EVALUATING THE IMPACT OF CHANNEL FADING AND ANTENNA ARCHITECTURE ON BEAMFORMING PERFORMANCE FOR NEXT-GENERATION WIRELESS SYSTEMS

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Abstract

Antenna beamforming has emerged as a promising solution for the advanced wireless communication systems particularly where large number of antennas is used at the transmitter and receiver (multiple input multiple output-MIMO) systems. The beamforming techniques MIMO system provides improved signal quality, enhances capacity and reduces interference. Telecommunication service providers need to address several challenges for implementation of the beamforming techniques because of its different aspects; beamforming for suitable applications, complexity, implementation cost, power consumption, capacity etc. This paper provides a comprehensive analysis of three types of beamforming techniques (analog, digital and hybrid) over various fading channels and antenna configurations. The analysis explores effect of fading conditions on the performance of the beamforming techniques and crucial parameters such as spectral efficiency (SE) and energy efficiency (EE). Further paper investigates the influence of multiple antenna configurations. While adding more antennas gradually improves spectral efficiency by leveraging spatial diversity, but it introduces increased power consumption, leading to diminishing returns in energy efficiency. The simulations are also carried out with different channel models such as Rician, Rayleigh and Nakagami. Moving from Rayleigh to Rician (K=5) channel model, boosts spectral efficiency of hybrid beamforming by approximately 11% at 10 dB signal to noise ratio. These results validate hybrid beamforming architecture as a pivotal technology for future wireless systems, enabling the deployment of massive MIMO to meet escalating data demands in a power-efficient and cost-effective manner.

Keywords:

Analog Beamforming, Digital Beamforming, Hybrid Beamforming, MIMO, Nakagami, Rayleigh, Rician

1. INTRODUCTION

In the recent years, wireless communication systems have experienced significant demand for rapid data transmission to provide quality of service (QoS) and quality of experience (QoE) to the users. High data rate is required for providing better services in the different domains. High data rate requires more bandwidth utilization which is considered as resource in communication. Conventional wireless systems are characterized by spectrum shortage [1], narrow bandwidth and lower data rates, which make them inappropriate for high data rate applications of higher generations of wireless communication. Therefore researchers have explored the higher frequency ranges between 30 and 300 GHz termed as Millimeter wave (mmWave) frequency bands for these applications [2], [3]. The mmWave spectrum will offer higher bandwidth and hence much higher data rate when compared with radio frequency bands. According to Friis' law [4], the free space path loss increases with the square of frequency. Therefore mmWave frequency bands will suffer from propagation loss. Use of multiple antennas at transmitter and receiver

(MIMO) configuration is leveraged in mmWave in order to minimize the propagation losses at these frequencies [5].

However, handling such large antenna array configuration requires a chain of radio frequency (RF) antennas having elements like phase shifters, converters etc. which are expensive and power intensive [6]. To address this problem, directional signal transmission technique called antenna beamforming is introduced in literature. With beamforming the signal generated from group of antennas are moved in the particular direction where user is present and minimizing transmission of energy in other directions [7]. Such technique will improve signal quality, provides higher data rate and system capacity. There are three beamforming techniques viz. digital beamforming (DBF), analog beamforming (ABF) and hybrid (analog digital) beamforming (HBF). The beamforming is performed in analog domain in ABF, at radio frequency (RF) stage at the transmitter, whereas beamforming is performed entirely in the digital domain at the baseband processing stage in DBF, and to balance between performance, cost and flexibility of implementation, operations of both ABF and DBF are combined in HBF [7]. In this paper authors have presented the concept of ABF, HBF and DBF for various antenna array configurations such as multiple input single output (MISO), and multiple input multiple output (MIMO) with different antenna sizes, channel assumption, power model and performed comparative analysis of these three techniques for different output parameters like spectral efficiency, energy efficiency over different signal to noise ratio values. Such analysis will be helpful for selecting the technique for particular applications depending on cost of implementation, flexibility and power consumptions.

The organization of this paper is as follow: Section 2 describes a brief overview of various existing techniques on different beamforming approaches. Section 3 discusses the system model for ABF, DBF and HBF with channel models, section 4 explains research methodology and parameters of evaluation and section 5 will discuss the simulation results and performance evaluation of the beamforming techniques Section 6 concludes the paper.

2. LITERATURE SURVEY

Beamforming is a signal processing [14] technique used in antenna arrays for directional signal transmission and reception. Phase and amplitude of the signal from each antenna element is controlled such that it generates a beam pattern that enhances signal strength in direction where user is present while reducing the signal strength in the other directions. Analog, digital and hybrid beamforming are the types of beamforming and each differing in complexity, requirement of hardware and performance. High frequency wireless system which uses mmWave band frequencies extensively uses these techniques.

Analog beamforming (ABF) is also called radio frequency (RF) beamforming uses, phase shifters and attenuators in the RF domain the steer the beam. Each antenna element is connected to a network of phase shifters. These phase shifts are controlled by only phase or amplitude and phase together to generate beam pattern. Minimal number of RF chains with each chain feeding all or a subset of the antennas is required. Such hardware required less power consumption compared with digital beamforming. However ABF suffers from limitation of advanced spatial multiplexing because same waveform is sent to each element with only phase change and such techniques will not be suitable in multi-beam scenario to support multiple simultaneous user in different direction as analog phase shifts creates a single main beam pattern.one of the simplest method for creating multiple beams from antenna array is using Butler matrix which is passive network that generates fixed beams based on predefined RF phase shifts. Authors in [8] and [9] present a study of low-complexity phase shifters design for analog beamforming used in mmWave systems. Adaptive analog beamforming is studies in [10] to explore the use of adaptive phase shifting networks that tracks beam direction and therefore improving robustness and link quality.

The Digital Beamforming (DBF) technique processes the baseband signals for each antenna element or for subgroup of element independently. Such processing allows generation of flexible beam patterns, multiple beams for multi user scenarios and also permits space division multiple access (SDMA). But this processing requires a dedicated RF chain per antenna element. The baseband signals for every element can be manipulated using digital signal processing techniques. Authors in [11] present the concept of massive MIMO digital beamforming highlighting gains in spectral and energy efficiency for the system. Linear precoders like zero forcing and minimum mean square error and nonlinear approaches are explored by authors in [12] for maximizing capacity. However increase in the system capacity with DBF is at the cost of computational complexity and hardware impairments like phase noise and non-linear amplification that are addressed in [13] and [14] to delve into robust beamforming that adapts to hardware constraints.

Hybrid beamforming (HBF) technique attempts to merge advantages of analog and digital beamforming approaches [15]. The number of digital RF chains are reduces then the number of antenna elements and then combined with analog phase-shifting network. In HBF signal is partially processed at the baseband level (DBF) and then mapped through analog phase shifters through multiple antenna elements (ABF). The disadvantage of requiring more number of RF chains (ADCs/DACs) are reduced thus cutting on power and cost, by providing more flexibility in beam pattern generation then purely analog beamforming. In HBF there are two approaches by which RF chains are connected to antenna element. In fully connected architecture, each RD chain is connected to every antenna element through a network of phase shifters which allows maximum flexibility at the cost of increase hardware complexity because of many phase shifters. Second is partially-connected architecture where, each RF chain is connected to a subset or sub array of the antenna elements, lowering hardware complexity but reduces beamforming flexibility. Multi-stage hybrid beamforming for mmWave system is proposed in [15], showing its capability to achieve near-optimal spectral efficiency with reduced hardware cost. Codebook based

hybrid precoding for mmWave MIMO system is explored in [16] and the proposed algorithm is efficient for phase shift designs. Authors [17] proposed alternating algorithms to jointly optimize digital and analog precoders in hybrid architecture. Authors in [18], [19], investigated beam selection and channel estimation strategies specifically tailored to large-scale mmWave MIMO system employing hybrid beamforming.

In all the literature papers mentioned above, authors have worked on the hardware like ADC/DAC, phase shifters, code book design, and algorithms for maximizing spectral efficiency etc. for ABF, DBF and HBF implementation, but there is gap in literature to extend the working of these beamforming techniques to include different channel conditions like Rayleigh, Rician and Nakagami-m. Authors in this paper have presented implementation of basic analog beamforming network with multiple input single output antenna system to simulate spectral efficiency and energy efficiency, further extended to implementation of DBF and HBF by varying transmitter and receiver antenna numbers and extended to incorporating different fading channel models.

3. SYSTEM MODEL

3.1 ANALOG BEAMFORMING

Analog beamforming (ABF) in a MIMO system is a technique where the phase of the signals transmitted from each antenna element is adjusted and aligned in the required direction where user is present [11]. Such method does not require complex digital signal processing at the transmitter and receiver side and also improves link quality. To provide spatial diversity and multiplexing gain, multiple antennas are used at transmitter and receiver side. The transmit beamforming vector w_{tx} will adjust the phase of the signal at each antenna to align in the desired direction. It is designed based on the channel state information (CSI) available at the transmitter. The model of analog beamforming with phase shifters is shown in Fig.1 below. The transmitted signal after beamforming is:

$$X = w_{tx}s \tag{1}$$

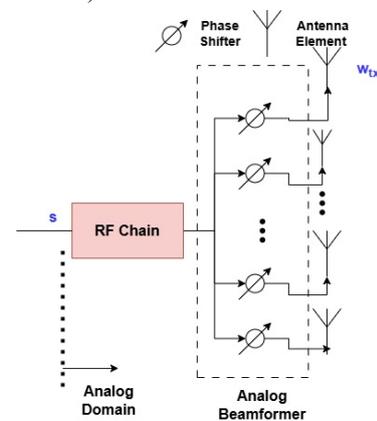where, X is the transmitted signal vector, s is the data symbol (assumed to be scalar)

Fig.1. System model for Analog Beamforming (ABF)

Analog beamforming uses phase shifts and does not adjust the amplitude of each antenna element's signal. The beamforming vector is given by:

$$w_{tx} = \left[e^{-j\phi_1}, e^{-j\phi_2}, \ldots, e^{-j\phi_{N_t}} \right] \qquad (2)$$

where, φ_i is the phase shift applied to the signal at the i-th transmit antenna.

The most common method [17], [20] to design the analog beamforming vector is by Maximum Ratio Transmission (MRT), where the phases of the beamforming vector are aligned with the conjugate of the channel coefficients:

$$w_{tx} = \frac{e^{-j\angle h_1}}{\| h \|} \qquad (3)$$

where, h_1 is the first element of the channel vector, $\|h\|$ is the norm of the channel vector, ensuring that the transmit power is normalized.

The channel between the transmitter and the receiver in MIMO system can be expressed as:

$$y = HX + n \qquad (4)$$

where, $y \in C^{N_r \times 1}$ is the received signal vector at the receiver, $H \in C^{N_r \times N_t}$ is the channel matrix, $X \in C^{N_t \times 1}$ is the transmitted signal vector at the transmitter, $n \in C^{N_r \times 1}$ is the noise vector at the receiver. Once the transmit beamforming vector w_{tx} has been applied, the received signal at the receiver can be expressed as:

$$y = H w_{tx} s + n \qquad (5)$$

The effective channel gain is gain is given by:

$$\text{Effective Channel Gain} = | h^H w_{tx} |^2 \qquad (6)$$

where, h^H is the conjugate response (Hermitian) of the channel vector w_{tx} is the transmit beamforming vector.

This Eq.(6) represents the strength of the received signal after beamforming. The effective gain depends on the alignment of the transmit beamforming vector w_{tx} with the channel.

3.2 DIGITAL BEAMFORMING

Digital beamforming (DBF) is a technique used in MIMO systems where the transmitted signals are processed digitally, and the phase and amplitude of each signal are controlled for each antenna element. Compared with ABF, digital beamforming allows full control over both phase and the amplitude of the transmitted signals, offering more flexibility in the forming beams and improving system performance. The digital beamforming model is shown in Fig.2 below.

The general MIMO system model in the presence of Digital Beamforming is given by:

$$y = H F_{tx} s + n \qquad (7)$$

where, $F_{tx} \in C^{N_t \times N_s}$ is the digital transmit beamforming matrix (where N_s is the number of data streams, typically N_s=1 for single stream communication). The other terms remain same as that of ABF. In DBF, the beamforming matrices F_{tx} (for transmission) and W_{rx} (for reception) are designed using Singular Value Decomposition (SVD) [21] based on channel state information.

The general principle of DBF is to control both amplitude and phase of the signal at each antenna.
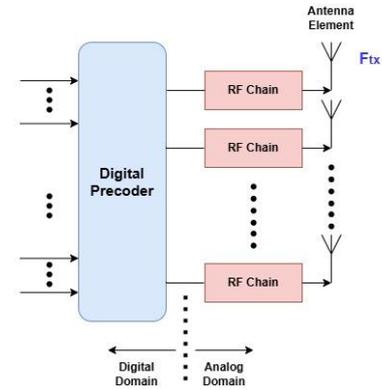

Fig.2. System model for Digital Beamforming (DBF)

To calculate digital transmit beamforming matrix, the SVD [17] of the channel matrix H is used:

$$H = USV^H \qquad (8)$$

where, $U \in C^{N_r \times N_r}$ is a unitary matrix containing the left singular vectors of H, $S \in C^{N_r \times N_t}$ is a diagonal matrix of singular values (representing the strength of each mode in the channel), $V^H \in C^{N_t \times N_t}$ is the conjugate transpose of the matrix containing the right singular vector of H.

The digital transmit beamforming matrix is chosen to be matrix V, which is the right singular matrix of H. This matrix aligns the transmitted signal with the strongest Eigen modes of the channel, providing optimal transmission over the MIMO link:

$$F_{tx} = V \qquad (9)$$

At the receiver, digital receive beamforming matrix W_{rx} is designed similarly using SVD of H. the matrix U, which contains the left singular vectors, can be used as the receive beamforming matrix:

$$W_{rx} = U \qquad (10)$$

Once transmit and receive beamforming matrixes are applied, the effective channel gain after beamforming is given by:

$$\text{Effective Channel Gain} = | W_{rx}^H H F_{tx} |^2 \qquad (11)$$

Since $W_{rx}=U$ and $F_{tx}=V$, we can simplify this expression to:

$$\text{Effective Channel Gain} = | S |^2 \qquad (12)$$

where, S is the diagonal matrix of singular values, representing the effective gains for each data stream.

3.3 HYBRID BEAMFORMING

Hybrid beamforming (HBF) is a method that combines the advantage of analog beamforming and digital beamforming in MIMO system. This method reduces the complexity and power consumption of fully digital systems while maintaining the performance benefits of digital beamforming. In HBF, a portion of the signal processing is done in the analog domain using phase shifters (similar to ABF), and the remaining processing is done digitally at the baseband (similar to DBF). This approach is partially useful in millimetre wave (mmWave) MIMO system where there is large antenna arrays, and use of fully digital

beamforming [22] would require more complex implementation of RF chains. The Hybrid beamforming model which consists of digital precoder and analog beamformer (phase shifter) is shown in Fig.3 below. MIMO system with Hybrid Beamforming is represented as:

$$y = HW_{rx}F_{tx}s + n \qquad (13)$$

where, $y \in C^{N_r \times 1}$ is the received signal vector at the receiver, $H \in C^{N_r \times N_t}$ is the channel matrix, $w_{tx} \in C^{N_r \times N_r}$ is the analog receive beamforming matrix, $F_{tx} \in C^{N_t \times N_s}$ is the digital transmit beamforming matrix, $s \in C^{N_s \times 1}$ is the data symbol vector (with N_s data streams), $n \in C^{N_r \times 1}$ is the noise vector at the receiver.
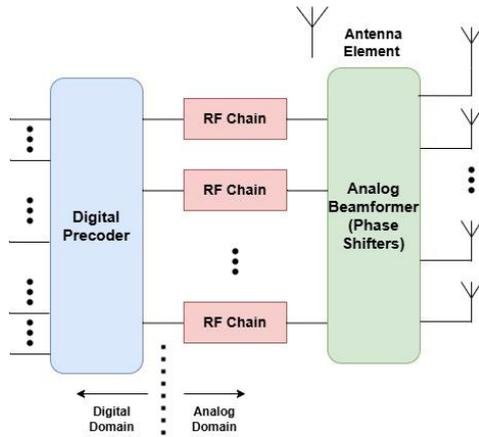

Fig.3. System model for Hybrid Beamforming (HBF)

The signal transmission involves, analog beamforming, where transmit signal x is passed through an analog beamforming matrix, which is implemented using phase shifters. The analog beam formed signal is then processed by a digital beamforming matrix to control the data stream and power allocation. The total beamforming process involves both an analog and digital component:

$$x = W_{rx}F_{tx}s \qquad (14)$$

where, w_{rx} is the analog beamforming matrix for the receiver and F_{tx} is the digital beamforming matrix at the transmitter. The system uses, N_t antennas but only N_t^{RF} RF chains (a subset of the antennas), N_r antennas at the receiver, but only N_r^{RF} RF chains.

The analog beamforming matrix w_{rx} can be designed by selecting a subset of the transmit antennas and aligning the phases to the dominant eigenvectors of the channel. This is done by performing SVD of the channel matrix. The digital beamforming matrix F_{tx} is obtained by performing SVD of the estimated channel matrix H, similar to the digital beamforming approach as stated in Eq.(8).

In HBF, the goal is to approximate the optimal digital beamforming with analog phase shifters to reduce power and hardware complexity. The hybrid beamforming matrix is given by:

$$H_{effective} = W_{rx}HF_{tx} \qquad (15)$$

After applying HBF, the effective channel gain is given by:

$$\text{Effective Channel Gain} = |W_{rx}^H HF_{tx}|^2 \qquad (16)$$

where, W_{rx}^H is the conjugate transpose of the analog receive beamforming matrix, F_{tx} is the digital transmit beamforming matrix, the magnitude of the resulting matrix gives the total gain achieved after beamforming.

3.4 CHANNEL MODELING

The analysis of Spectral Efficiency (SE) and Energy Efficiency (EE) are carried out over Signal to Noise Ratio (SNR) range for ABF, DBF and HBF over three different fading channel models of Rayleigh fading, Rician Fading and Nakagami-m fading.

3.4.1 Rayleigh Fading:

In a Rayleigh fading channel, all the multipath components contribute equally to the signal but without any dominant line of sight (LoS) path. This fading is modelled where there is no clear direct path between transmitter and receiver such as urban environment with high levels of scattering. This model is applicable in scenarios where the channel is random and each multipath component fades independently. For a Rayleigh channel, all entries of the channel matrix $H \in C^{N_r \times N_t}$ is modeled as independent and identically distributed (i.i.d) complex Gaussian random variables with zero mean and variance ½ per real dimension:

$$H_{Rayleigh} = \frac{1}{\sqrt{2}}(X + jY) \qquad (17)$$

where, X and Y are real *i.i.d*. normal random matrices.

3.4.2 Rician Fading:

For a Rician channel, the channel matrix comprises a deterministic line-of-sight (LoS) part and a scattered Rayleigh component. Rician channel represents a scenario where both LoS and scattered (non-LoS) components contribute to the signal transmission. The Rician fading model is characterizes by the Rician K- factor. With a Rician K-factor (ratio of LoS power to scattered power), the channel is modelled as:

$$H_{Rician} = \sqrt{\frac{K}{K+1}}H_{LoS} + \sqrt{\frac{1}{K+1}}H_{scatter} \qquad (18)$$

3.4.3 Nakagami-M Fading:

In the Nakagami-m model, the envelope of the channel coefficients follows a Gamma distribution with shape parameter m (with m=1 corresponding to Rayleigh fading). For each element, the squared magnitude is generated by:

$$|H_{i,j}|^2 \sim \text{Gamma}(m, \theta) \qquad (19)$$

where, the scale parameter is set as θ=1/m so that the expected value is 1. A uniformly distributed phase is then added:

$$H_{i,j} = \sqrt{|H_{i,j}|^2}\, e^{j\phi_{i,j}}, \qquad \phi_{i,j} \sim U(0, 2\pi) \qquad (20)$$

4. RESEARCH METHODOLOGY AND PARAMETERS

In this section the simulations of spectral efficiency and energy efficiency is carried with basic analog beamforming for multiple input single output (MISO) system assuming perfect

channel state information at transmitter for phase only beamforming using Maximum Ratio Transmission (MRT) principle. The simulations are further extended with analog beamforming, digital beamforming and hybrid beamforming for MIMO system with imperfect channel state information (CSI). To analyse the effect of noise, different fading channel models like Rayleigh, Rician and Nakagami-m models are considered for spectral efficiency and energy efficiency calculations and plots. The simulations are carried in MATLAB and parameters are plotted with different values of SNR, varying channel conditions and number of transmit and receive antennas for MIMO system. The flow of the work is shown in Fig.4 below.
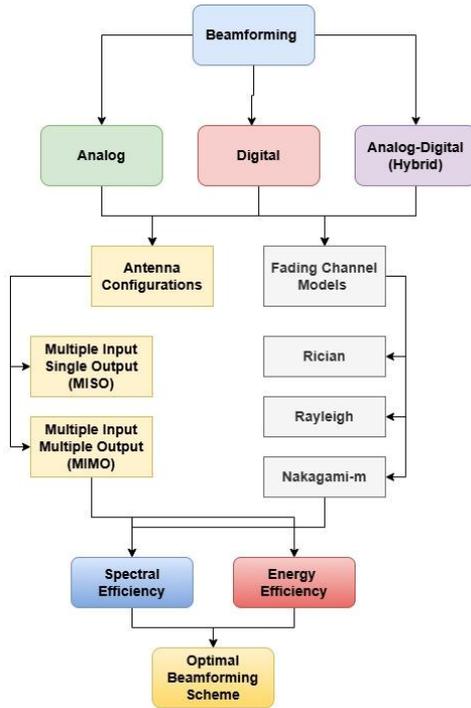

Fig.4: Research Methodology

4.1 SIGNAL-TO-NOISE RATIO (SNR)

For each simulation run, the transmit power P_{tx} is selected such that the nominal SNR is achieved:

$$P_{tx} = SNR_{linear} \times N_0 \qquad (21)$$

The instantaneous effective SNR after beamforming is given by:

$$SNR_{effective} = \frac{P_{tx} G_{eff}}{N_0 N_s} \qquad (22)$$

where, N_s is the number of data streams (here N_s=1).

4.2 SPECTRAL EFFICIENCY (SE)

Spectral Efficiency (SE) is a measure of how effectively the system uses the available bandwidth to transmit data. For a point-to-point MIMO system, the SE can be calculated using the Shannon Capacity formula:

$$SE = N_s \log_2(1 + SNR_{effective}) \quad \text{(bits/sec/Hz)} \qquad (23)$$

4.3 ENERGY EFFICIENCY (EE)

Energy Efficiency (EE) measures how efficiently the system consumes power to deliver data. It is defined as the ratio of the spectral efficiency to the total power consumption of the system P_{total}:

$$EE = \frac{SE}{P_{total}} \quad \text{(bits/Joule)} \qquad (24)$$

4.4 TOTAL POWER CONSUMPTION (P_{TOTAL})

The total power consumption P_{total}, which includes the power used by transmit and receive antennas, the power amplifier, phase shifters, and baseband processing. Power consumption is modelled for each beamforming technique by combining:

- Power Amplifier (PA) consumption:

$$P_{PA} = \frac{P_{tx}}{\eta} \qquad (25)$$

- RF chain power: P_{RF} is multiplied by the number of RF chains employed (which will be different for analog, digital and hybrid beamforming type)
  - For ABF: One RF chain at the transmitter and one at the receiver.
  - For DBF: N_t at the transmitter and N_r at the receiver.
  - For HBF: N_t^{RF} at the transmitter and N_r^{RF} at the receiver.

- Phase shifter power (P_{PS}): Each antenna (transmit and receive) is assumed to require a phase shifter, so its total consumption is proportional to $N_t + N_r$.

- Baseband processing power: A fixed power P_{BB}.

- Total power for ABF is:

$$P_{total} = P_{PA} + P_{RF} + N_t P_{PS} + N_r P_{PS} + P_{BB} \qquad (26)$$

- Total power for DBF is:

$$P_{total} = P_{RF} + N_t P_{PS} + P_{BB} \qquad (27)$$

- Total power for HBF is:

$$P_{total} = P_{PA} + N_t^{RF} P_{RF} + N_r^{RF} P_{RF} + N_t P_{PS} + N_r P_{PS} + P_{BB} \qquad (28)$$

The simulations is carried out in in MATLAB by defining system parameters like number of transmit antenna N_t, number of receive antenna N_r, SNR range, setting channel model and corresponding parameters for Rayleigh, Rician and Nakagami-m channel. The power consumption values for each element are set. The channel model is selected in MATLAB and beamforming computations are carried out for analog, digital and hybrid beamforming. The plots of spectral efficiency vs. SNR and energy efficiency vs. SNR for the different beamforming types are observed; in addition for digital beamforming performance for the different N_t values are compared.

5. RESULTS AND DISCUSSION

5.1 ANALOG BEAMFORMING FOR MISO

The basic analog beamforming is simulated for the MISO configuration with different values of transmitting antenna from

2 to 64 keeping number of receiving antenna as 1 only (MISO) system. The plots of the spectral and energy efficiency are given in the Fig.5 and Fig.6 below.
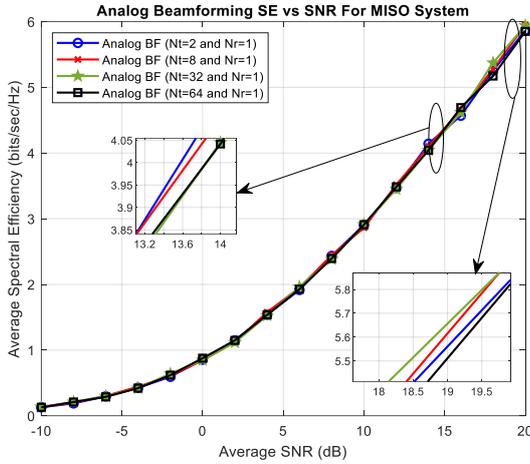

Fig.5. Spectral Efficiency Comparison of Analog Beamforming for MISO (various antenna configurations)

The performance of analog beamforming in a MISO system, as illustrated in Fig.5, reveals a clear and consistent trend of improved spectral efficiency (SE) with increasing SNR across all antenna configurations. At lower SNR values (-10 dB to 0 dB), the SE remains relatively low and closely clustered, regardless of the number of transmit antennas. This behaviour is expected due to the dominant impact of noise in this regime, which limits the system's ability to leverage spatial gain effectively. For instance, at 0 dB, the SE ranges between approximately 0.3 and 0.4 bits/sec/Hz for all configurations. As the SNR increases to 10 dB, the impact of additional transmit antennas becomes more pronounced. The SE for the N_t=2 and N_r=1 configuration reaches around 2.6 bits/sec/Hz, while the N_t=64, N_r=1 configuration approaches 3.1 bits/sec/Hz. This improvement highlights the growing role of beamforming gain in enhancing throughput as the system transitions from noise-limited region to signal-dominated conditions. The difference in SE becomes even more apparent at 20 dB SNR, where the N_t=64, N_r=1 setup achieves approximately 6 bits/sec/Hz, compared with 5.7 bits/sec/Hz for the N_t=2 and N_r=1 system. Although the absolute gains in SE diminish at higher SNRs, the incremental improvements offered by additional antennas remain valuable in systems requiring higher data rates and wide coverage. The zoomed-in regions of the Fig.around 13-14 dB and 18-20 dB offers a more granular comparison of system behaviour. These visual insets clearly show that while performance gap between configurations narrow at high SNRs, it does not vanish entirely. Such observations are crucial for hardware-aware system design, where the marginal benefits of deploying more antennas must be weighed against power, cost, and complexity constraints.

The Fig.6 presents the variation of average energy efficiency (EE), measured in Mbits/Joule, with respect to average SNR for MISO system employing analog beamforming. At low SNR level (-10 dB to 0 dB), EE increases sharply for all antenna configurations, with the N_t=2 and N_r=1 setup outperforming others. Specifically, the N_t=2 and N_r=1 and N_t=8 and N_r=1 configurations reach peak EE values of approximately 3.3 ×10⁻⁷

and 3.1 ×10⁻⁷ Mbits/Joule, respectively, around 0 to 5 dB. Notably, the configurations with a larger number of transmit antennas 32 and 64 exhibit lower peak energy efficiency values of around 2.5 ×10⁻⁷ and 2.1 ×10⁻⁷ Mbits/Joule, respectively. This decline is primarily due to increase hardware power consumption that offsets the modest gains in spectral throughput at these antenna scales. Beyond 5 dB SNR, all configurations begin to experience a gradual decline in EE. This trend reflects the diminishing marginal returns of increasing power in analog beamforming systems. The EE values for all configurations converge towards a common lower bound, settling between 2.4 ×10⁻⁸ and 2.5 ×10⁻⁸ Mbits/Joule, as shown in the zoomed inset near the high –SNR regime.
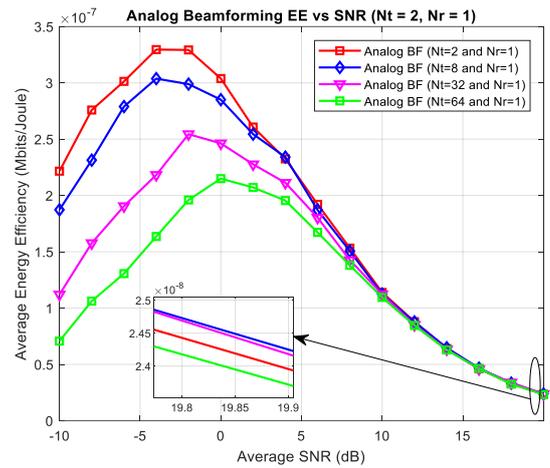

Fig.6. Energy Efficiency Comparison of Analog Beamforming for MISO (various antenna configurations)

5.2 ABF, DBF AND HBFFOR MIMO

This section presents the comparison of spectral efficiency and energy efficiency for multiple inputs multiple output antenna system. The results are shown in Fig.7 and Fig.8.
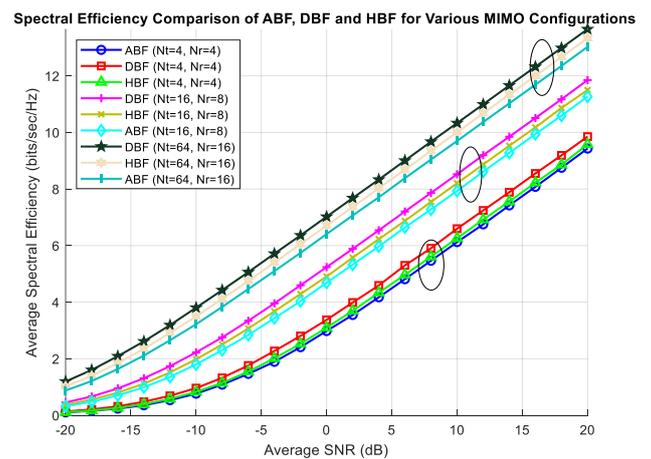

Fig.7. Spectral Efficiency Comparison of ABF, HBF and DBF for MIMO Configurations

The Fig.7 illustrates the average spectral efficiency as a function of average SNR. As theoretically expected, the SE of all beamforming techniques is a monotonically increasing function of SNR. The results clearly establish that DBF achieves the higher

spectral efficiency across all scenarios, owing to its capability to control the phase and amplitude of the signal at each antenna element independently. However the HBF scheme demonstrates remarkably competitive performance, closely trailing the upper-bound performance of DBF. For instance, in the massive MIMO configuration of (N_t=64, N_r=16) at an SNR of 10 dB, DBF achieves an SE of approximately 10 bits/sec/Hz, whereas HBF reaches a very close 9.6 bits/sec/Hz. In contrast, ABD shows the lowest SE, achieving only 8.7 bits/sec/Hz under the same conditions. This trend consistently holds across all antenna configurations, underscoring that HBF provides a compelling trade-off, realizing near-optimal SE with significantly hardware complexity compared to DBF.
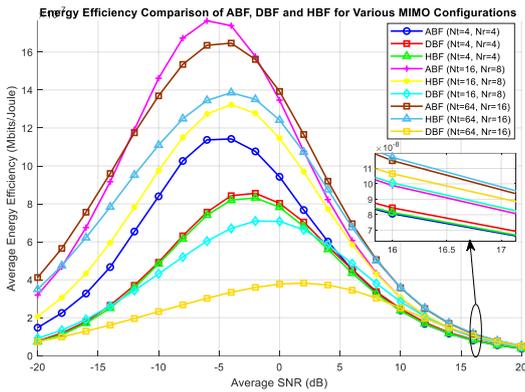

Fig.8. Spectral Efficiency Comparison of ABF, HBF and DBF for MIMO Configurations

The Fig.8 provides the corresponding energy efficiency comparison, revealing a crucial trade-off. Unlike, the EE performance in not monotonic, exhibiting a quasi-concave behaviour where it peaks at the specific SNR and then decreases. This decline in the high-SNR regime is attributed to the fact that the increase in power consumption eventually outweighs the saturating gains in data rate. The analysis highlights that the HBF scheme consistently offers superior energy efficiency compared to DBF. For the (N_t=16, N_r=8) system, HBF achieves a peak EE of approximately 14 Mbits/Joule at an SNR of -5 dB, significantly outperforming DBF, which peaks at around 11.5 Mbits/Joule at -4 dB. Interestingly, for the massive MIMO case (N_t=64, N_r=16), ABF shows the highest peak EE (approx... 17.2 Mbits/Joule at -6 dB), slightly edging out HBD (approx.... 16.5 Mbits/Joule at -6dB). This is due to ABF's extremely low static power consumption. However, its SE performance is severely compromised, as shown in Fig.7. DBF remains the least energy-efficient architecture, achieving a peak of only 14 Mbits/Joule. It is seen that EE does not monotonically improve with more antennas, while larger arrays offer beamforming and diversity gains, the associated increase in hardware power consumption leads to diminishing returns in EE. ABF emerges as the most energy-efficient solution, especially in the mid-to-large-scale array, due to its reduced RF chain count and lower computational overhead.

5.3 ABF, DBF AND HBF FOR MIMO WITH RICIAN CHANNEL

This section presents the comparison of spectral efficiency and energy efficiency for analog, digital and hybrid beamforming with Rician channel for different values of 'K'. The results are presented in Fig.9 and Fig.10.
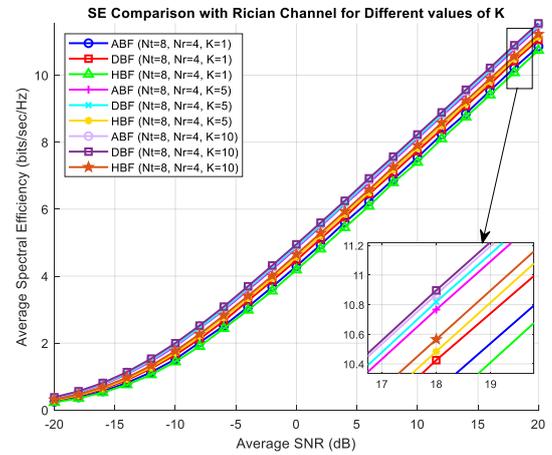

Fig.9. Spectral Efficiency Comparison of ABF, HBF and DBF with Rician Channel (for different K)

The Fig.9 presents the variation in average spectral efficiency (SE) for three beamforming techniques- over a Rician fading channel. The results are shown for a MIMO configuration with 8 transmit and 4 receive antennas, under three different Rician K-factor conditions, reflecting a spectrum of propagation environments from rich scattering (low-K) to line-of sight (high-K) dominated scenarios. The impact of Rician K-factor is significant. A stronger LoS component (higher K) enhances channel reliability and gain, benefiting all beamforming schemes. For instance, at an SNR of 10 dB, the SE for the superior DBF architecture increases from approximately 9.8 bits/sec/Hz at K=1 to 10.4 bits/sec/Hz at K=10. A similar trend is observed for HBF, where the SE improves from 9.4 to 10 bits/sec/Hz as K increases from 1 to 10 at the same SNR. This demonstrates that channels with dominant LoS paths are highly favourable for achieving higher spectral efficiencies, and the performance gap between ideal DBF and practical HBF remains relatively small, particularly in such a LoS rich environment.
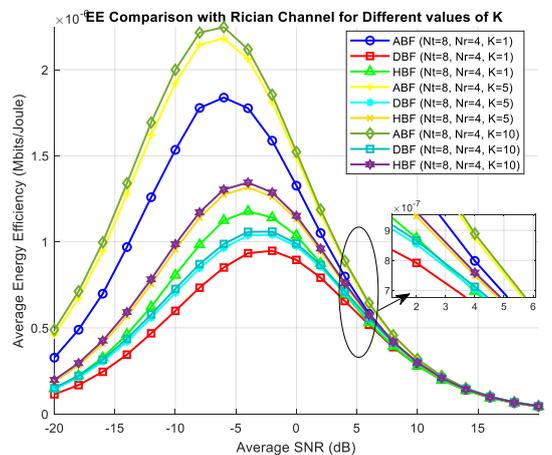
Fig.10. Energy Efficiency Comparison of ABF, HBF and DBF
with Rician Channel (for different K)

The Fig.10 details the average EE in Mbits/Joule. The performance ranking if beamforming architectures mirrors the SE results: DBF>HBF>ABF. The superior performance of DBF directly translates to higher energy efficiency. The Rician K-factor also plays a crucial role in enhancing EE. At the peak efficiency point (~7dB), the EE of DBF improves from approximately 1.8×10^{-6} Mbits/Joule for K=1 to a slightly higher 2.25×10^{-6} Mbits/Joule for K=10, representing 25% increase. This underscores that a strong LoS component not only boost throughput but also allows for more energy-efficient communication. The HBF architecture again proves to be viable and efficient alternative, achieving a peak EE of 1.35×10^{-6} Mbits/Joule at K=10, which is substantially better than the 1.1×10^{-6} Mbits/Joule achieved by ABF under the same conditions. This highlights the practical advantage of HBF in delivering performance that is a large fraction of ideal DBF's performance while mitigating its prohibitive hardware complexity and cost.

5.4 ABF, DBF AND HBF FOR MIMO WITH NAKAGAMI CHANNEL

This section presents the comparison of spectral efficiency and energy efficiency for analog, digital and hybrid beamforming with Nakagami channel for different values of '*m*'. The results are presented in Fig.11 and 12.
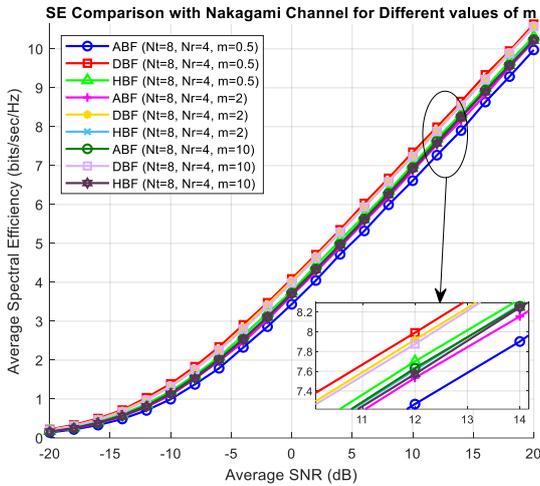

Fig.11. Spectral Efficiency Comparison of ABF, HBF and DBF
with Nakagami Channel (for different m)

The Fig.11 shows performance evaluation of ABF, HBF and DBF under Nakagami-m fading channel model, which accurately represents a wide range of fading environments by varying the fading severity parameter-*m*. The impact of the Nakagami-m fading parameter on SE is also significant. As *m* increases, the channel conditions improve, signifying a reduction in the severity of fading. For instance, at an SNR of 10 dB, the SE of DBF increases from approximately 7.5 bits/sec/Hz for *m=0.5* (sever fading) to about 8 bits/sec/Hz for *m=10* (less sever, more LoS like propagation). A similar trend is observed for HBF and ABF, with all schemes benefiting from the improved channel quality associated with higher *m* values. The zoomed-in portion of the SE

graph clearly illustrates that for a given SNR, the SE for all beamforming types increases with the *m* parameter. For example, at an SNR of 12 dB, the HBF scheme's SE rises from approximately 7.6 bits/sec/Hz at *m=0.5* to nearly 8.2 bits/sec/Hz at *m=10*.

The Fig.12 illustrates the energy efficiency (EE) of the different beamforming architectures. A critical finding from the EE analysis is the superior performance of the hybrid beamforming architecture across wide range of SNRs, particularly in the low to moderate SNR regime where the energy efficiency is a primary concern. For instance, at an SNR of -5 dB and m=10, the HBF scheme achieves a peak EE of approximately 1.4×10^{-6} Mbits/Joule, outperforming both DBF (around 1.3×10^{-6} Mbits/Joule) and ABF (around 1.05×10^{-6} Mbits/Joule). The superior EE of HBF stems from its ability to achieve a spectral efficiency comparable to DBF but with significantly lower power consumption due to the reduced number of RF chains. The influence of the Nakagami-m parameter on EE is also evident. As m increases, indicating a more favourable channel, the EE improves for all beamforming techniques. This is because a better channel allows for higher data rates to be achieved for the same power expenditure. For example, the peak EE for HBF increases from approximately 1.5×10^{-6} Mbits/Joule at *m*=0.5 to 1.4×10^{-6} Mbits/Joule at m=10. The zoomed-on section of the EE plot around 0 dB SNR clearly shows that for a given beamforming type, the EE curves are higher for larger values of *m*.
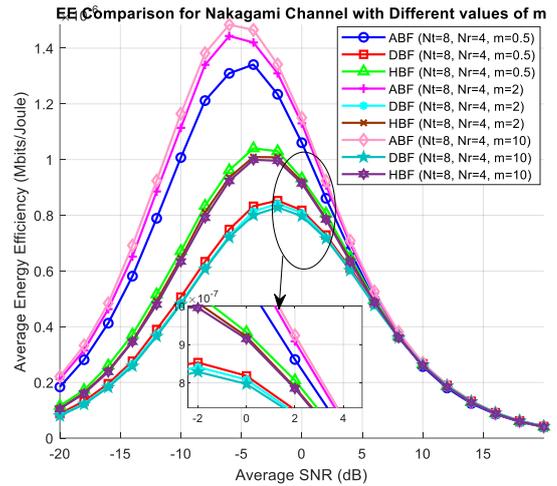

Fig.12. Energy Efficiency Comparison of ABF, HBF and DBF
with Nakagami Channel (for different m)

5.5 COMPARISON OF ABF, DBF AND HBF WITH RICIAN AND RAYLEIGH CHANNEL

The spectral efficiency values are compared for analog, digital and hybrid beamforming for MIMO configuration with Rician channel (optimum value of '*K*') and Rayleigh channel. The comparisons are presented in Fig.13 and Fig.14.

The Fig.13 presents a rigorous comparative analysis of the HBF, DBF and ABF under two distinct channel models: a sever-fading Rayleigh channel and a more favourable Rician channel with a K-factor of 5, representing a scenario with a strong line-of-sight (LoS) component. For any given beamforming architecture, the Rician channel consistently yields a higher SE than the Rayleigh channel. This is due to the presence of a stable LoS path

in the Rician model, which provides a more reliable communication link compared to the non-LoS, multipath-only Rayleigh environment. For instance, at an SNR of 10 dB, the HBF under the Rician channel achieves an SE of approximately 8 bits/sec/Hz, whereas under the Rayleigh channel, its SE is about 7.2 bits/sec/Hz, representing an improvement of approximately 11%.
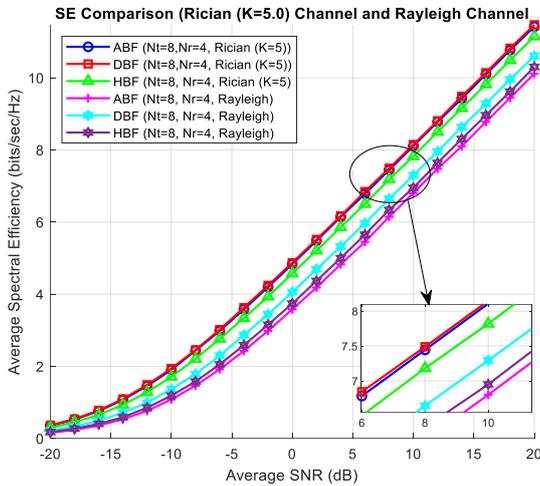

Fig.13. Energy Efficiency Comparison with Rician and Rayleigh Channel

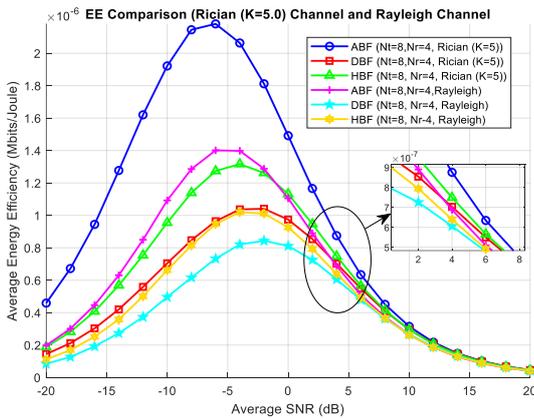
Fig.14. Energy Efficiency Comparison with Rician and Rayleigh Channel

The Fig.14 illustrates EE performance. The most striking result is the superiority of the Rician channel in enhancing EE. The improved link quality from the LoS component means that higher data rates are achieved for the same power expenditure, thus boosting overall efficiency. For the HBF scheme, the peak EE in the Rician channel is approximately 2.25×10^{-6} Mbits/Joule at an SNR of -7 dB. This is substantial improvement over its performance in the Rayleigh channel, where the peak EE is only about 1.4×10^{-6} Mbits/Joule at a similar SNR. Under Rayleigh fading, the EE for all methods drops noticeably: ABF peaks at $\sim 1.4 \times 10^{-6}$ Mbits/Joule, while HBF and DBF achieves only $\sim 1.2 \times 10^{-6}$ and $\sim 0.9 \times 10^{-6}$, respectively. This $\sim 30\%$ degradation in energy efficiency highlights the impact of increased multipath scattering and channel uncertainty on energy utilization.

The findings are summarised in Table.1 below which emphasize the importance of channel characteristics in shaping the performance boundaries of different beamforming schemes. While DBF continues to dominate in terms of spectral efficiency, its high circuit power costs undermine its energy efficiency-particularly in non-line-of-sight (Rayleigh) conditions. In contrast, ABF provides strong energy-efficient operation, particularly under favourable channel conditions (e.g. Rician fading), making it attractive for low-power or green communication application. HBF consistently offers a middle ground combining SE performance close to DBF with energy demands closer to ABF, especially in moderate SNR and K-factor environments.

Table.1. Summary of SE and EE at 20 dB SNR

Method	Channel Type	Antennas (*Tx,Rx*)	SE (bits/sec /Hz)	EE (Mbits/ Joule)	Notable Advantage
ABF	Rician (*K*=5)	(8,4)	10.4	2.1×10^{-6}	Best EE
DBF	Rician (*K*=5)	(8,4)	10.9	1.0×10^{-6}	Best SE
HBF	Rician (*K*=5)	(8,4)	10.6	1.4×10^{-6}	Balanced SE+EE
ABF	Rayleigh	(8,4)	10.1	1.45×10^{-6}	EE drop in fading
HBF	Nakagami (*m*=10)	(8,4)	10.6	1.45×10^{-6}	Stable across *m*
DBF	MIMO	(64,16)	13.2	0.9×10^{-6}	Max SE, High cost

6. CONCLUSION

This comprehensive study quantitatively evaluates the spectral and energy efficiency of Analog Beamforming (ABF), Digital Beamforming (DBF), and Hybrid Beamforming (HBF) across various MIMO configurations, fading environments, and channel conditions. Results consistently show that DBF achieves the highest spectral efficiency, reaching up to 13.2 bits/sec/Hz at 20 dB SNR for N_t=64 and N_r=16, but at the cost of increased energy consumption. In contrast, ABF exhibits the best energy efficiency, peaking at $\sim 2.1 \times 10^{-6}$ Mbits/Joule under Rician fading (*K*=5) at 0 dB SNR, making it favourable for low-power IoT or energy-constrained systems. HBF emerges as the most balanced solution, delivering spectral efficiency within ~ 5-10% of DBF (e.g. 10.6 vs. 11.2 bits/sec/Hz at 20 dB) while maintain energy efficiency close to ABF (e.g. $\sim 1.4 \times 10^{-6}$ Mbits/Joule). Performance scales significantly with antenna configurations, as SE improves by $\sim 30\%$ when mobbing from N_t=4 to N_r=64. In addition, HBF shows robust behaviour across varying Nakagami-m and Rician-K parameters, indicating suitability for deployment in dynamic mobile environments with fluctuating LoS components. These findings strongly advocate for HBF in next generation wireless system use cases such as vehicular communications, mmWave backhaul, and energy-sensitive edge nodes, where the trade-off between throughout and power is critical. The proposed evaluation provides a clear guideline for

selecting beamforming schemes under diverse system constraints and channel behaviours.

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