J. Electrical Systems 20-10s (2024):1564-1570

[1] Mridula Korde

Hybrid Beam-Forming Techniques for 6G Terahertz Communication: Challenges

Abstract: - The terahertz band is the main pillar of 6G wireless communication system. It is difficult to meet the high data rate of 1Tbps by millimeter frequency support systems. The terahertz band suffers huge propagation loss limiting wireless distance. Terahertz band imposes ultra massive multiple input multiple output antenna (UM-MIMO) systems which produce high array gain with narrow beamforming. The conventional methods for MIMO beamforming are Analog and Digital beamforming. The fully digital beamforming methods utilize dedicated structure of DAC/ADC and RF chains. These structures increase hardware complexity and are power hungry. The analog beamforming structures utilize ADC/DAC with phase shifters with less hardware complexity but support less data rates. As a result, a hybrid beamforming method can be adapted for UM-MIMO systems. This paper investigates challenges in hybrid beamforming architecture which will address the low spatial degrees of freedom (SDoF) limitation in Terahertz (THz) Communication. The flexible hardware connections are proposed, in order to switch the system in an adaptive manner so as to minimize the power requirements.

Keywords: 6G, Terahertz Communication, Beam forming.

I. INTRODUCTION

Communication in the Terahertz band holds promise for 6G technology, offering high data rates and wide bandwidth. This band falls between the mmWave and far-infrared spectra, providing greater transmission bandwidth than mmWaves and better propagation characteristics than infrared. Terahertz communication finds applications in indoor wireless mobile networks, nanoscale communication, and space communication. Despite challenges in designing components like Terahertz antennas, they offer advantages such as high gain and rapid beam scanning. Sub terahertz communication aims to boost spectral efficiency using advanced MIMO technologies, achieving data transmission rates beyond 5G, reaching the terabits-per-second level.

6G beamforming encounters several challenges. Firstly, in terahertz (THz) communications, the extreme sparsity of the THz channel results in poor spatial degree-of-freedom (SDoF). Secondly, in millimeter-wave (mmWave) bands, high penetration loss and blockage by objects present difficulties. Additionally, the utilization of ultra-massive (UM) MIMO systems with large antenna arrays brings challenges such as the requirement for dynamic sub array architecture, efficient energy system as well as estimation of propagation loss. Furthermore, the beam squint effect in THz communications and the necessity for intelligent sub array architecture in dual-function radar-communication (DFRC) systems are also hurdles. These challenges underscore the need for innovative hybrid beamforming architectures to cater to the specific demands of 6G beamforming.

Motivated by these challenges, hybrid beamforming technique is suggested to improve the achievable data rate, power consumption, and antenna gain for THz communications.

Researchers have explored the fully connected (FC) architecture among hybrid beam forming architectures, where each radio frequency (RF) chain controls all antennas using phase shifters [1]. The FC architecture requires a number of phase shifters equal to the product of the antennas and RF chains, leading to high hardware complexity and power consumption, which are impractical for implementation [2]. To address this challenge, researchers have proposed the array-of-sub arrays (AoSA) architecture, where each RF chain is connected to a subset of antennas (a sub-array) through phase shifters, which reduces the number of phase shifters to match the number of antennas [3]. Also most hybrid beam forming architectures use two step algorithm by optimizing analog and digital beam forming matrices separately [4].

The FC and AoSA architectures represent two extremes in hybrid beamforming design. Achieving a balance between power consumption and data rate is crucial for hybrid beam forming architectures [5]. However, both architectures rely on phase shifters, leading to the beam squint problem, which reduces power consumption [6].

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[1] Department of Electronics and Communication Engineering, Ramdeobaba University, Nagpur, India

Overcoming these limitations and addressing the remaining challenges necessitates the meticulous design of innovative THz-specific hybrid beam forming architectures [7]. These architectures aim to bridge the gap between theoretical concepts and practical system implementations.

This paper is arranged as follows: 6G Systems and Beamforming Architectures along with important features of 6G System are discussed in Section 2. The challenges involved in beamforming have been discussed in Section 3. The proposed system of hybrid beamforming has been discussed in Section 4 and conclusive thoughts are discussed in Section 5.

II. 6G SYSTEMS AND BEAMFORMING ARCHITECTURES

One of the fundamental pillars of sixth-generation (6G) wireless systems is Terahertz (THz) communications. Due to tiny wavelengths, scattering loss as well as propagation loss due to surrounding physical objects becomes extreme. This creates a challenge to achieve high array gain. Hybrid beam forming is particularly promising in UM-MIMO systems, offering the potential for high data rates and reduced power consumption [8].

6G, the hypothetical successor to 5G, is envisioned to revolutionize connectivity and communication even further. Some potential use cases for 6G include:

A. Super –Fast Wireless Networks:

6G aims to provide even faster data speeds than 5G, potentially reaching terabits per second. This could enable real-time transmission of high-definition and even 3D holographic videos [9].

B. Ultra-Reliable Low Latency Communication (URLLC):

6G can significantly reduce latency to under a millisecond, enabling applications like automated industry, driverless cars, and remote surgery to function seamlessly.

C. Massive Internet of Things (IoT):

6G could support an even larger number of connected devices, potentially in the order of millions per square kilometer. This would be essential for smart cities, smart grids, and other IoT applications.

D. Advanced AI and Machine Learning:

The high speeds and low latencies of 6G could enable more advanced AI and machine learning applications to run in real-time, such as AI-powered autonomous systems and robotics.

E. Augmented Reality (AR) and Virtual Reality (VR):

6G could enhance AR and VR experiences by enabling high-resolution, low-latency streaming of immersive content, leading to more realistic and interactive experiences.

F. Environmental Sensing and Sustainability:

6G could enable more advanced environmental sensing technologies, such as remote monitoring of climate change, pollution levels, and wildlife habitats, aiding in sustainability efforts.

G. Healthcare and Telemedicine:

With ultra-reliable and low-latency connectivity, 6G could support remote surgery, real-time patient monitoring, and other healthcare applications that require high levels of reliability and responsiveness.

H. Security and Privacy:

6G is expected to incorporate enhanced security and privacy features to protect users' data and devices, crucial for the increasing digitization of society.

I. Space Communications:

6G could also extend communication networks into space, supporting satellite communications, space exploration, and potentially interplanetary communication.

It's important to note that while these are potential use cases, the actual implementation and deployment of 6G will depend on technological advancements, regulatory frameworks, and market demands [10].

In the realm of beamforming architectures, two traditional choices are fully-digital and analog. In a fully-digital setup, each antenna has its own dedicated RF chain and DAC/ADC, which consume a significant amount of power. However, in THz UM-MIMO systems, the large number of antennas makes the hardware complexity and power consumption of fully-digital architecture impractical. In analog beamforming, antennas are controlled via phase shifters. Further DAC/ADC and RF chain which can support one data stream can be used for controlling antenna to reduce power consumption and hardware complexity. Hybrid beam forming addresses challenges of analog and digital beam forming to make it an attractive technology for THz UM-MIMO systems [11].

While hybrid beamforming technologies have been thoroughly researched for microwave and mmWave frequencies, the distinctive features of THz UM-MIMO systems present novel challenges for THz hybrid beamforming design.

III. DEFIANCES OF THZ HYBRID BEAMFORMING

This section discusses the defiance and distinctive characteristics of THz hybrid beamforming from the perspectives of the channel and UM-MIMO system

A. Defiances in THz Channel Consideration

1. Channel Sparsity and Low SDoF:

The THz band is highly sensitive for diffraction as well as scattering losses because of sub millimeter wavelength. This gives rise to limited multipath as THz band mostly consists of a line-of-sight (LoS) path and a few reflection paths. The scarcity of multipath components in the THz channel makes it sparser compared to microwave and mmWave channels. This sparsity constrains the spatial degrees of freedom (SDoF), which in turn limits the spatial multiplexing gain of THz UM-MIMO systems. Despite the high array gain provided by ultra-massive antennas, the limited multiplexing gain considerably restricts the potential data rate of THz UM-MIMO systems.

2. Blockage Problem:

Because of large reflection losses, the line-of-sight (LoS) path in the THz channel is much stronger than the reflection paths, frequently surpassing 15 dB. Because of the LoS path's supremacy, THz wireless networks are very prone to obstruction. Even while THz systems often require substantially higher data rates, the reflection routes in the THz channel are much weaker than at mmWave frequencies. Consequently, in THz networks, the remaining reflection channels may be too weak to sustain high data rates if the line-of-sight (LoS) path is blocked. When compared to mmWave links, this circumstance makes the obstruction problem

B. Perspectives on Challenges in THz UM-MIMO Systems

1. Large-scale Antenna Array:

THz UM-MIMO systems often employ a huge number of antennas, exceeding 1024, leading to significant power consumption challenges. The individual hardware devices in the THz band, such as power amplifiers and phase shifters, consume ultra-high power due to the band's high frequency. Additionally, the use of ultra-massive antennas results in a large quantity of devices, further increasing power consumption.

2. Beam Squint Effect:

The THz band, particularly, has a much larger fractional bandwidth compared to traditional microwave frequencies. This causes a severe beam squint problem in THz hybrid beamforming architectures. In these architectures, signals on antennas require phase shifts for concentration, which are frequency-dependent. However, most existing hybrid beamforming architectures use phase shifters, which are frequency-independent devices. They tune the same phase shift for signals with different frequencies, leading to phase errors for signals at different frequencies. This leads to squinted beams and reduced array gains, a phenomenon known as the beam squint problem. While traditional narrowband hybrid beamforming architectures can withstand the performance degradation caused by beam squint, THz hybrid beamforming architectures with large fractional bandwidth experience a significant reduction in array gain, up to 5 dB. This necessitates serious consideration of this issue.

C. Hybrid Beamforming Technique:

In Terahertz (THz) Ultra-Massive Multiple Input Multiple Output (UM-MIMO) systems, multiple antennas can be utilized to exploit multiplexing gain, thereby enhancing data rates alongside beamforming. Previous studies on Fully Connected (FC) and Angle of Arrival (AoSA) architectures typically assume antennas are spaced at half the wavelength, i.e., critically spaced. This critically spaced antenna array allows for spatial multiplexing gain derived from channel multipath, known as inter-path multiplexing. To further boost multiplexing gain, the Wide-Spaced Massive Sub arrays (WSMS) hybrid beamforming architecture shows promise in THz UM-MIMO systems, as shown in Fig. 1. This architecture consists of multiple sub arrays, each with antennas spaced at half the wavelength, critically spaced like FC and AoSA architectures. However, the sub arrays themselves are widely spaced, spanning hundreds of wavelengths, which reduces correlation between them.

IV. PROPOSED SYSTEM

When it comes to beamforming architectures, two conventional options are fully digital and analog. In the fully digital architecture, each antenna has its own dedicated Radio Frequency (RF) chain and Analog-to-Digital Converter/Digital-to-Analog Converter (DAC/ADC), which are power-hungry components.

However, the fully digital approach becomes impractical for use in Terahertz (THz) Ultra Massive Multiple Input Multiple Output (UM-MIMO) systems due to the prohibitively high number of antennas, leading to excessive hardware complexity and power consumption.

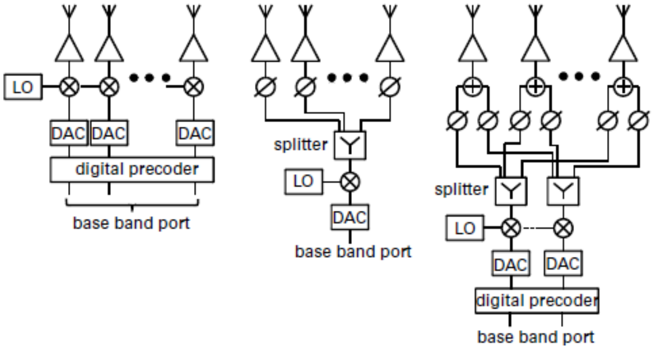

Figure 1. a) Digital Beamformer b) Analog Beamformer c) Hybrid Beamformer

However, the fully digital approach becomes impractical for use in Terahertz (THz) Ultra Massive Multiple Input Multiple Output (UM-MIMO) systems due to the prohibitively high number of antennas, leading to excessive hardware complexity and power consumption. Fig 1 denotes analog, digital and hybrid beamforming architecture respectively.

Hybrid beamforming represents a middle ground between analog and full digital beamforming. In this approach, a digital beamformer operates on a limited number of baseband ports, followed by an analog beamforming network. The proposed hybrid beamforming system is shown in Fig 2. This architecture offers a balanced compromise in terms of complexity and flexibility compared to purely analog or fully digital solutions. As a result, hybrid beamforming is considered an attractive technology for THz UM-MIMO systems.

The design goals of hybrid beamforming technique can be:

1. Maximize spherical coverage

2. Minimize the codebook size to reduce the beam sweeping time, power consumption and memory space by limiting overlap between the adjacent beams

The antennas are organized into multiple sub-arrays, with switches inserted between each RF chain and sub-array. These switches can be controlled to adjust the connection between RF chains and sub-arrays, enabling intelligent adjustment of data rates and power consumption. By dynamically configuring switch connections, a balance between power consumption and data rate can be achieved. The hybrid algorithm is divided into switched network and beamforming structure. The switched network can perform adaptive decisions to maximize spectral efficiency and minimize required power while maintaining maximum achievable data rate.

The beamforming matrices can be used to maximize the data rate. Since the switched network will work in adaptive manner, the analog and digital beamforming matrices will be scanned element by element. The design may suffer hardware complexity at the cost of high data rate and low power consumption.

In analog beamforming, a solitary baseband port supplies an analog beamforming network, where the beamforming weights are directly applied to the analog baseband components. This can occur at an intermediate frequency or at the Radio Frequency (RF) stage. For example, an RF beamforming network may include multiple phase shifters, each corresponding to an antenna element, along with optional variable gain amplifiers.

Nevertheless, while an analog beamforming network typically produces physical beams, it cannot generate a complex beam pattern. This limitation can lead to interference, especially in a multi-user environment, if pure beam separation is not sufficient.

A digital beamformer, as shown in Fig 2 provides the highest level of flexibility, with each antenna element having its own dedicated baseband port. However, the use of ADCs and Digital-to-Analog Converters (DACs) operating at multi-GHz sampling rates consumes significant power. Therefore, implementing a full digital beamformer with several hundred antenna elements might be impractical, or at the very least, feasible but requiring high power consumption and complexity.

Hybrid beam forming is a promising technique for 6G wireless communication systems, aiming to combine the advantages of both analog and digital beam forming to achieve efficient and high-performance beam forming. Here are some methodologies typically used for hybrid beam forming in 6G:

A. Channel Estimation and Feedback:

1. Sparse Channel Estimation: Given the complexity and high-dimensional nature of the Terahertz band, sparse channel estimation techniques, such as compressed sensing or subspace methods, can be employed to estimate the channel state information (CSI) efficiently.

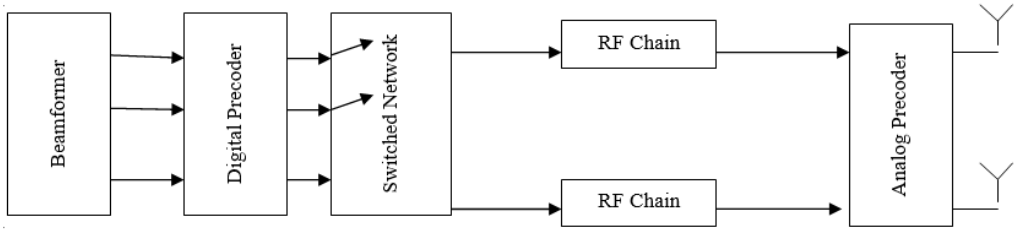

Figure 2. Proposed Hybrid Beam former

2. Feedback Reduction: To minimize feedback overhead, techniques like codebook-based quantization or adaptive quantization can be used to convey CSI from the user equipment (UE) to the base station (BS) with reduced signaling overhead.

B. Digital Baseband Processing:

1. Precoding and Combining: Utilizing digital precoding and combining algorithms (e.g., zero-forcing, minimum mean square error, maximum ratio transmission) to optimize the digital beam forming weights based on the estimated CSI.

2. Interference Management: Implementing interference management techniques such as interference alignment or cancellation to mitigate inter-beam interference and enhance spectral efficiency.

C. Analog RF Processing:

1. Analog Beam forming Design: Designing analog beam formers using phase shifters or phase arrays to shape the radiation pattern and steer beams towards the intended directions.

2. Beam forming Codebooks: Employing predefined beam forming codebooks or learning-based approaches to adaptively select analog beam forming vectors based on the channel conditions.

D. Hybrid Beamforming Architecture Design:

1. Architecture Optimization: Optimizing the architecture of hybrid beam forming systems considering factors such as the number of antennas, RF chains, and beam forming granularity to balance performance and complexity.

2. Beam Training and Tracking: Implementing efficient beam training and tracking algorithms to adapt beam forming weights in real-time based on the dynamic channel conditions and UE mobility.

E. Machine Learning and Optimization:

1. Learning-Based Beam forming: Leveraging machine learning techniques, such as deep learning or reinforcement learning, to optimize beam forming strategies and adapt beam forming parameters based on historical data or real-time measurements.

2. Joint Optimization: Conducting joint optimization of analog and digital beam forming weights to maximize spectral efficiency or minimize power consumption under various constraints (e.g., power, interference, and quality of service requirements).

F. Practical Implementation Considerations:

1. Power Consumption: Addressing power consumption challenges associated with hybrid beam forming architectures through efficient hardware design, power management techniques, and low-power RF components.

2. Cost and Complexity: Balancing the trade-offs between cost, complexity, and performance by exploring scalable and cost-effective implementation solutions for hybrid beam forming in 6G systems.

By applying these methodologies, hybrid beam forming can effectively harness the potential of the Terahertz band in 6G networks, enabling high data rates, low latency, and improved spectral efficiency for next-generation wireless communications.

V. CONCLUSION

Hybrid beamforming has the potential to significantly improve energy and spectral efficiency while enabling ubiquitous connectivity in future 6G networks. To understand and address the challenges associated with this technology; this article provides a comprehensive overview of the issues in hybrid beamforming. Beginning with the features of 6G systems, it discusses the challenges in beamforming techniques, focusing on THz channel considerations and THz UM-MIMO systems. Design principles for hybrid beamforming, incorporating both analog and digital systems, are introduced based on performance metrics and prevalent approaches. Finally, future research directions are outlined to help realize the full potential of hybrid beamforming technology.

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