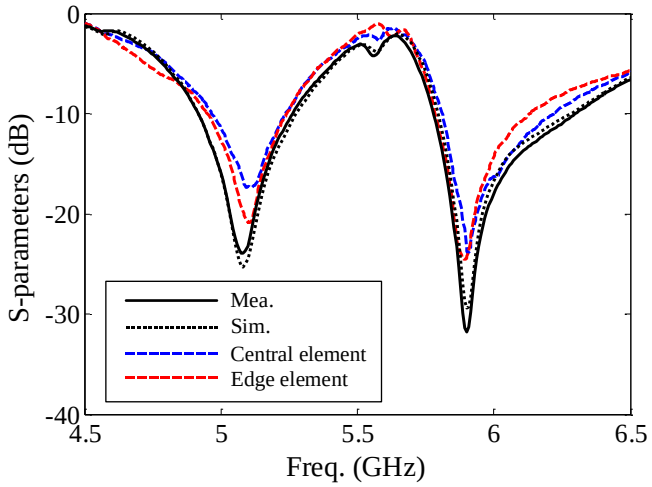


Fig. 2. S-parameters of the isolated and embedded antenna element. The black solid and dotted lines indicate the measurement and simulation results of the isolated element. The blue lines indicate the measurement results of the central element. The red lines indicate the measurement results of the edge element.

II. ANTENNA ELEMENT

The required bands are 5.1 and 5.9 GHz which are authorized by the Norwegian government for testing. A dual-band antenna array rather than a wideband antenna array is more desired, since using a single wideband antenna to cover the separated required bands may introduce unwanted signals in the receiver [12]. The schematic view and the prototype of the antenna element are given in Fig. 1. A grounded crossed dipole topology [13] was chosen to achieve the dual-polarized characteristics. This topology has a broadside radiation pattern [9], which is desired in massive MIMO systems. On top, it is able to easily realize two orthogonal radiation patterns. For each polarization (port), two dipole radiators are designed to achieve the dual-band operation. In detail, a smaller dipole radiator and a larger dipole radiator are integrated, see also [14], [15]. In this way, the dual-band dual-polarized operation is realized. The proposed antenna element has two PCB layers: the radiation layer which carries two perpendicularly placed dipole-based radiators, and the ground layer which carries a metal reflector. This element is achieved with a size of only 0.38 λ × 0.38 λ at 5.1 GHz for the radiator. This is very important for dual-band arrays, since in the array design process discussed next, more freedom is obtained for varying the element spacing. The antenna element is fed by two coaxial cables which are used to excite two orthogonal radiation patterns.

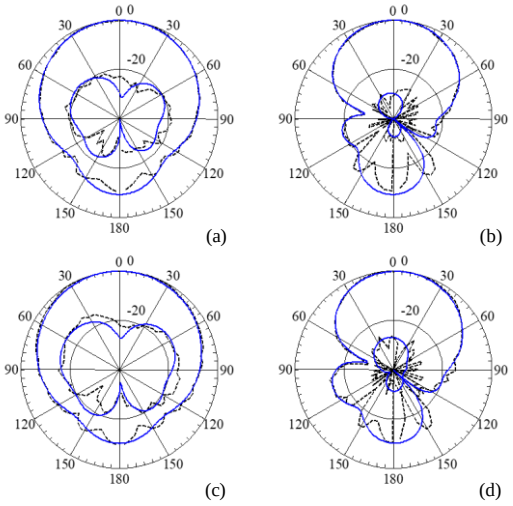


Fig. 3. Normalized radiation pattern of Port 1 at 5.1 GHz (a) E-plane, (b) H-plane. Port 1 at 5.9 GHz (c) E-plane, (d) H-plane. The black lines indicate the measurement results, the blue lines indicate the simulation results.

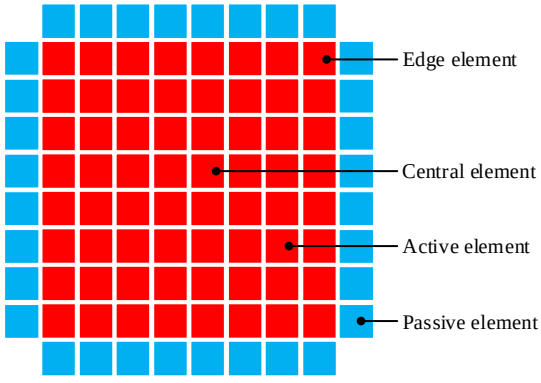


Fig. 4. Schematic of the massive MIMO array. Red indicates active elements, blue indicates passive elements.

The measured and simulated S-parameters of the isolated antenna element (port 1) are given in Fig. 2. With two resonances, around 5.1 GHz and 5.9 GHz, the antenna element fully covers the 5-5.2 GHz, and 5.8-6.1 GHz bands using the 10 dB return loss criterion. The measured and simulated normalized radiation patterns of port 1 are shown in Fig. 3. The radiation patterns of port 2 are similar to the ones

of port 1. Broadside radiation patterns for both ports and both bands are achieved thanks to the presence of the ground. Note that an asymmetry is observed for the radiation patterns, which is caused by the asymmetrical feeding structures. A trade-off has been made between the complex antenna performance and the radiation patterns. The measured and simulated realized gain and radiation efficiency of the antenna element are summarized in Table 2. The realized gain is above 6 dBi for both bands and both ports. The radiation efficiencies of the proposed antenna are very high: above 90%.

Table 2. Radiation performance of the antenna element.

	Realized gain		Radiation efficiency	
	Mea.	Sim.	Mea.	Sim.
Port 1, 5.1 GHz	6.7 dBi	6.8 dBi	95 %	96 %
Port 1, 5.9 GHz	6.2 dBi	6.4 dBi	93 %	94 %
Port 2, 5.1 GHz	6.7 dBi	6.8 dBi	95 %	96 %
Port 2, 5.9 GHz	6.2 dBi	6.4 dBi	93 %	94 %

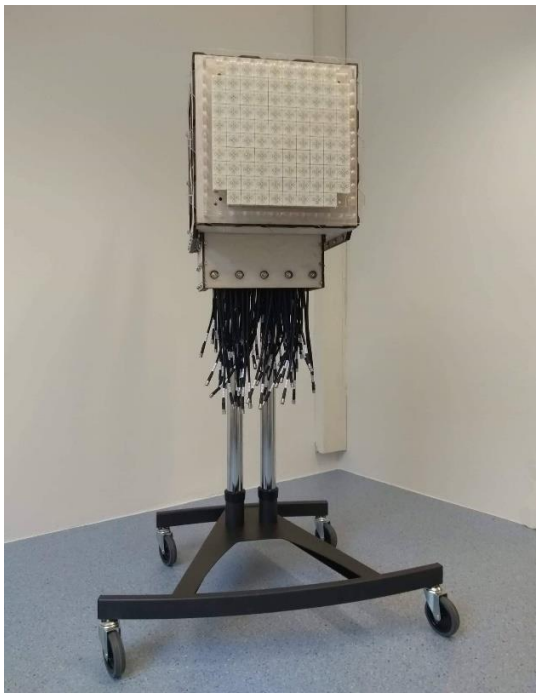


Fig. 5. The realized dual-band dual-polarized massive MIMO array.

III. MASSIVE MIMO ARRAY DESIGN

The massive MIMO array was developed based on the aforementioned dual-band dual-polarized antenna element. The schematic of the array is shown in Fig. 4. The realized prototype of the massive MIMO array with the supporting structure is shown in Fig. 5. In order to reach a larger channel capacity and to achieve a more reliable maritime communication, a massive MIMO array with 64 (8×8) active elements (indicated in red) and 32 passive elements (indicated in blue) was designed. Since this realistic array is finite, a gain pattern variation over the embedded active antenna elements occurs, which may have a negative impact on the array performance [9]. The reason for the introduction of the passive elements at the edge of the array is precisely to reduce the gain pattern variation. By extending the array with the passive elements at the edge, the mutual coupling conditions for all active elements become similar, and very well approach the conditions for the central elements. The gain difference between the central elements and the edge elements, as simulated with CST Microwave Studio, is reduced to below 1 dB in the 5.1 GHz band and below 0.5 dB in the 5.9 GHz band after the introduction of the passive elements. These gain differences are larger than 1.5 dB without the passive elements. The measured gain difference between the central element and the edge element of the proposed array with the passive elements present, as shown in Fig. 4, is 0.8 dB at 5.1 GHz, and 0.5 dB at 5.9 GHz. Note that during operation the passive elements are connected to a matched load.

Since the element spacing in the array determines the mutual coupling levels, consequently also the scanning range in both elevation and azimuth, and as a result of this also the spectral efficiency of the array, it was optimized for the scanning ranges as required by the maritime applications targeted. In the proposed design, the maximum mutual coupling occurs between two ports of two adjacent active antenna elements generating parallel polarizations, thus in each other's H-plane. Fig. 6 gives this maximum mutual coupling. The mutual coupling reduces with the increasing of the element spacing, especially in the lower band. The scanning range in both E- and H-plane, defined as when grating lobes are avoided, is presented in Fig. 7 as a function of the element spacing (in wavelengths at 5.1 GHz). It is seen that the scanning range in both bands becomes smaller when the element spacing increases. Fig. 8 shows the system spectral efficiency calculated with the method of [9]. The system capacity is slightly higher when the element spacing is larger. The reason is that for a larger element spacing, the ground size needs to be larger, yielding a larger embedded element gain.

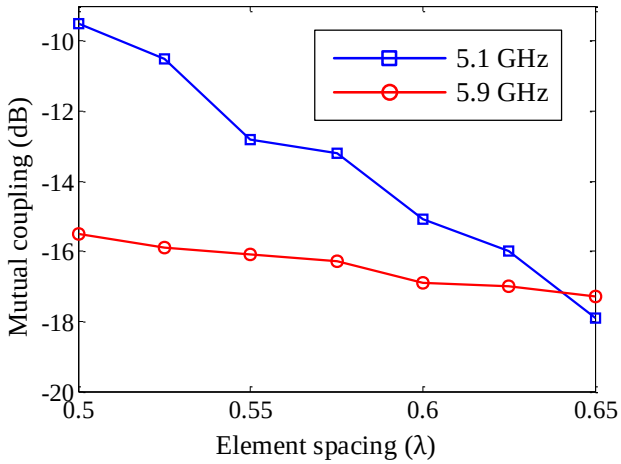


Fig. 6 The maximum mutual coupling between two adjacent active antenna elements in each other's H-plane.

As seen from Fig. 6, Fig. 7, and Fig. 8, the mutual coupling, the array-level performance (i.e. scanning range), and the system-level

performance (i.e. spectral efficiency), are all related to the element spacing. The relationship between the element spacing and the array performance is quite complex, especially for a dual band array. A tradeoff between the level of mutual coupling, the scanning range, and the system capacity has to be made in order to obtain an optimal array topology in terms of element spacing. For the proposed maritime applications, a wide scanning range is crucially important in order to provide a wide communication coverage for various moving boats in the vast ocean. Therefore, in the array design process, i.e. in the optimization of the element spacing, a higher weight is given to the scanning range performance. In the proposed design, an element spacing of 0.55 λ at 5.1 GHz was chosen, when taking all discussed factors into account. The measured return losses for the embedded central element (port 1) are 17.3 dB and 23.3 dB at 5.1 GHz and 5.9 GHz, respectively; the ones for the embedded edge element (port 1) are 20.8 dB and 24.2 dB at 5.1 GHz and 5.9 GHz, respectively, see Fig. 2 (the locations of the central element and the edge element are shown in Fig. 4). The measured mutual coupling between two adjacent central elements is -13.7 dB at 5.1 and -16.5 dB at 5.9 GHz. This study shows how the element spacing impacts the complex array performance. A general selection guideline can thus be obtained based on the requirements of an application targeted.

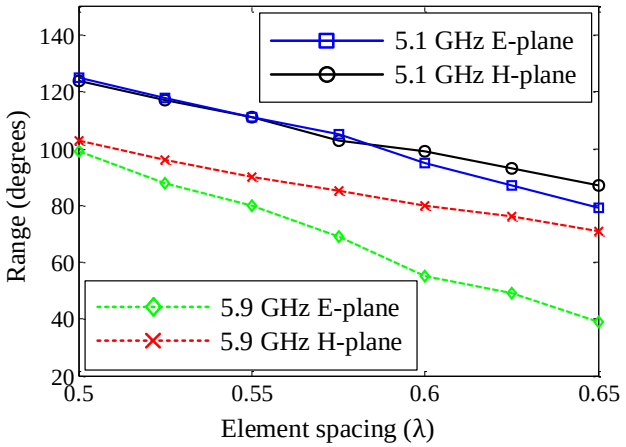


Fig. 7 The scanning range of the array. E-plane indicates the azimuth direction; H-plane indicates the elevation direction.

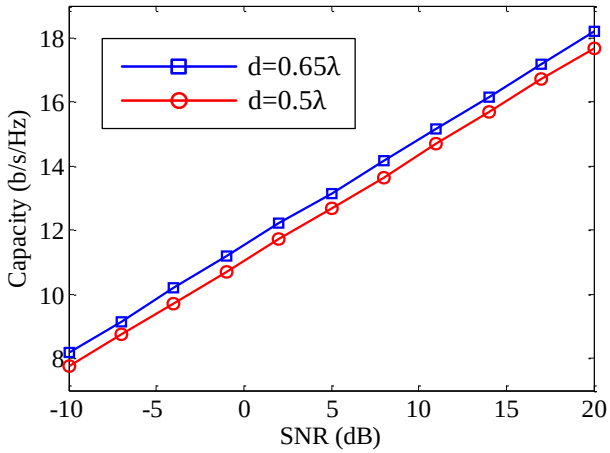


Fig. 8 The spectral efficiency.

IV. CONCLUSION

A dual-band dual-polarized 96 element massive MIMO array for maritime applications was presented in this Letter. It has 64 (8×8) active elements and 32 passive elements at the edges, used in order to reduce the gain pattern variation. The array design in terms of element spacing was discussed based on the mutual coupling, the scanning range, and the system capacity. This Letter paves the way for a proper topology selection for complex dual-band massive MIMO antenna arrays.

ACKNOWLEDGMENT

This work was supported in part by the MAMIME project (LTE, WIFI, and 5G Massive MIMO Communications in Maritime Propagation Environents) under Grant Agreement No. 256309 by Norwegian Research Council.

REFERENCES

[1] S. Sharma, A. Gupta, and V. Bhatia, “IR-UWB sensor network using massive MIMO Decision fusion: design and performance analysis,” IEEE Sensors Journal, vol. 18, no. 15, pp. 6290-6302, Aug. 2018.

[2] J. Zhang, S. Yan, and G. A. E. Vandenbosch, “Metamaterial-inspired dual-band frequency-reconfigurable antenna with pattern diversity,” Electronics Letters, vol. 55, no. 10, pp. 573-574, May 2019.

[3] X. Yang, W. Lu, N. Wang, K. Nieman, C.-K. Wen, C. Zhang, S. Jin, X. Mu, I. Wong, Y. Huang, and X. You, “Design and implementation of a tdd-based 128-antenna massive MIMO prototype system,” China Communications, vol. 14, no. 12, pp. 162-187, Dec. 2017.

[4] S. Malkowsky, J. Vieira, L. Liu, P. Harris, K. Nieman, N. Kundargi, I. C. Wong, F. Tufvesson, V. Öwall, and O. Edfors, “The world's first real-time testbed for massive MIMO: design, implementation, and validation,” IEEE Access, vol. 5, pp. 9073-9088, 2017.

[5] M. S.-Fernandez, E. R.-Iglesias, O. Q.-Teruel, and M. L. P.-Gonzalez, “Spectral efficiency in MIMO systems using space and pattern diversities under compactness constrains,” IEEE Transactions on Vehicular Technology, vol. 57, no. 3, pp. 1637-1645, May 2008.

[6] D. Piao, and Y. Wang, “Experimental evaluation of the tri-polarized MIMO channel properties based on a compact multimode antenna,” IEEE Access, vol. 7, pp. 67807-67817, May 2019.

[7] C. Masouros, M. Sellathurai, and T. Ratnarajah, “Large-scale MIMO transmitters in fixed physical spaces: The effect of transmit correlation and mutual coupling,” IEEE Transactions on Communications, vol. 61, no. 7, pp. 2794–2804, Jul. 2013.

[8] B. Clerckx, C. Craeye, D. Vanhoenacker-Janvier, and C. Oestges, “Impact of antenna coupling on 2×2 MIMO communications,” IEEE Transactions on Vehicular Technology, vol. 56, no. 3, pp. 1009–1018, May 2007.

[9] C.-M. Chen, V. Volski, L. Van der Perre, G. A. E. Vandenbosch, and S. Pollin, “Finite large antenna arrays for Massive MIMO: characterization and system impact,” IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6712-6720, Dec. 2017.

[10] M. Komandla, G. Mishra, S. K. Sharma, “Investigations on dual slant polarized cavity-backed massive MIMO antenna panel with beamforming,” IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6794-6799, Dec. 2017.

[11] H. Yuan, C. Wang, N. Li, and G. Cui, “The design of array antennas used for massive MIMO system in the fifth generation mobile communication,” in 11th International Symposium on Antennas, Propagation and EM Theory (ISAPE2016), 2016.

[12] J. Zhang, K. Yang, E. Edie, S. Yan, and G. A. E. Vandenbosch, “Simple triple-mode dual-polarized dipole antenna with small frequency separation ratio,” IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 2, pp. 262-266, Feb. 2020.

[13] S. X. Ta, I. Park, and R. W. Ziolkowski, “Crossed dipole antennas: a review,” IEEE Antennas and Propagation Magazine, vol. 57, no. 5, pp. 107-122, Oct. 2015.

[14] H. Zhai, K. Zhang, S. Yang, and D. Feng, “A low-profile dual-band dual-polarized antenna with an AMC surface for WLAN Applications,” IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2692-2695, Aug. 2017.

[15] Q. Liu, H. Liu, W. He, and S. He, “A low-profile dual-band dual-polarized antenna with an AMC reflector for 5G communications,” IEEE Access, vol. 8, pp. 24072-24080, Jan. 2020.