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DIGITAL COMMUNICATIONS TERM PROJECT

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Holographic MIMO Communication Systems

The link to the referenced articles:

https://ieeexplore.ieee.org/document/10130638/;jsessionid=F6ED337FB213118C451D14379F66334D

https://ieeexplore.ieee.org/document/10232975

The opportunities and some challenges that holographic MIMO communication systems will present in the future

***ABSTRACT---*The need for increased data speeds, an increase in the number of wireless devices and connections, and the high demands of various applications form the foundation for 6G wireless networks. Therefore, transitioning to 6G network technology, which will utilize even higher frequencies than 5G networks to provide higher capacity and significantly lower latency, is expected. During this era of 6G network technology, an increase in data traffic, along with the emergence of high-end and precise manufacturing techniques, is foreseeable, as well as the integration of holographic communications into our lives. One of these is holographic MIMO (Multiple-Input and Multiple-Output) communication systems.**

1.INTRODUCTION

The integration of the powerful capabilities of holography and meta-surfaces into wireless communications will cause a revolutionary change in sixth-generation communication systems such as Massive MIMO. Holographic MIMO surfaces can be seen as an efficient application of large antenna systems [1]. Holographic MIMO denotes a large array with a great number of separately controlled and densely deployed antennas. Three different approaches have been adopted for holographic MIMO communication systems.

After this section, respectively, following the second part (part 2), which discusses potential research ways, the third part (part 3) addresses the integration of Holographic MIMO technology with developing technologies in other fields. In the fourth part (part 4), comparisons are made with traditional MIMO communications such as mMIMO, and all these approaches are synthesized in the conclusion section (part 5) of the article.

2. POTENTIAL RESEARCH WAYS

A. Architecture of Hardware

The use of holographic metasurfaces, considering their energy efficiency and cost, can significantly reduce the number of required RF chains to achieve performance equivalent to traditional MIMO architectures. Advanced Holographic MIMO hardware designs typically rely on a multi-layer architecture, with signal processing operations performed directly in the wave domain. Given that wave-based processing can occur at the speed of light, there is a significant potential for reducing processing latency. The SIM (Stacked Intelligent Metasurface) architecture eliminates the need for digital beamforming by implementing transmit precoding and receiver combining operations in the EM wave domain. Additionally, by operating in the wave domain, it can reduce transmit precoding delay. A SIM-assisted transceiver can achieve good performance even with reduced energy consumption and hardware costs, using A/D converters and RF chains. Despite all these positive aspects, researching the technical challenges of implementing multi-layered architectural design and optimizing wave-based processing algorithms is one of the important topics to be explored.

B. EMIT (EM Information Theory)

EMIT integrates the theories of Shannon and Maxwell. It evaluates the fundamental limits of wireless communication and aims to determine optimal EM functions at the transmitter-receiver ends. As a result, it can be characterized independently of many parameters (such as the number of antenna elements). This indirectly enables Holographic MIMO systems to realize their full potential in the spatial domain.

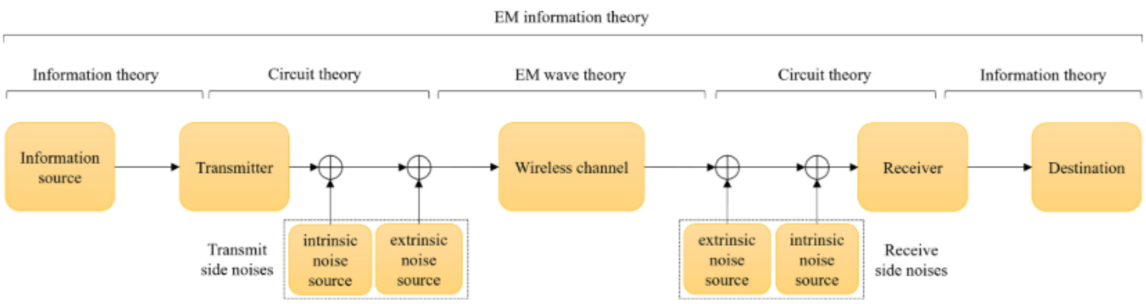

Figure 1. Schematic diagram of EMIT [2]

C. EM Waves Sampling

In Holographic MIMO communication, explaining spatial domain sampling theory is important due to the critical role of electromagnetic (EM) wave sampling and reconstruction for signal processing. Continuous sampling from the surface is required to reconstruct the EM field without loss of information. Research conducted considering scattering conditions has resulted in an efficient representation achieved through longitudinal hexagonal sampling. As a result, it has been shown that non-isotropic propagation expects a 13% sample reduction per square meter compared to half-wavelength sampling, which only includes some of the evanescent waves occurring when the receiver is near the scatterers.

Figure 2. Adaptation of HMIMO communication with various technologies different domains [3]

3. ADAPTATION WITH DEVELOPING TECHNOLOGIES

In this section, the compatibility of Holographic MIMO with emerging technologies is examined. It presents the benefits of positive compatibility with techniques emerging/emerging in next-generation networks, as well as potential challenges for advanced stages. Figure 2 depicts the integration of holographic MIMO communication with various technologies in different fields.

A. *Wireless Power Transfer*

Charging wireless devices with limited battery capacity without relying on existing wired infrastructure is important. By utilizing metasurfaces in holographic beamforming, the energy efficiency of WPT systems can be enhanced. The behavior of metamaterials as parasitic elements or load components can improve the performance of WPT systems. Additionally, there are many advantages to having metasurfaces. Improving conversion efficiency (such as with rectennas) and enhancing circuit size are among the advantages of having metasurfaces. In summary, the ways in which holographic MIMO communication can enhance WPT performance can be listed as follows:

i) increasing the WPT distance

ii) suppressing unwanted EM radiation by reflecting the EM field in different directions

iii) directing the EM field to the receiver.

B. *Joined Sensing and Communication*

It is anticipated that Holographic MIMO has the potential to considerably enhance both detection and communication performance by providing a thin detailed high-gain beam model [4]. In addition to reducing hardware costs, it can be stated according to theoretical analysis that densely packed radiation elements may increase beamforming gain by at least 1.5 times compared to a traditional MIMO array of the same dimensions. HMIMO communication can provide high localization resolution, which assigns it a critical role in the localization of future-generation wireless systems. By incorporating HMIMO communication into THz communication, as previously mentioned, it may be possible to achieve higher data rates, reduce latency, increase communication distance, and simplify hardware architecture as described in the preceding section.

C. *Satellite Communication*

Holographic MIMO surfaces can compensate for significant path losses and hardware limitations in satellite communications, providing high gain with a small antenna. For instance, overcoming such challenges with the use of HMIMO is highly likely in LEO satellites placed in orbits ranging from 180 to 2000 km, which can offer high-speed data transmission performance. According to a study, reconfigurable holographic surfaces have been employed to support numerous LEO satellites.

A satellite tracking scheme based on the temporal variation of satellite positions has been developed to handle the mobility of LEO satellites and ensure seamless communication among them without issues. Subsequently, a holographic beamforming algorithm has been devised to maximize the total speed. Simulation results have shown that higher performance in both total speed and cost-effectiveness is achieved compared to traditional phased arrays. It can be said that using HMIMO communication in satellite communication can significantly enhance the quality of service provided.

4. COMPARISONS

In this section, various MIMO communication technologies are compared with holographic MIMO communication. First, a comparison is made with XL-MIMO. Then, secondly, a comparison is made with mMIMO in terms of coverage area, capacity, and energy efficiency.

A. XL-MIMO

Shannon's information theory-based XL-MIMO can essentially be seen as a natural evolution of mMIMO. In XL-MIMO, unlike in mMIMO where the spacing of antenna elements is discretely aligned with the half-wavelength requirement, in Holographic MIMO, the antenna elements have nearly continuous aperture. Furthermore, the potential exploration of new physical phenomena with the use of mutual coupling of antenna elements and OAM modes in HMIMO brings forth many benefits such as super-directivity and massive mode multiplexing [5]. HMIMO's elimination of interdisciplinary boundaries, through its utilization of EM wave theory, EMIT, communication theory, and other disciplines, facilitates interdisciplinary fusion. In conclusion, HMIMO not only brings new features to communication systems compared to XL-MIMO but also provides numerous attractive benefits.

B. mMIMO

In terms of coverage, super-directivity in HMIMO will result in higher gain compared to mMIMO arrays, thereby enabling HMIMO to have a broader coverage area than mMIMO systems with equivalent transmit power.

When capacities are compared, as mentioned in the previous paragraph, super-directivity in HMIMO is expected to result in a higher receive SNR. The additional capacity gain due to the increase in receive SNR implies that the HMIMO communication system will have more capacity compared to mMIMO.

From a hardware perspective, while HMIMO surfaces exhibit an almost continuous aperture, massive MIMO antenna arrays offer a discrete aperture with limited shape flexibility. Even the fully analog schematic, which ensures minimum cost and power consumption in mMIMO, still proves to be more costly and power-consuming compared to HMIMO surfaces. Thus, it can be said that it is a reality that HMIMO will offer better performance in terms of energy efficiency compared to mMIMO.

5.CONCLUSION

Although HMIMO communication is still in its early stages, it was noted that it offers many advantages compared to traditional communication techniques. These advantages primarily include energy efficiency, lower latency, and higher capacity. Further exploration of potential research ways and the refinement of practical applications, such as addressing technical challenges in multi layer architectures, will facilitate its further development. It was emphasized that the paradigm shift brought about by adaptation to other technologies positions Holographic MIMO communication as a prominent candidate among next-generation communication techniques (6G). The purpose of this three-part article is to foster the adoption of the rapidly evolving field of communication systems and find out the evolution of holographic MIMO communication.

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