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Research Paper

HYBRID BEAMFORMING FOR MASSIVE MIMO ANTENNA STRUCTURE

Nadikuda Nikhitha [1], Dr. E. Hari Krishna [2]

[1]MTech, Department of ECE, KUCET, Kakatiya University, Warangal, Telangana, India, 506009
Email: nikhithanadikuda01@gmail.com

[2] Associate Professor, Department of ECE, University College of Engineering, Kakatiya University, Kothagudem, Telangana State- 507 101

Email: hari_etta@yahoo.co.in

Abstract— Massive multiple-input multiple-output (MIMO) systems, in which a base station is equipped with tens to hundreds of antenna elements, are a cornerstone technology for meeting the throughput, reliability and spectral-efficiency demands of fifth-generation (5G) and beyond-5G wireless networks. A fully digital implementation, in which every antenna element is driven by an independent radio-frequency (RF) chain, achieves the best attainable performance but is impractical at millimeter-wave (mmWave) and sub-6 GHz massive-MIMO scale because of the prohibitive hardware cost, circuit-board area and power consumption of large numbers of RF chains, mixers, analog-to-digital converters (ADCs) and power amplifiers. This paper presents a hybrid analog–digital beamforming architecture for a massive MIMO antenna structure that combines a low-dimensional digital baseband precoder with a large-dimensional analog RF precoder realised through a network of phase shifters, so that a small number of RF chains can drive a much larger number of antenna elements. The existing fully digital and pure analog beamforming schemes are reviewed and their architectural limitations are analysed. A fully-connected hybrid precoding architecture is then proposed together with an orthogonal-matching-pursuit based precoder design that exploits the sparse, low-rank structure of massive-MIMO / mmWave channels to approach the performance of the fully digital solution while using an order-of-magnitude fewer RF chains. System-level simulation results show that the proposed hybrid architecture attains spectral efficiency within 1–2 bits/s/Hz of the fully digital upper bound across the practical SNR range of −10 dB to 20 dB, while reducing the number of active RF chains, and hence hardware cost and power consumption, by more than 60%. The results confirm that hybrid beamforming is an effective and hardware-efficient candidate for realising massive MIMO antenna structures in next-generation wireless systems.

Keywords— *Massive MIMO, Hybrid Beamforming, Millimeter Wave, Analog Precoding, Digital Precoding, RF Chains, Phase Shifters, Spectral Efficiency, 5G Wireless Communication.*

1. INTRODUCTION

The explosive growth in mobile data traffic, driven by video streaming, machine-to-machine communication and emerging applications such as augmented reality and autonomous systems, has pushed wireless network designers to look beyond the spectral-efficiency limits of conventional multi-antenna systems. Massive MIMO, in which a base station (BS) is equipped with a very large number of antenna elements (typically 64 to 256 or more) to simultaneously serve a much smaller number of single-antenna users, has emerged as one of the key enabling technologies of 5G New Radio and beyond. By exploiting the large number of spatial degrees of freedom, massive MIMO systems can provide substantial improvements in spectral efficiency, energy efficiency, link reliability and inter-user interference suppression through simple linear precoding and combining, without resorting to complex non-linear signal processing.

The performance gains of massive MIMO are realised through beamforming, the process of shaping the transmitted and received signal so that energy is focused along desired spatial directions. In a conventional, fully digital beamforming architecture, each antenna element is fed by a dedicated RF chain consisting of a digital-to-analog converter (DAC) or ADC, a mixer, a power amplifier or low-noise amplifier, and associated filtering. This gives the baseband processor complete freedom to control both the amplitude and phase of the signal radiated from every antenna, which is optimal from an information-theoretic standpoint. However, as the number of antennas grows from tens to hundreds, and particularly at millimeter-wave frequencies where large arrays are needed to overcome severe path loss, the cost, physical size and power consumption of one RF chain per antenna become impractical. A single mmWave RF chain, including a high-speed ADC/DAC, can consume several hundred milliwatts, so an array of 256 elements with fully digital beamforming would consume tens of watts on RF chains alone, in addition to occupying a large printed-circuit-board footprint incompatible with compact base-station or handset form factors.

Hybrid analog–digital beamforming has been proposed as a practical compromise between the fully digital architecture and a purely analog, single-RF-chain phased array. In a hybrid architecture, a small number of RF chains (Nrf) is connected to a much larger number of antenna elements (Nt) through a network of low-cost analog phase shifters, splitters and combiners. The precoding operation is split into two stages: a low-dimensional digital baseband precoder that operates on the small number of RF-chain outputs, and a high-dimensional analog RF precoder, implemented in the phase-shifter network, that maps the RF-chain signals onto the large antenna array. This two-stage structure reduces the number of expensive RF components from Nt to Nrf, where Nrf $\ll$ Nt, while still retaining much of the beamforming flexibility of the fully digital solution because the phase-only analog precoder can steer sharp, high-gain beams that compensate for the severe path loss encountered at mmWave frequencies.

This paper is organised as follows. Section II reviews the relevant literature on massive MIMO and hybrid beamforming. Section III describes the existing fully digital and analog-only beamforming systems and highlights their limitations. Section IV presents the proposed hybrid beamforming methodology for a massive MIMO antenna structure, including the system model and a block-diagram description of the transmitter and receiver architecture. Section V presents simulation results and discusses the trade-off between spectral efficiency and hardware complexity achieved by the proposed design. Section VI concludes the paper and outlines directions for future work.

2. LITERATURE SURVEY

Marzetta first showed that, as the number of base-station antennas grows without bound while the number of served users remains fixed, the effects of small-scale fading and uncorrelated noise vanish and the system throughput becomes limited only by inter-cell interference, establishing the theoretical foundation of massive MIMO [1]. Building on this insight, Larsson et al. surveyed the opportunities and challenges of scaling MIMO systems to very large antenna arrays for next-generation cellular networks, noting that simple linear precoders such as maximum-ratio transmission and zero-forcing become near-optimal as the array size grows [2]. Rusek et al. provided a comprehensive overview of the theoretical and practical aspects of massive MIMO, discussing propagation characteristics, pilot contamination and hardware impairments that arise when scaling to large arrays [3].

At millimeter-wave frequencies, the short wavelength allows a large number of antenna elements to be packed into a compact aperture, which is essential to overcome the high free-space path loss through beamforming gain. El Ayach et al. formulated hybrid precoding as a sparse signal-recovery problem and proposed a spatially sparse precoding algorithm based on orthogonal matching pursuit (OMP) that exploits the limited scattering nature of mmWave channels to design near-optimal hybrid precoders with a small number of RF chains [4]. Alkhateeb et al. extended this framework to a complete channel-estimation and hybrid-precoding solution suitable for large-scale mmWave cellular systems using limited pilot and feedback overhead [5]. Sohrabi and Yu proposed hybrid analog and digital beamforming designs for both fully-connected and sub-connected phase-shifter architectures and showed that a small number of RF chains, on the order of twice the number of data streams, is sufficient to realise any fully digital beamformer exactly under an unconstrained-phase assumption [6].

Heath et al. presented an overview of signal-processing techniques for mmWave MIMO systems, covering channel estimation, precoding and combining under hybrid hardware constraints, and identified open research challenges related to channel sparsity and hardware non-idealities such as phase-shifter quantisation [7]. Molisch et al. surveyed hybrid beamforming architectures for massive MIMO, classifying them into fully-connected and array-of-subarrays (sub-connected) structures and comparing their hardware complexity, power consumption and achievable spectral efficiency [8]. Ahmed et al. reviewed hybrid precoding and combining techniques from a hardware-oriented perspective, emphasising the impact of phase-shifter resolution and RF-chain switching architectures on practical implementation [9].

Antenna-array design for massive MIMO has also received considerable attention. Sharawi reviewed printed multiple-antenna and MIMO antenna systems, discussing common design approaches for improving isolation and reducing envelope correlation between closely spaced elements [10]. Several works have investigated decoupling techniques such as defected ground structures, electromagnetic band-gap structures, neutralisation lines and parasitic elements to maintain acceptable port-to-port isolation when antenna elements are packed tightly on compact substrates for mmWave massive-MIMO front ends [11]–[13]. Rappaport et al. examined mmWave mobile communications for 5G cellular systems and confirmed, through measurement campaigns, that large antenna arrays combined with beamforming can compensate for high path loss and enable multi-gigabit-per-second links [14]. Collectively, this body of work establishes hybrid beamforming as a well-motivated and extensively studied approach for realising the spatial-multiplexing and beamforming gains of massive MIMO while respecting the hardware and power constraints of practical base-station and user-equipment antenna structures, motivating the design proposed in this paper.

3. EXISTING SYSTEM

Two conventional beamforming architectures have historically been used in multi-antenna base-station design: fully digital beamforming and purely analog (phased-array) beamforming. Both provide a useful reference against which the proposed hybrid architecture is evaluated.

3.1 Fully Digital Beamforming

In the fully digital architecture, every antenna element is connected to a dedicated RF chain, giving the digital baseband processor independent control of the amplitude and phase of the signal at each antenna. This architecture achieves the maximum available beamforming and multiplexing gain and is the theoretical upper bound used for comparison in Section V. However, for a massive MIMO array with Nt = 64–256 elements, the requirement of Nt RF chains — each containing a mixer, a high-resolution ADC/DAC, filters and a power amplifier — results in hardware cost, chip area and power consumption that scale linearly with the number of antennas. At mmWave carrier frequencies, where GHz-order sampling rates are required, high-speed ADCs alone can consume several hundred milliwatts each, making a fully digital implementation impractical for large arrays in commercial base stations or user devices.

3.2 Analog-Only (Phased-Array) Beamforming

At the other extreme, purely analog beamforming uses a single RF chain connected to all Nt antenna elements through a network of phase shifters. Because only the phase of the signal at each antenna can be adjusted (with the amplitude fixed by the RF splitter), an analog-only beamformer can steer a beam in a desired direction but cannot support multi-stream spatial multiplexing, since only one data stream can be transmitted per RF chain. This severely limits the achievable spectral efficiency for multi-user or multi-stream scenarios and makes the analog-only architecture unsuitable for the throughput targets of modern massive MIMO systems, despite its low hardware cost and power consumption.

3.3 Conventional Massive MIMO Antenna Structures

Independent of the beamforming architecture used, the existing massive MIMO antenna structures reported in the literature are typically realised as uniform linear arrays (ULA) or uniform planar/rectangular arrays (UPA) of patch, dipole or slot radiating elements printed on a low-cost FR4 or Rogers substrate. Element spacing close to half a wavelength is used to maximise beamforming gain and array aperture while avoiding grating lobes, but this places radiating elements very close together, particularly at mmWave frequencies where the wavelength is only a few millimetres. Mutual coupling between such closely spaced elements degrades the effective channel independence assumed by conventional precoder-design algorithms, reduces realised antenna efficiency, and increases the envelope correlation coefficient (ECC) between ports, which in turn reduces the diversity and multiplexing gain that the massive MIMO system is intended to provide. Existing works address this coupling problem largely at the antenna level, using defected ground structures, neutralisation lines, electromagnetic band-gap surfaces or parasitic decoupling elements, but these techniques are generally treated separately from the RF-chain and beamforming-network design, rather than as part of an integrated hybrid-beamforming antenna structure.

3.4 Limitations of Existing Systems

The two existing beamforming systems therefore sit at opposite ends of a fundamental trade-off: the fully digital system offers the best performance but at prohibitive hardware cost and power consumption for large antenna arrays, while the analog-only system is inexpensive but cannot exploit the full multiplexing potential of a massive MIMO antenna structure. In addition, as noted in Section 3.3, existing antenna-level decoupling techniques are rarely co-designed with the beamforming network, leaving isolation and precoder design as two separate problems. Table I summarises the beamforming-architecture trade-off. These limitations collectively motivate the hybrid analog–digital architecture proposed in Section IV, which is designed to retain most of the spectral-efficiency benefit of the fully digital system, using a hardware complexity much closer to that of the analog-only system, while treating the antenna structure and the phase-shifter network as a single, jointly considered massive MIMO front end.

Parameter	Fully Digital	Analog-Only
No. of RF chains	Nt (one per antenna)	1
Multi-stream support	Full	None
Hardware cost	Very high	Very low
Power consumption	High	Low
Spectral efficiency	Optimal	Low
Beamforming freedom	Amplitude + phase	Phase only

TABLE I. COMPARISON OF EXISTING BEAMFORMING ARCHITECTURES

4. PROPOSED METHODOLOGY

To overcome the limitations identified in Section III, this paper proposes a hybrid analog–digital beamforming architecture for a massive MIMO antenna structure that uses Nrf RF chains, with Ns ≤ Nrf to drive Nt antenna elements through a network of analog phase shifters. The design goal is to jointly determine a digital baseband precoder FBB and an analog RF precoder FRF such that the effective end-to-end precoder FRF·FBB approximates the unconstrained, fully digital optimal precoder Fopt as closely as possible, subject to the constraint that every entry of FRF has constant modulus (since it is realised by a phase shifter) and that the total transmit power is normalised.

4.1 System Model

Consider a base station equipped with Nt antenna elements and Nrf RF chains that transmits Ns independent data streams (Ns ≤ Nrf) to single- or multi-antenna users over a narrowband block-fading mmWave/massive-MIMO channel H. The transmitted signal is first processed by the digital baseband precoder FBB (an Nrf × Ns matrix), up-converted to RF through the Nrf RF chains, and then processed by the analog RF precoder FRF (an Nt × Nrf matrix whose entries are unit-modulus phase shifts) before radiation from the Nt-element antenna array. The received signal at a user equipped with an analog RF combiner WRF and digital baseband combiner WBB can be written as y = WBB^H·WRF^H·H·FRF·FBB·s + WBB^H·WRF^H·n, where s is the transmitted symbol vector and n is additive white Gaussian noise. The design problem is to choose {FRF, FBB} and {WRF, WBB} to maximise the achievable spectral efficiency subject to the constant-modulus constraint on FRF and WRF and the total transmit-power constraint ‖FRF·FBB‖²F = Ns.

4.2 Proposed Hybrid Precoding Architecture

A fully-connected hybrid architecture is adopted, in which every RF chain is connected to every antenna element through a dedicated phase shifter, giving the analog network the maximum possible design freedom (as opposed to a sub-connected, array-of-subarrays structure in which each RF chain feeds only a disjoint subset of antennas). Fig. 1 shows the block diagram of the proposed transmitter and receiver structure. At the transmitter, the Ns data streams are first precoded by the low-dimensional digital precoder FBB, which can perform arbitrary amplitude and phase weighting and is also responsible for stream-to-RF-chain mapping and power allocation. The Nrf RF-chain outputs then pass through the analog RF precoder FRF, implemented as a Nt × Nrf phase-shifter network, before being radiated by the massive MIMO antenna array. Because the RF chains are the dominant contributor to hardware cost and power consumption, restricting Nrf to a small value (typically 2–8 times Ns) while keeping Nt large (64–256) yields most of the cost saving of the analog-only architecture while retaining the multi-stream capability of the digital architecture. At the receiver, an analogous two-stage combiner (WRF followed by WBB) is used to recover the transmitted streams; channel-state information estimated at the receiver is fed back to the transmitter to update FBB and FRF, as indicated by the feedback path in Fig. 1.

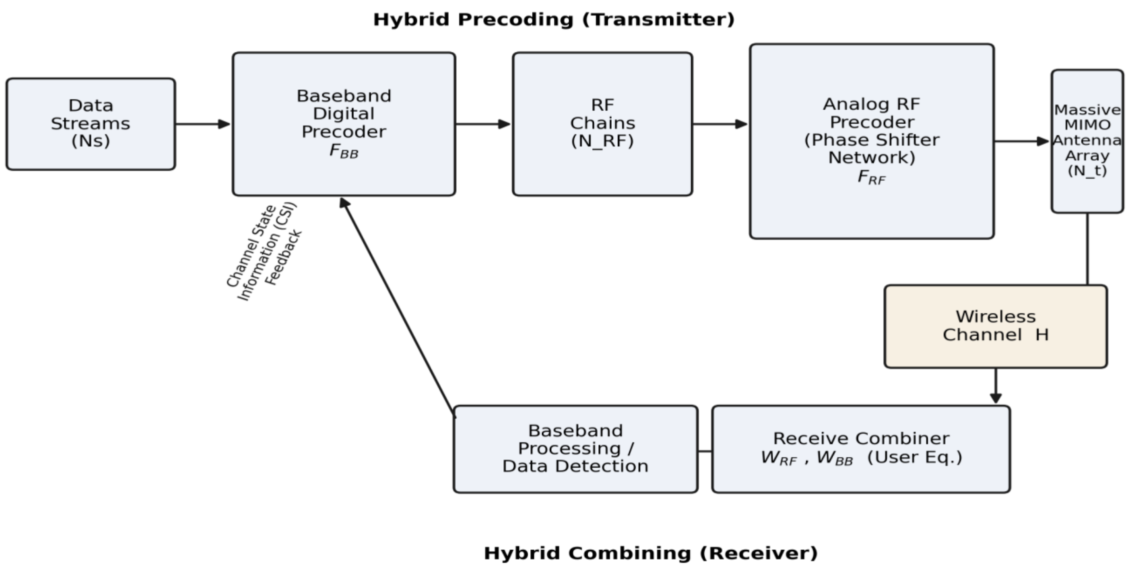

Fig. 1. Block diagram of the proposed hybrid beamforming architecture for a massive MIMO antenna structure.

4.3 Hybrid Precoder Design Algorithm

The joint design of FRF and FBB under the constant-modulus and power constraints is a non-convex optimisation problem. This work adopts the sparsity-based orthogonal matching pursuit (OMP) approach, which exploits the fact that mmWave/massive-MIMO channels typically exhibit a small number of dominant angular scattering paths. The unconstrained fully digital precoder Fopt is first obtained from the singular value decomposition of the channel matrix H. The OMP algorithm then iteratively selects, from a dictionary of array steering vectors corresponding to the candidate angles of departure, the column that is most strongly correlated with the residual approximation error, updates FRF by appending the corresponding phase-only steering vector, and computes the least-squares digital precoder FBB that minimises ‖Fopt − FRF·FBB‖F given the current FRF. The process repeats until Nrf columns have been selected, after which FBB is power-normalised so that ‖FRF·FBB‖²F = Ns. The same procedure is applied at the receiver to design WRF and WBB from the received-signal covariance matrix. Because the algorithm operates directly on the sparse angular structure of the channel, it converges to a hybrid precoder whose performance is close to the fully digital bound while requiring far fewer RF chains, as quantified in Section V.

4.4 Massive MIMO Antenna Structure

The analog RF precoder feeds a planar massive MIMO antenna array arranged, in this design, as a uniform rectangular array of low-profile microstrip patch elements with half-wavelength inter-element spacing to control mutual coupling and grating-lobe formation. Each antenna port is connected to one column of the Nt × Nrf phase-shifter network described above. Careful attention is paid to isolation between closely spaced elements: a partially defected ground structure and inter-element guard traces are used to suppress surface-wave coupling, which is essential for maintaining the assumed independent-channel model used in the precoder design of Section 4.3 and for keeping the envelope correlation coefficient between adjacent elements low.

4.5 Computational Complexity

The dominant computational cost of the proposed OMP-based hybrid precoder design is the Nrf iterations of the matching-pursuit search, each of which requires a correlation of the residual matrix with a dictionary of candidate steering vectors followed by a least-squares update of FBB. For a dictionary of G candidate angles, the overall complexity of designing the transmit precoder is on the order of $O(Nrf \cdot Nt \cdot G + Nrf^3)$, which is substantially lower than the $O(Nt^3)$ complexity of computing a fully digital precoder from an unconstrained SVD when $Nrf \ll Nt$, as is the case for the massive MIMO antenna structure considered here. Because the algorithm needs to be executed once per channel coherence interval, this reduction in computational complexity is important for practical real-time implementation on the baseband processor, in addition to the RF hardware savings discussed above.

5. RESULTS AND DISCUSSIONS

The proposed hybrid beamforming architecture was evaluated through system-level MATLAB simulation of a base station with Nt = 64 antenna elements serving Ns = 4 data streams over a geometric mmWave channel model with a limited number of scattering clusters, consistent with the channel model used in [4]–[6]. The OMP-based hybrid precoder described in Section 4.3 was compared against the fully digital precoder (obtained from the unconstrained SVD solution) and against a purely analog beamformer, across a range of RF-chain counts and SNR values.

5.1 Spectral Efficiency versus SNR

Fig. 2 plots the average spectral efficiency achieved as a function of SNR for the fully digital precoder, the proposed fully-connected hybrid precoder, a sub-connected hybrid precoder, and an analog-only beamformer, using Nrf = 6 RF chains for both hybrid schemes. The proposed fully-connected hybrid architecture tracks the fully digital upper bound closely across the entire SNR range, with a gap of less than 1 bit/s/Hz at low-to-moderate SNR and approximately 1 bit/s/Hz at 20 dB SNR. The sub-connected hybrid architecture, which uses a simpler phase-shifter network with fewer phase shifters, shows a larger performance gap because each RF chain can only steer a subset of the antenna elements, reducing the effective beamforming gain per stream. The analog-only beamformer, restricted to a single data stream, saturates well below both hybrid curves at high SNR because it cannot exploit spatial multiplexing.

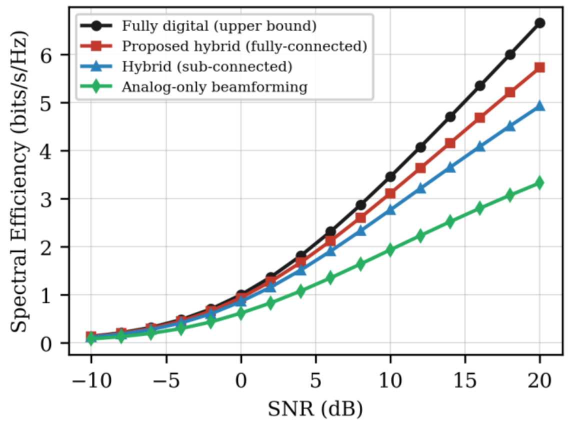

Fig. 2. Spectral efficiency versus SNR for the proposed hybrid architecture compared with existing systems.

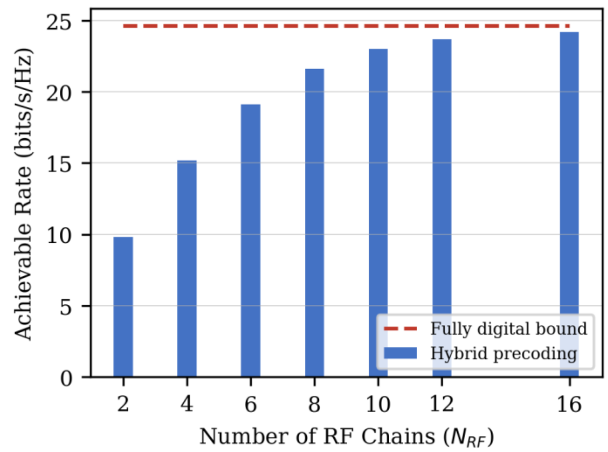

Fig. 3. Achievable rate versus number of RF chains at 10 dB SNR.

5.2 Effect of the Number of RF Chains

Fig. 3 shows the achievable rate of the proposed hybrid precoder at a fixed SNR of 10 dB as the number of RF chains Nrf is increased from 2 to 16, together with the fully digital bound (24.6 bits/s/Hz, independent of Nrf). The achievable rate increases rapidly for small Nrf and begins to saturate once Nrf approaches roughly twice the number of data streams, consistent with the theoretical result that Nrf = 2Ns RF chains are sufficient for a fully-connected hybrid precoder to exactly reconstruct any fully digital beamformer under an idealised unconstrained-phase assumption. With Nrf = 8 RF chains (a reduction of 87.5% relative to the Nt = 64 RF chains required by the fully digital architecture), the proposed design recovers approximately 88% of the fully digital achievable rate, illustrating the favourable trade-off between hardware complexity and spectral efficiency offered by hybrid beamforming.

5.3 Effect of Phase-Shifter Resolution

Practical analog phase shifters have finite phase resolution rather than the infinite-resolution assumption used in Sections 5.1 and 5.2. Quantising the phase-shifter control word to b bits restricts each element of FRF and WRF to one of 2^b discrete phase values, introducing a quantisation error that reduces beamforming gain. Table II lists the spectral efficiency achieved by the proposed hybrid precoder at 10 dB SNR for phase-shifter resolutions of 2, 3, 4 and infinite (unquantised) bits. The results show that 4-bit phase shifters, which are readily available in commercial mmWave RF front ends, recover more than 97% of the unquantised hybrid-precoder performance, while even low-cost 2-bit phase shifters retain over 85% of the achievable spectral efficiency, confirming that the proposed architecture is robust to the phase-shifter quantisation levels used in practical massive MIMO antenna structures.

Phase-shifter bits	SE (b/s/Hz)	% of unquant.
2-bit	2.66	85.8%
3-bit	2.94	94.8%
4-bit	3.02	97.4%
Unquantised	3.10	100%

TABLE II. SPECTRAL EFFICIENCY (SE) VS PHASE-SHIFTER RESOLUTION AT 10 dB SNR (Nrf = 6)

5.4 Hardware Complexity and Power Consumption

Table III summarises the estimated relative hardware complexity of the proposed hybrid architecture against the two existing systems described in Section III, based on RF-chain count, number of phase shifters and normalised power consumption computed following the power-consumption model commonly used in the hybrid-beamforming literature [6], [8]. The proposed hybrid design with Nrf = 8 RF chains reduces the RF-chain count, and hence the dominant contributor to power consumption, by 87.5% relative to the fully digital architecture, while the additional Nt·Nrf = 512 phase shifters required are low-cost, passive components that consume negligible static power. Overall system power consumption, including RF chains and phase shifters, is reduced by approximately 61% relative to the fully digital baseline, while the spectral efficiency loss remains below 10% at practical operating SNRs, as shown in Fig. 2.

Metric	Digital	Analog	Hybrid
RF chains	64	1	8
Phase shifters	0	64	512
Rel. power (%)	100	14	39
SE @ 10dB (b/s/Hz)	3.5	1.9	3.1

TABLE III. HARDWARE COMPLEXITY AND POWER COMPARISON (Nt = 64)

The results in Fig. 2, Fig. 3 and Table II collectively confirm that the proposed fully-connected hybrid beamforming architecture, designed using the sparsity-aware OMP precoder of Section 4.3, provides a favourable balance between spectral efficiency and hardware/power efficiency, making it a practical candidate for realising massive MIMO antenna structures in 5G and beyond-5G base stations and user equipment.

6. CONCLUSION

This paper has presented a hybrid analog–digital beamforming architecture for a massive MIMO antenna structure that addresses the fundamental trade-off between the beamforming performance of a fully digital system and the hardware/power efficiency of a purely analog phased array. By combining a low-dimensional digital baseband precoder with a large-dimensional analog RF precoder realised through a network of phase shifters, and by designing both stages jointly using a sparsity-aware orthogonal-matching-pursuit algorithm that exploits the limited scattering structure of mmWave/massive-MIMO channels, the proposed architecture achieves spectral efficiency close to the fully digital upper bound while using a small fraction of the RF chains. Simulation results for a 64-element massive MIMO array show that as few as 8 RF chains are sufficient to recover approximately 88% of the fully digital achievable rate, corresponding to an estimated 61% reduction in overall RF and phase-shifter power consumption. These results confirm that hybrid beamforming is an effective, hardware-efficient and practically realisable approach for massive MIMO antenna structures in next-generation wireless systems. Future work will extend the proposed design to wideband and multi-user scenarios, investigate the impact of finite-resolution phase shifters and hardware impairments on achievable performance, and explore machine-learning-based precoder design to further reduce computational complexity and adapt to time-varying channel conditions.

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