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Implementation of Massive Multiple-Input Multiple-Output (MIMO) 5G Communication System using Modified Least-Mean-Square (LMS) Adaptive Filters Algorithm

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ABSTRACT- The massive MIMO systems are the more popular field in the present era for the 5G wireless communication system. The MIMO system is a demanding research topic for the last four decades. This topic is under implementation and observation from the last few years. These systems have many advantages and many research sub-areas but this paper investigates the modified model of the massive MIMO receiver system. The traditional receiver system model of massive MIMO system reduces the channel noise using a linear filter in the receive combiner bank (RCB) but the proposed model removes the channel noise before the RCB using an adaptive filter bank (AFB). The AFB is the combination of LMS adaptive filters. The analysis parameters are channel noise, signal-to-noise ratio (SNR) and bit-error-rate (BER) using the hybrid precoder and combiner computation algorithms – Quantized Sparse Hybrid Beamforming (QSHB) and Hybrid Beamforming Peak Search (HBPS). Therefore, the proposed massive MIMO system model gives the less channel noise in the received signal, higher SNR and lower BER as compared to the traditional massive MIMO receiver systems.

Keywords: Massive MIMO; LMS Adaptive Filters; Channel Noise; SNR; BER.

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1. INTRODUCTION

The most commonly trends for 5G wireless communication system are massive MIMO based communication system [1, 2]. There are many advantages of using massive MIMO 5G technology like very large antenna array [3], high throughput [4], decreased computational complexity [5], better SNR [6], increased SINR [5, 7], high spectral efficiency [8, 9], ultra-low latency [10], [11] [12], high data rate etc. The Massive MIMO technology is applicable for wireless communication system which has large groups of users existing in small region [13]. Due to large number of transmitting and large number of receiving antennas, spatial multiplexing provides high spectral efficiency [14]. Most essential part of massive MIMO 5G system is precoder and combiner [8, 12, 15–17]. Hybrid precoder and combiner (HPC) is advance design of precoder and combiner in massive MIMO system. Few key advantages of HPC are effective channel gain [18], low channel capacity [19], maximize SNR [20], high spectral efficiency and inter primary base station interference [1].

In this paper, LMS adaptive filters have been used in AFB to propose a new model of Massive MIMO 5G systems including its mathematical analysis. The LMS adaptive filters have been used as adaptive noise cancellation for the channel noise cancellation of the massive MIMO channel or systems to improve the performance of RCB. In conventional massive MIMO system, channel noise was associated with input signal, therefore it resulted low SNR. This paper investigates an advance model of massive MIMO receiver system, which eliminated channel noise by using AFB. This adaptive filter noise cancellation model provides enhanced parameters like: SNR, bit-error rate, etc. The fundamentals, more technical aspects, and benefits of Massive MIMO systems and LMS filters are explained in the appendixes C and D respectively.

2. SYSTEM MODEL

Figure 1 and 2 represent the massive MIMO 5G transmitter and receiver systems respectively. This system consists of N_{tr} number of transmitting antennas and N_{re} number of receiving antennas. The transmitter system includes the N_x number of data streams and input signal vector x with size N_xx1. As input is in Quadrature Amplitude Modulation (QAM) form so it will be considered as complex vector form.

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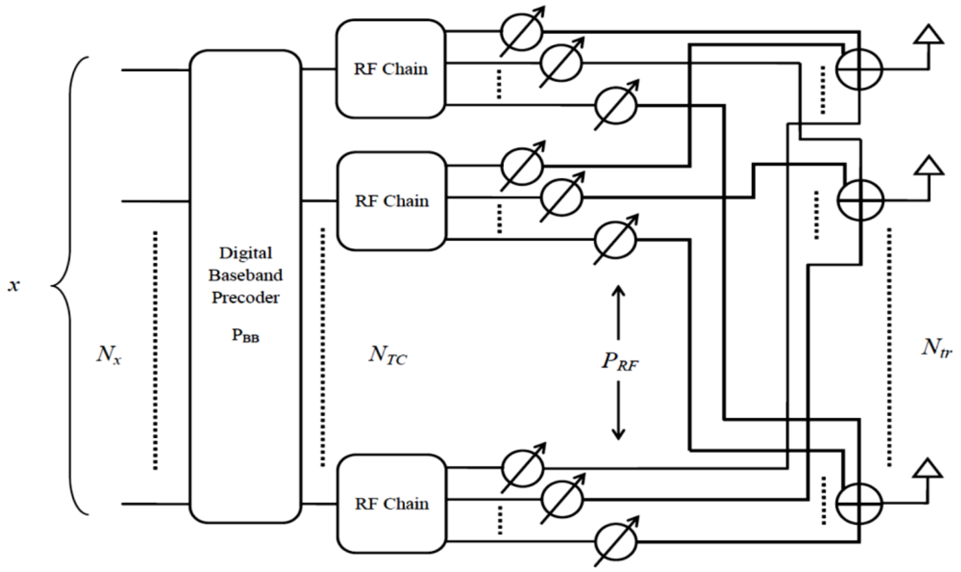

Figure 1. Block diagram of Massive MIMO 5G transmitter system

Equation (1) describes pre-processing of received signal $s$of the massive MIMO 5G systems.

$$s = \sqrt{\rho} H_C P_{RF} P_{BB} x + \eta \tag{1}$$

Table 1 describes pre-processing parameters of the massive MIMO 5G system. *Equation (2)* shows the input vector.

$$x = \begin{bmatrix} x_1 & x_2 & x_3 & \dots & x_m & \dots & x_{N_{tr}} \end{bmatrix}^T \tag{2}$$

Where, $x_m$is the m^{th} transmitted signal or symbol and$1 \leq m \leq N_{tr}$. The m^{th} transmitted symbol is further divided into its real and imaginary parts, as shown in *equation (3)*. Superscript $(.)^T$ denotes the transpose of the given vector.

$$x_m = x_{m,R} + j x_{m,I} \tag{3}$$

Where, the m^{th} transmitted signal or symbol x_m has $x_{m,R}$ and $x_{m,I}$ as the real and imaginary parts respectively.

Equation (4) presents the energy of the of input data stream.

$$E[(x)(x^{*T})] = \frac{1}{N_x} I_{N_x} \tag{4}$$

Where, $E(.)$presents the expectation of given signal or variable, I_K presents the identity matrix with size KxK and $(.)^{*T}$ denotes the complex conjugate and transpose vector.

Table 1. Pre-processing parameters of the massive MIMO 5G transmitter system

Parameter	Description	Size/Dimension	Parameter Type
N_x	Number of input data streams	1x1	Real Integer
N_{TC}	Number of transmitting RF chains	1x1	Real Integer
N_{tr}	Number of transmitting antennas	1x1	Real Integer
ρ	Average received power	1x1	Real Integer
x	Input symbol vector	N_xx1	Complex Valued Vector
H_C	Channel matrix	N_{re}xN_{tr}	Complex Valued Vector
P_{BB}	Baseband precoder matrix	N_{TC}xN_x	Complex Valued Vector
P_{RF}	Analog RF phase shifter matrix	N_{tr}xN_{TC}	Complex Valued Vector
η	Complex Gaussian Channel Noise	N_{re}x1	Complex Valued Vector
s	Pre-processing received signal vector	N_{re}x1	Complex Valued Vector
$\tilde{x}$	Transmitted signal	N_{tr}x1	Complex Valued Vector

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The data stream x passes through the digital baseband precoder and the hardware structure of precoder depends on complex valued precoder matrix P_{BB} with their size N_{TC}xN_x, where N_{TC} is the number of transmitting RF chains. The output vector of the digital precoder is passes to the N_{TC} number of transmitting RF chains followed by the N_{TC}xN_{tr} number of analog phase shifters. The size of transmitting signal $\tilde{x}$ is N_{tr}x1 by the transmitting systems of the massive MIMO 5G system after the addition of the phase shifters generated signals. The transmitted signal $\tilde{x}$ is defined in the *equation (5).*

$$\tilde{x} = P_{RF}P_{BB}x \tag{5}$$

The combination of RF chains, phase shifters and adders are named as analog precoders. The analog precoder matrix is presented as P_{RF} with size N_{tr}xN_{TC}. The elements of the analog precoder matrix are following the given relation in *equation (6).*

$$(P_{RF}^{j}P_{RF}^{j*T})_q = \frac{1}{N_{tr}} \tag{6}$$

Where, $(.)^j$ is presenting the j^{th} column vector of the given vector and $(.)_q$ presents the q^{th} diagonal element of the given matrix.

Due to the power constraints of the transmitter, the P_{BB} is normalized by the given relation in the *equation (7).*

$$\|P_{RF}P_{BB}\|_E^2 = N_x \tag{7}$$

Where, $\|.\|_E$ presents the Euclidean norm of the given vector. Channel matrix H_C with size N_{re}xN_{tr} represented as,

$$\mathrm{H_C} = \begin{bmatrix} \mathrm{H_{1,1}} & \mathrm{H_{1,2}} & \cdots & \mathrm{H_{1,m}} & \cdots & \mathrm{H_{1,N_{tr}}} \\ \mathrm{H_{2,1}} & \mathrm{H_{2,2}} & \cdots & \mathrm{H_{2,m}} & \cdots & \mathrm{H_{2,N_{tr}}} \\ \mathrm{H_{3,1}} & \mathrm{H_{3,2}} & \cdots & \mathrm{H_{3,m}} & \cdots & \mathrm{H_{3,N_{tr}}} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \mathrm{H_{n,1}} & \mathrm{H_{n,2}} & \cdots & \mathrm{H_{n,m}} & \cdots & \mathrm{H_{n,N_{tr}}} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \mathrm{H_{N_{re},1}} & \mathrm{H_{N_{re},2}} & \cdots & \mathrm{H_{N_{re},m}} & \cdots & \mathrm{H_{N_{re},N_{tr}}} \end{bmatrix} \tag{8}$$

Where, $H_{n,m}$ is the channel matrix coefficient of massive MIMO 5G systems between n^{th} receiving antenna and m^{th} transmitting antenna, $1 \le m \le N_{tr}$ and $1 \le n \le N_{re}$.

The channel matrix satisfies the relation given in *equation (9).*

$$E[\|H_C\|_E^2] = N_{tr}N_{re} \tag{9}$$

The block-fading propagation channel is considered here for the simplicity. The parameter ρ presents the average received power and η is additive white Gaussian noise (AWGN) vector with size N_{re}x1. The noise vector is independent and identically distributed (i.i.d.) with zero mean and σ_n^2 variance. The pre-processing received signal vector s is shown in *equation (1)* by the receiving antenna of the receiver systems and its size is N_{re}x1. The channel noise vector η and received signal vector s are described in the *equations (10) and (11)* respectively.

$$\eta = [\eta_1 \quad \eta_2 \quad \eta_3 \quad \ldots \quad \eta_n \quad \ldots \quad \eta_{N_{re}}]^T \tag{10}$$

Where η_n is the received channel noise signal component at the n^{th} receiving antenna and$1 \le n \le N_{re}$.

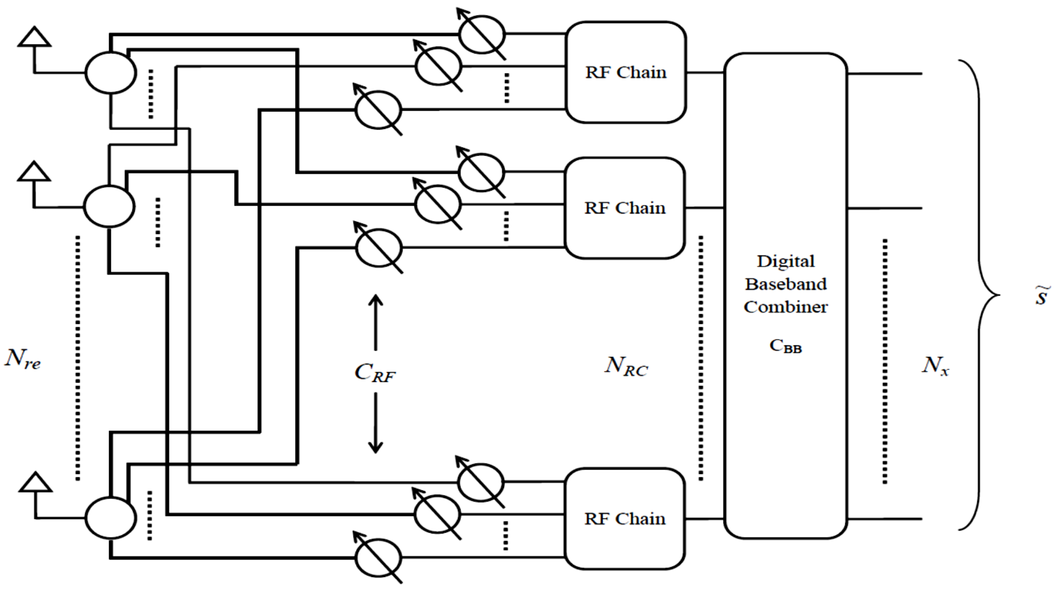

Figure 2. Block diagram of Massive MIMO 5G receiver system

$$s = [s_1 \quad s_2 \quad s_3 \quad \ldots \quad s_n \quad \ldots \quad s_{N_{re}}]^T \tag{11}$$

Where, s_n is the n^{th} output signal and$1 \le n \le N_{re}$.

The block diagram of the massive MIMO 5G receiver system is shown in *figure 2.* The post-processing received signal $\tilde{s}$of the massive MIMO 5G receiver system is described in the *equation (12).*

$$\tilde{s} = C_{BB}^{*T}C_{RF}^{*T}s = \sqrt{\rho}C_{BB}^{*T}C_{RF}^{*T}H_CP_{RF}P_{BB}x + C_{BB}^{*T}C_{RF}^{*T}\eta \tag{12}$$

The post-processing parameters of the massive MIMO 5G receiver system are described in the *table 2.*

The receiver consists of N_{re} number of splitters to transfer the received signal vector to N_{RC} number of receiving RF chains through N_{re} x N_{RC} number of phase shifters. The RF chain combiner matrix C_{RF} with size N_{re}xN_{RC} is used to generate the output signal vector and this output vector passes to the digital baseband combiner. The output signal vector of receiving RF chains is $C_{RF}^{*T}s$ and its size is N_{RC}x1. The RF chain combiner matrix coefficients have must satisfy the given relation in shown in *equation (13).*

$$(C_{RF}^{j}C_{RF}^{j*T})_q = \frac{1}{N_{re}} \quad (13)$$

The output signal vector of RF chains passes to the digital baseband combiner and generates the final output signal vector $\tilde{s}$ of the massive MIMO 5G receiver system with size N_xx1. This post-processing output signal vector is generated with the help of digital baseband combiner matrix C_{BB} with size N_{RC}xN_x. The output signal vector $\tilde{s}$ is described in the *equation (14).*

$$\tilde{s} = [\tilde{s}_1 \quad \tilde{s}_2 \quad \tilde{s}_3 \quad \dots \quad \tilde{s}_o \quad \dots \quad \tilde{s}_{N_x}]^T \quad (14)$$

Where, $\tilde{s}_o$ is the o^{th} output signal and$1 \leq o \leq N_{re}$.

Table 2. Post-processing parameters of the massive MIMO 5G receiver system

Parameter	Description	Size/Dimension	Parameter Type
N_{RC}	Number of receiving RF chains	1x1	Real Integer
N_{re}	Number of receiving antennas	1x1	Real Integer
C_{BB}	Baseband combiner matrix	N_{RC}xN_x	Complex Valued Vector
C_{RF}	Analog RF combiner matrix	N_{re}xN_{RC}	Complex Valued Vector
C_{BB}^{*T}	Complex conjugate and transpose of Baseband combiner matrix	N_xxN_{RC}	Complex Valued Vector
C_{RF}^{*T}	Complex conjugate and transpose of Analog RF combiner matrix	N_{RC}xN_{re}	Complex Valued Vector

3. PROPOSED WORK

Proposed model cancels the massive MIMO channel noise by using a combination of N_{re} adaptive filters as shown in *figure 3*. AFB used the combination of adaptive filters. The process of noise cancellation using the adaptive filter is known as an adaptive noise cancellation (ANC). The block diagram of q^{th} ANC system using LMS adaptive filter for proposed Massive MIMO receiver system is shown in the *figure 4.* Multiple benefits can be achieved using LMS adaptive filters like low structural architecture, low computational complexity, high SNR, low latency, etc.

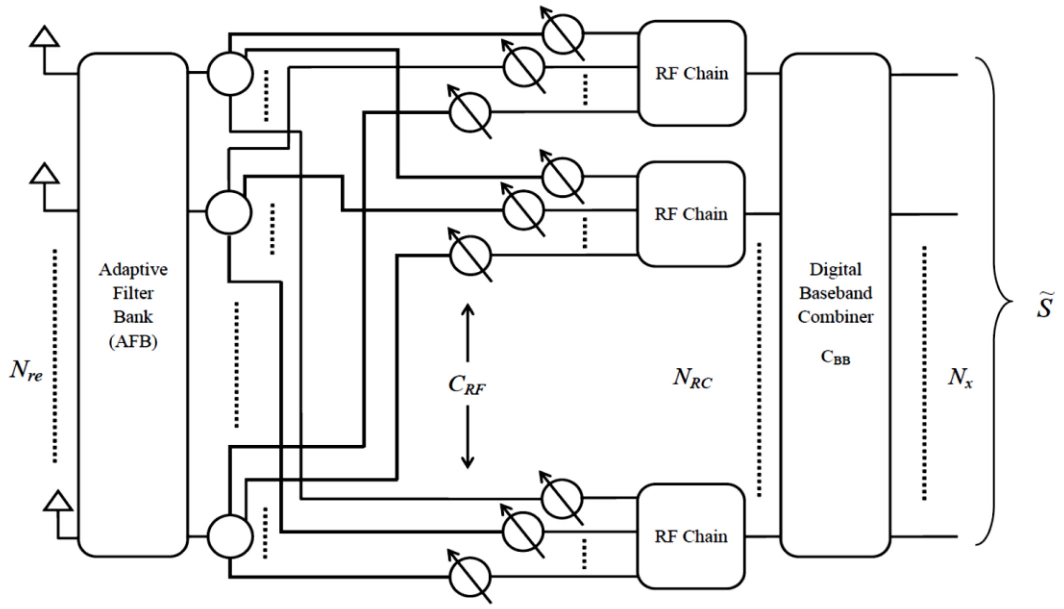

Figure 3. Block diagram of Proposed Massive MIMO 5G receiver system.

The reference input noise is compulsory to cancel the channel noise from the received primary input information signal, that's why noise detector is being used to detect the channel noise at the receiver end. The q^{th} reference noise signal is transferred to LMS adaptive filer with the help of a q^{th} noise detector and q^{th} receiving antenna. The filtered q^{th} noise signal is subtracted from the q^{th} received primary input information signal and generated the channel noise-less signal as system output.

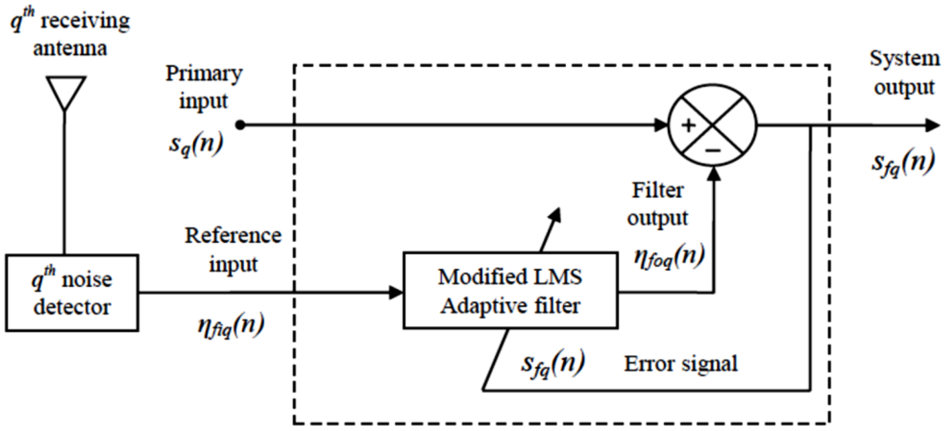

Figure 4. Block diagram of q[th] ANC system using modified LMS adaptive filter for proposed Massive MIMO receiver system

The q^{th} ANC system has three algorithms are follows using modified LMS adaptive filter:

The first algorithm is adaptive filter output signal $\eta_{foq}(n)$ algorithm is given in *equation (15).*

$$\eta_{foq}(n) = W_q^T(n)\bar{\eta}_{fiq}(n) \tag{15}$$

Where, $W_q^T(n)$ is the filter coefficient vector and $\bar{\eta}_{fiq}(n)$ is the reference input signal vector. The signals vectors $W_q^T(n)$ and $\bar{\eta}_{fiq}(n)$ are given in the *equations (16) and (17)* respectively.

$$W_q(n) = [w_{q,0}(n) \quad w_{q,1}(n) \quad \dots \quad w_{q,L-1}(n)]^T \tag{16}$$

$$\bar{\eta}_{fiq}(n) = [\eta_q(n) \quad \eta_q(n-1) \quad \dots \quad \eta_q(n-L+1)]^T \tag{17}$$

Where, L is the filter length.

The second algorithm is system output $s_{fq}(n)$ algorithm of the ANC is given in *equation (18).*

$$s_{fq}(n) = s_q(n) - \eta_{foq}(n) \tag{18}$$

The third algorithm is weight update algorithm is given in *equation (19)* for traditional LMS adaptive filter.

$$W_q(n+1) = W_q(n) + \mu_q\bar{\eta}_{foq}(n)s_{fq}(n) \tag{19}$$

Where, μ_q is the step-size and $W_q(n+1)$ is the updated weight of the q^{th} LMS adaptive filter.

The third algorithm is weight update algorithm is given in *equation (20)* for modified LMS adaptive filter.

$$W_q(n+1) = \alpha\left[W_q(n) + \mu_q\bar{\eta}_{foq}(n)s_{fq}(n)\right] \tag{20}$$

Where, α (0 < α < 1) is the variable to control the rate of the convergence rate the q^{th} LMS adaptive filter. The convergence rate is useful to get the optimum result of modified LMS adaptive filter. The ANC is having better performance due to the modified LMS adaptive filter's algorithm.

The filter weighs will be adjusted on the system error signal due to iterative process based on minimal mean square error technique and uncorrelated behaviour of primary input and reference input. The post-processing received signal $\tilde{S}$of the massive MIMO receiver system model is described in the *equation (21).*

$$\tilde{S} = C_{BB}^{*T}C_{RF}^{*T}(s-\eta) = \sqrt{\rho}C_{BB}^{*T}C_{RF}^{*T}H_C P_{RF} P_{BB} x \tag{21}$$

Table 2 describes the post-processing parameters of the massive MIMO receiver system. The receiver model after AFB consists of N_{re} number of splitters to transfer the received signal vector to N_{RC} number of receiving RF chains through N_{re} x N_{RC} number of phase shifters. The RF chain combiner matrix C_{RF} with size N_{re}xN_{RC} is used to generate the output signal vector and this output vector passes to the digital baseband combiner. The output signal vector of receiving RF chains is $C_{RF}^{*T}s$ and its size is N_{RC}x1. The RF chain combiner matrix coefficients must satisfy the given relation in shown in *equation (22).*

$$(C_{RF}^{j}C_{RF}^{j*T})_q = \frac{1}{N_{re}} \tag{22}$$

The output signal vector of RF chains passes to the digital baseband combiner and generates the final output signal vector $\tilde{S}$ of the massive MIMO receiver system with size N_xx1. This post-processing output signal vector is generated with the help of digital baseband combiner matrix C_{BB} with size N_{RC}xN_x. *Equation (23)* describes output signal vector$\tilde{S}$.

$$\tilde{S} = [\tilde{S}_1 \quad \tilde{S}_2 \quad \tilde{S}_3 \quad \dots \quad \tilde{S}_o \quad \dots \quad \tilde{S}_{N_x}]^T \tag{23}$$

Where, $\tilde{S}_o$ is the o^{th} output signal and$1 \le o \le N_{re}$.

4. MODEL SIMULATION, RESULTS AND DISCUSSION

The traditional and proposed Massive MIMO receiver system model has been implemented and simulated on MATLAB simulation software as shown in *figure A.1*. The MATLAB model is implemented with the help of block diagrams presented in the *figures 1, 2, 3 and 4* of Massive MIMO 5G

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systems. The SNR, BER and radiation pattern have been analysed with the help of simulation using the parameters values given in the *table 3*. The directivity of transmitting and receiving MIMO antennas is shown in *figure 4*. The radiation pattern of MIMO transmitting and receiving antennas are shown in *figure B.1* in the appendix B as per the range of transmitting and receiving antennas given in the *table 3*. The directivity of the transmitting and receiving MIMO antennas increasers while increasing the size of antennal elements as shown in the *figure 5*.

Table 3. Proposed Massive MIMO 5G System Simulation Parameters.

Description	Value/Range
Number of input data streams	2
M-QAM Modulator	64
Number of transmitting RF chains	4
Number of transmitting antennas	2^m (m = 2 to 12)
Average received power	2 dB
Input symbol vector	1x1000
Number of receiving RF chains	4
Number of receiving antennas	2^m (m = 2 to 12)
Mean value of MIMO channel	0
Variance value of MIMO channel	20
Gain of MIMO Channel	10
LMS Adaptive Filter Length	4
LMS Adaptive Filter Step Size	0.05
LMS Adaptive Filter Leakage Factor	1
LMS Adaptive Filter Initial Weight	0
Carrier Frequency	30 GHz

In the traditional Massive MIMO system, hybrid beamforming is based on the algorithms HBPS and QSHB including the MIMO channel noise for the computation of precoder and combiner weight matrixes. In the proposed Massive MIMO system, receiver system is upgraded with AFB before the receiving RF chains and combiner and hybrid beamforming is based on the algorithms HBPS and QSHB.

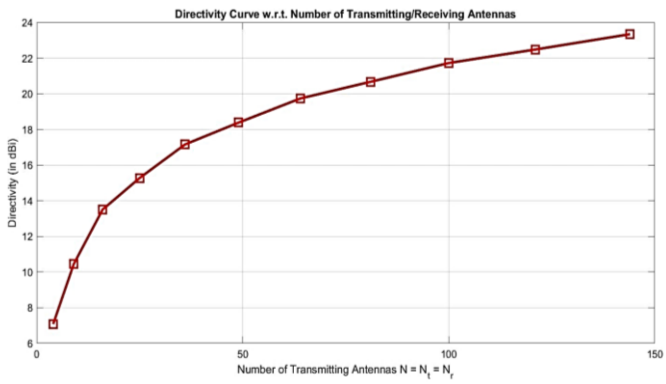
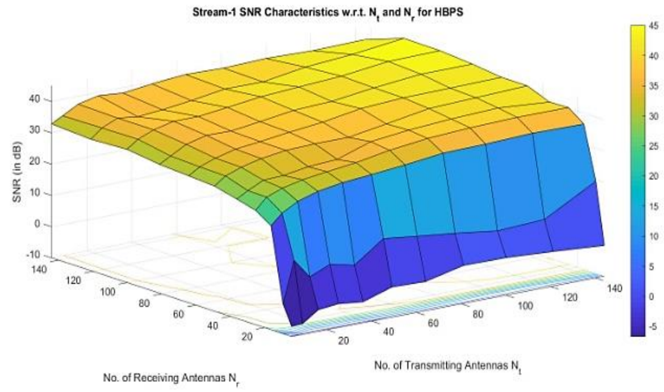
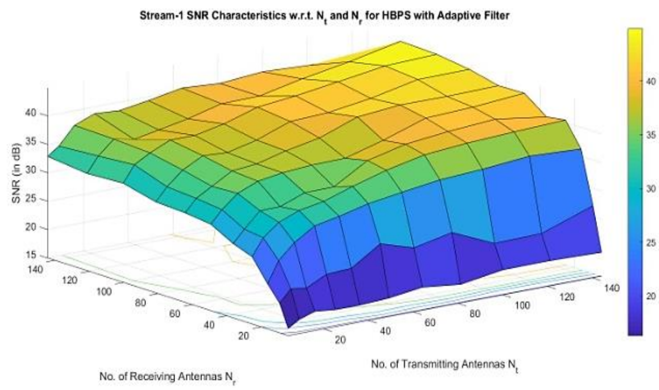


Figure 5. Directivity characteristics w.r.t. $N_{tr} = N_{re}$ of the proposed Massive MIMO system for both transmitting and receiving end.



(a)



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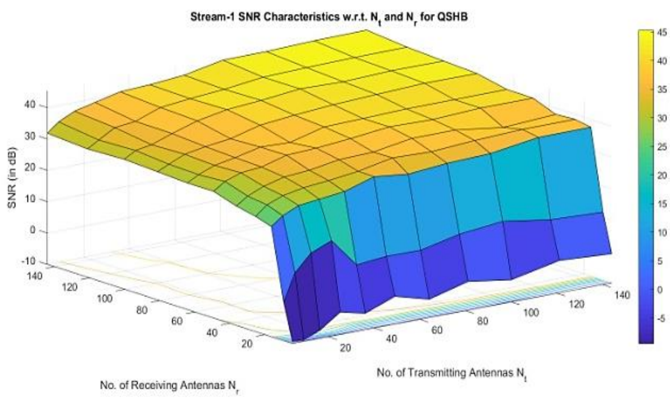

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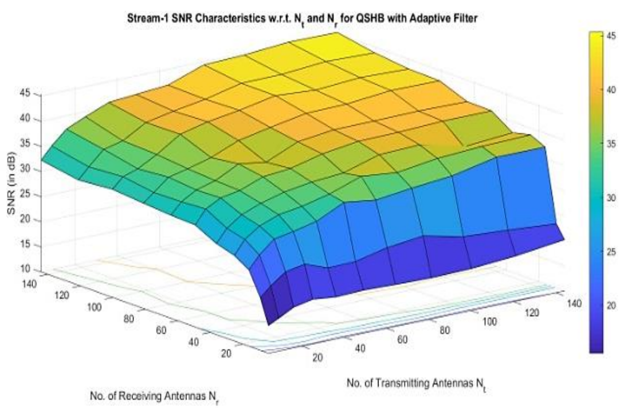

(d)

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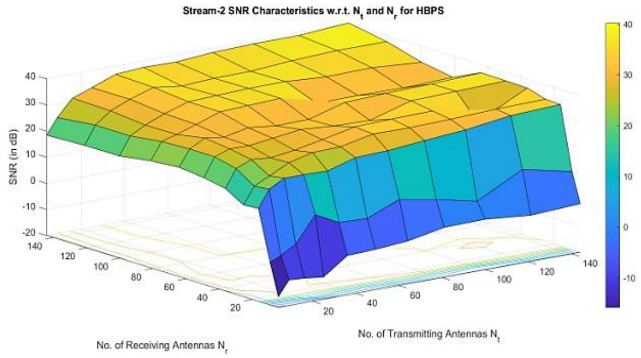

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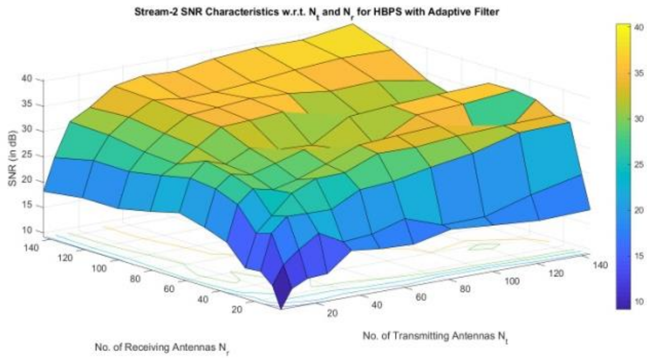

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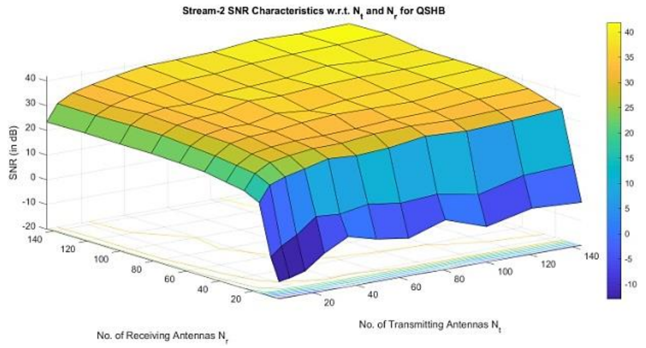

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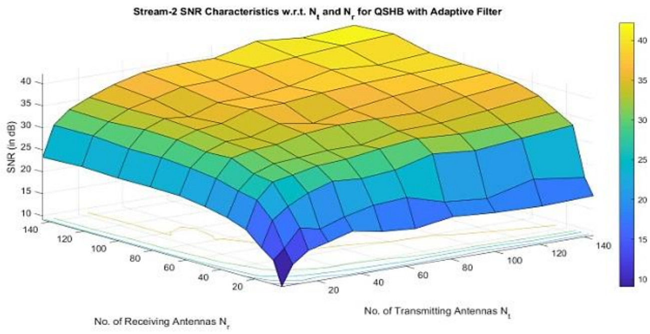
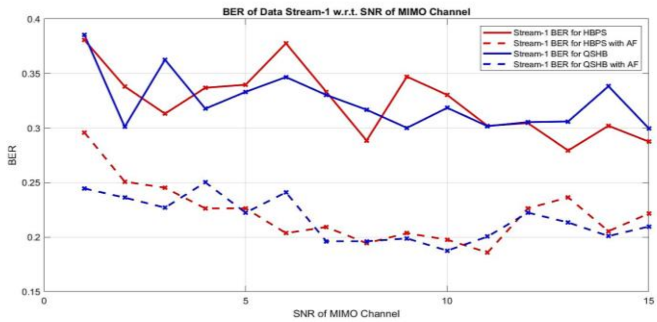


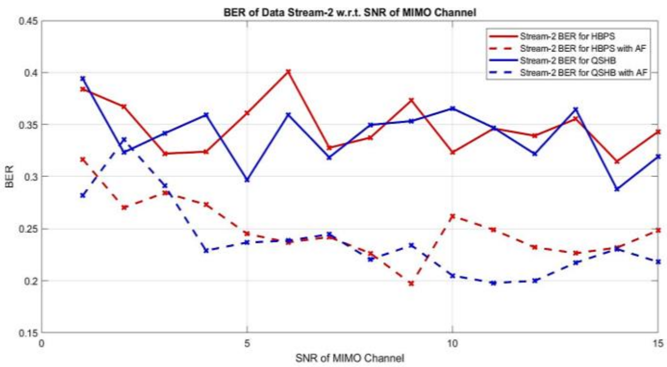
(h)

Figure 6. SNR characteristics w.r.t. Ntr and Nre of the proposed Massive MIMO system for (a) data stream-1 using HBPS algorithm (b) data stream-1 using LMS adaptive filters and HBPS algorithm (c) data stream-1 using QSHB algorithm (d) data stream-1 using LMS adaptive filters and QSHB algorithm (e) data stream-2 using HBPS algorithm (f) data stream-2 using LMS adaptive filters and HBPS algorithm (g) data stream-2 using QSHB algorithm (h) data stream-2 using LMS adaptive filters and QSHB algorithm.

The AFB is based on the LMS algorithm module to reduce the Massive MIMO channel noise. The LMS hardware architecture having efficient, low computational complexity, high accuracy, easy hardware structure or architecture, low propagation delay, rapid computation, low power consumption. *Figure 6* shows the SNR comparative analysis of the received stream-1 and stream-2 signals with and without AFB Massive MIMO system model using HBPS and QSHB algorithms. The AFB Massive MIMO system model having the higher SNR as compared to traditional Massive MIMO system model. The SNR characteristics analysed with respect to number of transmitting antennas and number of receiving antennas.



(a)



(b)

Figure 7. BER characteristics of proposed Massive MIMO system using HBPS and QSHB algorithms with and without LMS adaptive filters for (a) Stream-1 (b) Stream-2.

Table 4 presents the comparative result analysis of the traditional and proposed Massive MIMO 5G system. This analysis concludes that the proposed massive MIMO 5G system having better performance with respect to traditional Massive MIMO 5G system in terms of analysed parameters signal-to-noise ratio and bit error rate.

Table 4. Comparative result analysis between traditional and proposed Massive MIMO 5G System.

Result Parameters	Traditional Massive MIMO System	Proposed Massive MIMO System
Minimum SNR (in dB) of Stream-1 with HBPS	-6.702942657	16.29459129
Maximum SNR (in dB) of Stream-1 with HBPS	45.02088445	44.87846532
Average SNR (in dB) of Stream-1 with HBPS	31.21823233	34.27326327

Minimum SNR (in dB) of Stream-2 with HBPS	-15.872387	9.121042035
Maximum SNR (in dB) of Stream-2 with HBPS	40.27508895	40.34568306
Average SNR (in dB) of Stream-2 with HBPS	25.48153192	28.7102836
Minimum SNR (in dB) of Stream-1 with QSHB	-9.487631356	15.52879075
Maximum SNR (in dB) of Stream-1 with QSHB	45.31048111	45.35005312
Average SNR (in dB) of Stream-1 with QSHB	31.16269464	34.25385828
Minimum SNR (in dB) of Stream-2 with QSHB	-12.96058536	9.057259146
Maximum SNR (in dB) of Stream-2 with QSHB	41.85616489	42.18222207
Average SNR (in dB) of Stream-2 with QSHB	27.51853613	30.77617514
Average BER of Stream-1 with HBPS	0.324076232	0.22193187
Average BER of Stream-1 with QSHB	0.324249566	0.21648325
Average BER of Stream-2 with HBPS	0.348047161	0.249495478
Average BER of Stream-2 with QSHB	0.340207125	0.238743204

5. CONCLUSIONS

The proposed Massive MIMO 5G system model is implemented in this paper using hybrid beamforming algorithms HBPS and QSHB. These algorithms are used to maximize the spectral efficiency of the MIMO system. Two random bit steams are used to transmit in the proposed Massive MIMO 5G systems at carrier frequency 30GHz. The QAM signal transmitted and received at the receiver end of the proposed Massive MIMO 5G systems. The proposed model has a new structure using AFB based on LMS algorithm and gives higher SNR while receiving signals at receiver end. The *figure 6* shows that the SNR characteristics increases throughout the region while increasing number of transmitting antennas and or number of receiving antennas. The *figure 7* is showing the BER of the stream-1 and stream-2 signals. The *figure 7* clearly shows that the proposed Massive MIMO 5G system model gives the lower BER as compared to traditional Massive MIMO 5G system model. Therefore, this paper concludes that the proposed Massive MIMO 5G system giving the higher SNR and lower BER as compared to traditional Massive MIMO 5G system. The limitations and the potential weakness of the proposed Massive MIMO 5G systems are as follows: (a) slightly higher structure/architecture as compared to traditional Massive MIMO 5G system (b) slightly higher power consumption as compared to traditional Massive MIMO 5G system (c) slightly increase the computational complexity and propagation delay as compared to traditional Massive MIMO 5G system.

Author Contributions: The contribution of corresponding author is the conceptualization, methodology, investigation, simulation and original draft preparation. The contribution of co-author is methodology validation, simulation validation, formal analysis, supervision, review and editing of manuscript. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The complete MATLAB model of traditional and proposed Massive MIMO 5G systems is presented in the *figure A.1*. This MATLAB model is implemented with the help of *figures 1 to 4*.

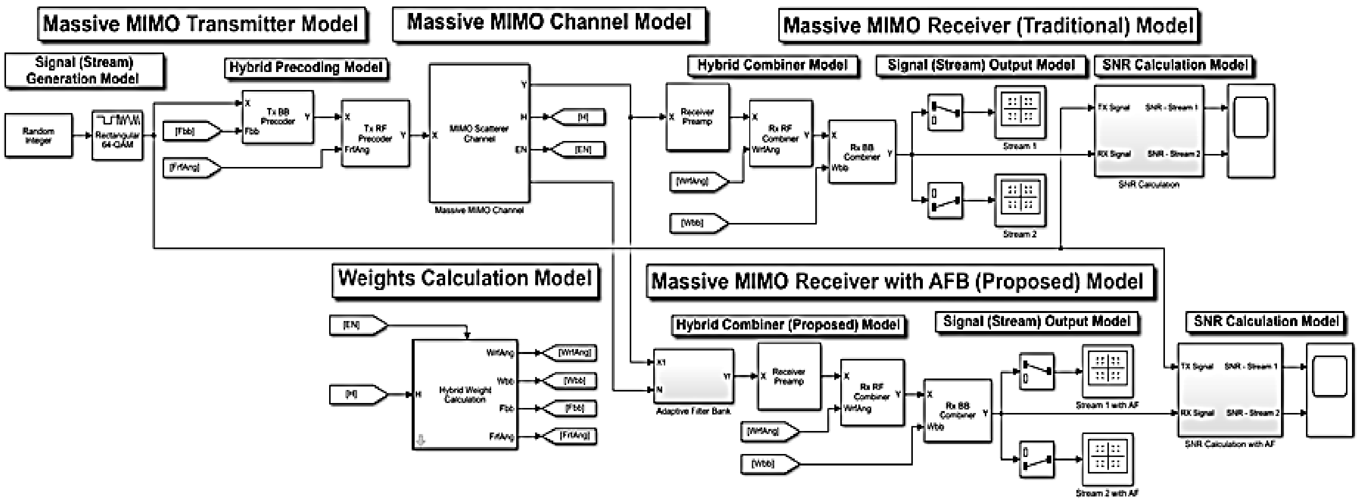


Figure A.1. MATLAB model of traditional and proposed massive MIMO 5G system

Appendix B

Antenna array and radiation pattern of Massive MIMO system at both transmitting (Tx) and receiving (Rx) end for antenna array at $N_t = N_r$ for the range 2^m (m = 2 to 12) are shown in *figures B.1(a) to B.1(v).*

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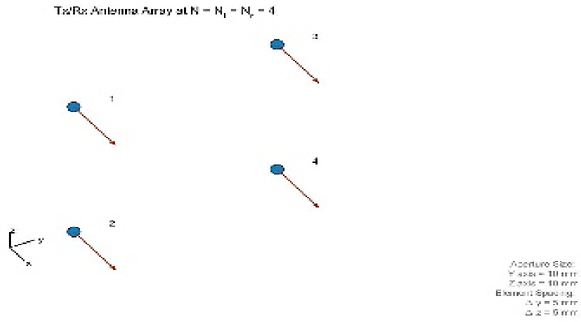

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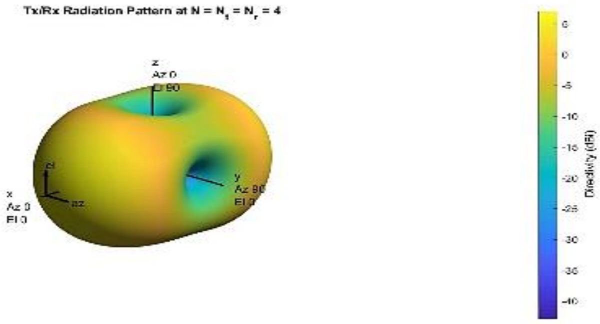

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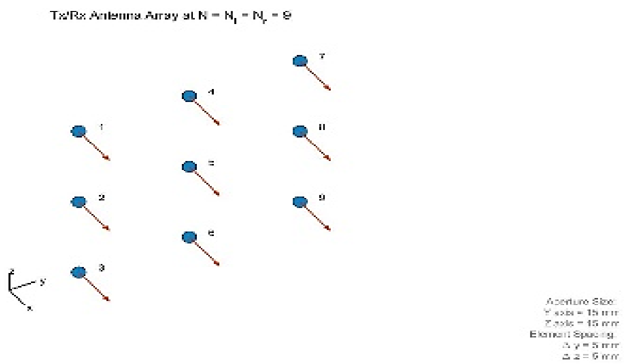
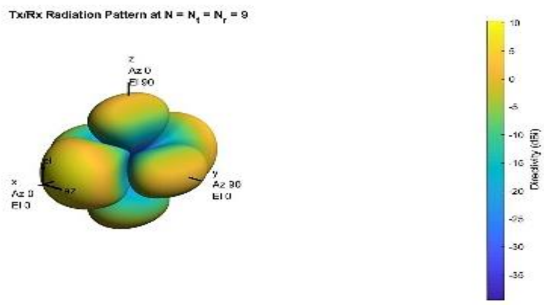


(c)



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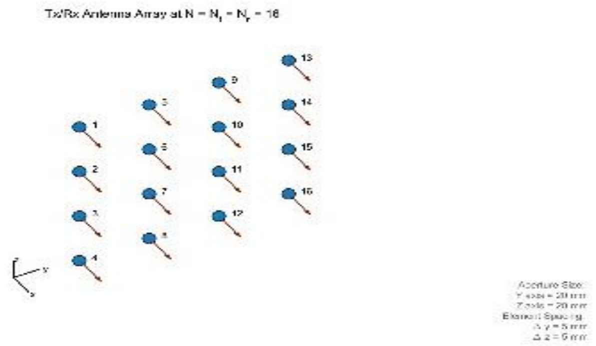

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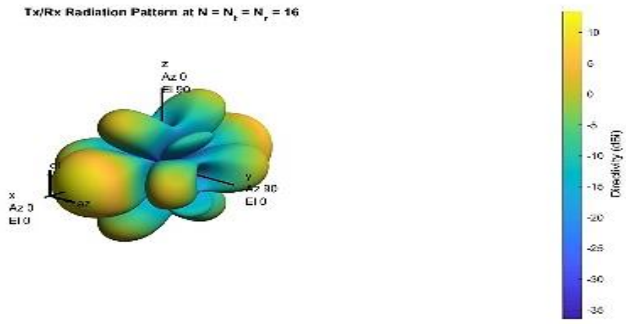
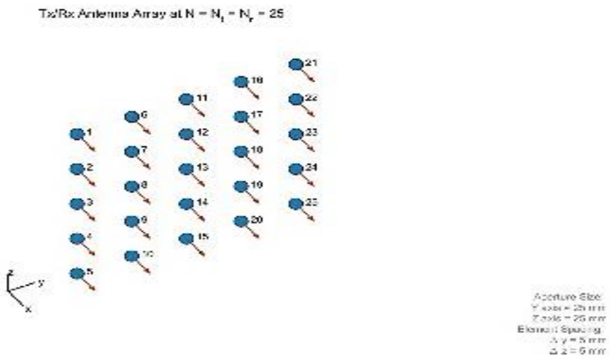
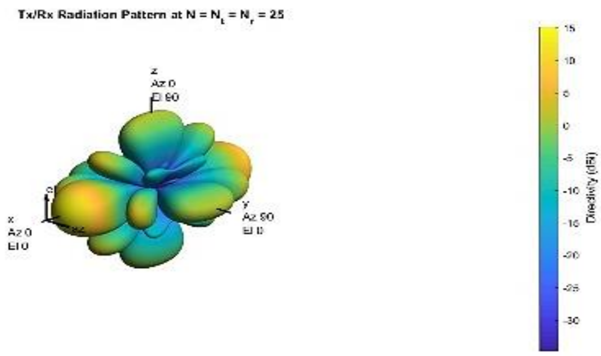


(f)



(g)



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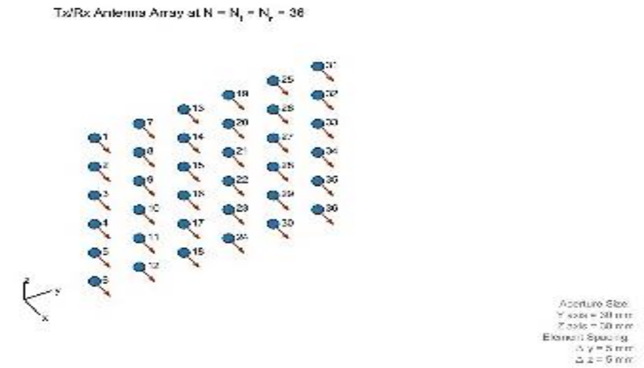
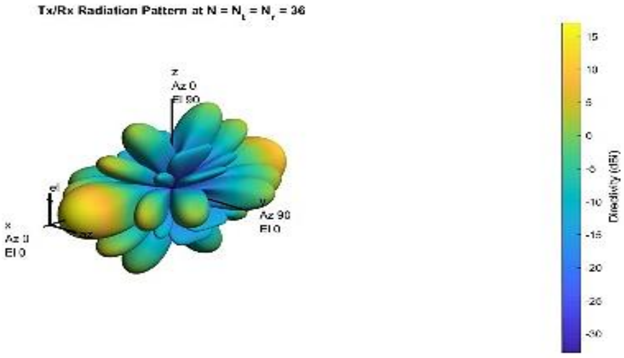
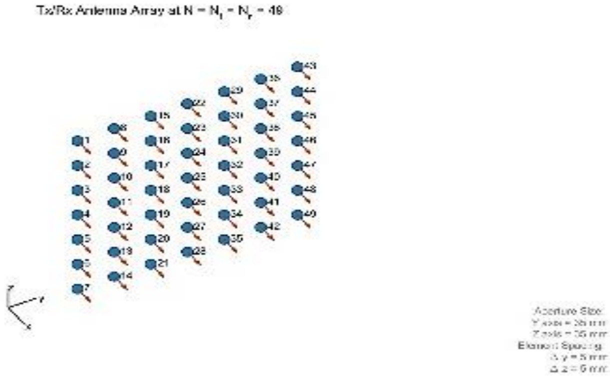

Tx/Rx Antenna Array at N = N_t = N_r = 36

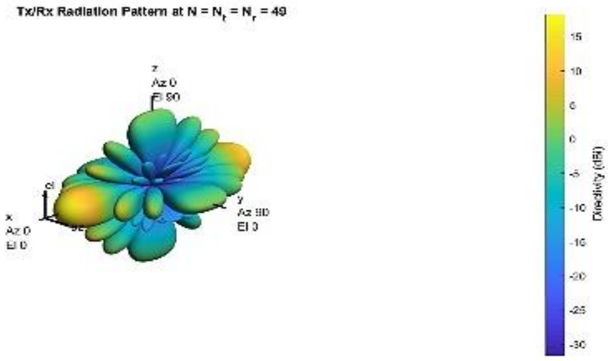
(i)


Tx/Rx Radiation Pattern at N = N_t = N_r = 36
Directivity (dBi)

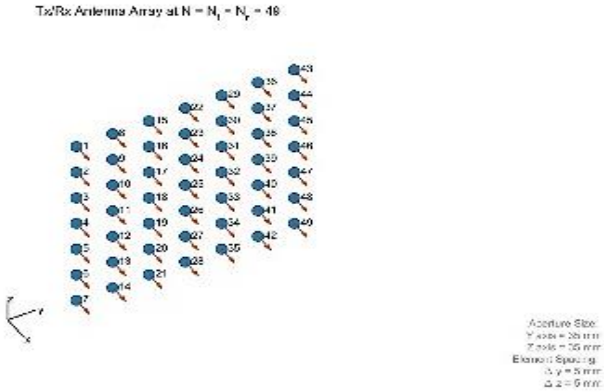
(j)


Tx/Rx Antenna Array at N = N_t = N_r = 49

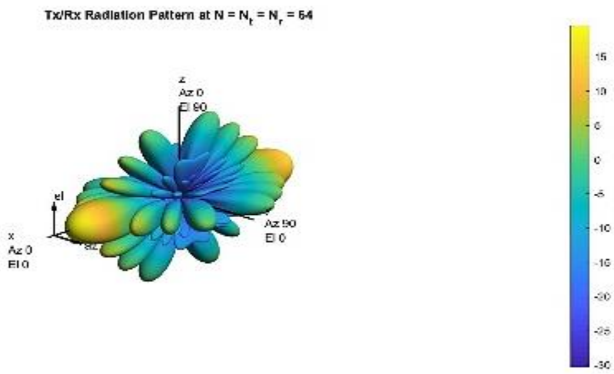
(k)


Tx/Rx Radiation Pattern at N = N_t = N_r = 49
Directivity (dBi)

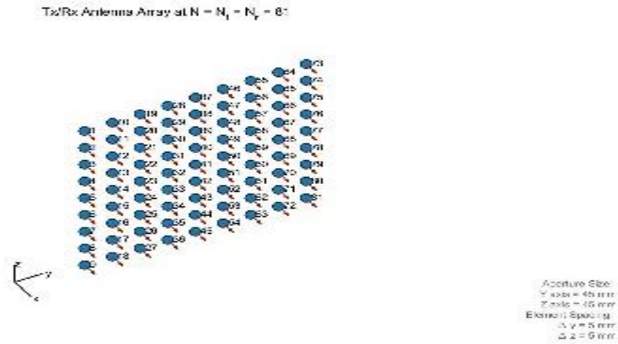
(l)


Tx/Rx Antenna Array at N = N_t = N_r = 49

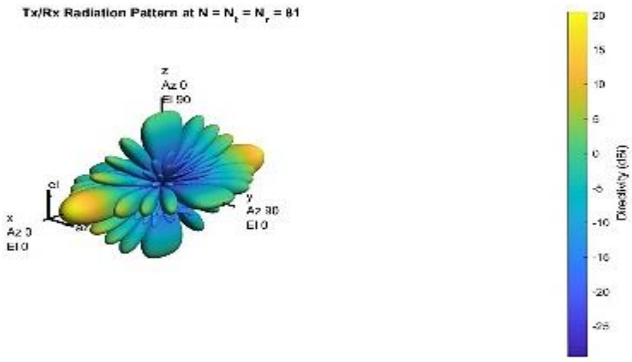
(m)


Tx/Rx Radiation Pattern at N = N_t = N_r = 64
Directivity (dBi)

(n)


Tx/Rx Antenna Array at N = N_t = N_r = 81

(o)


Tx/Rx Radiation Pattern at N = N_t = N_r = 81
Directivity (dBi)

(p)

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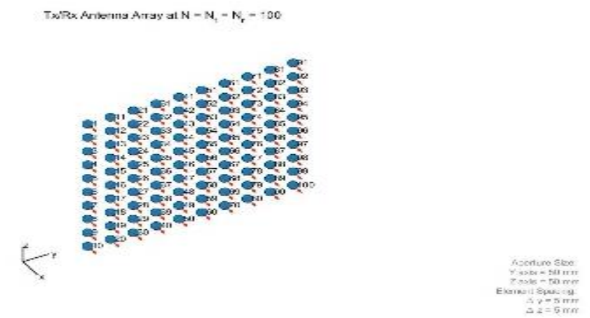
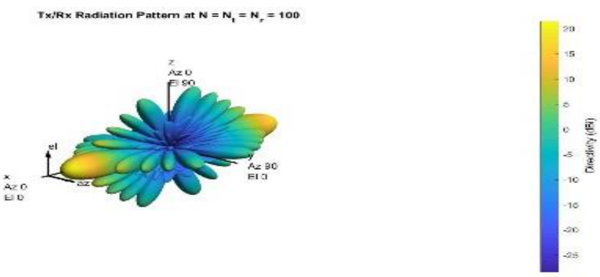
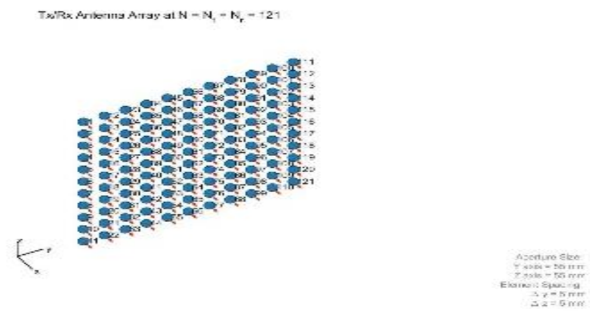


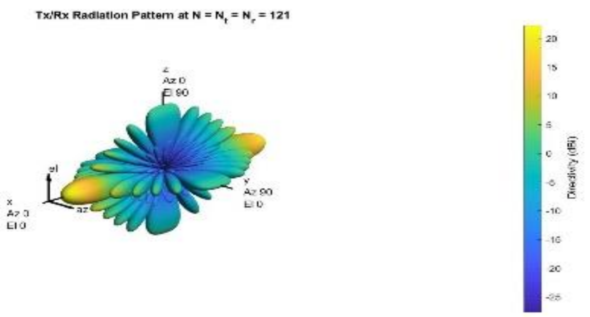
(q)



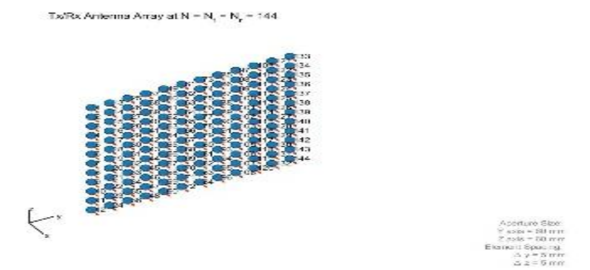
(r)



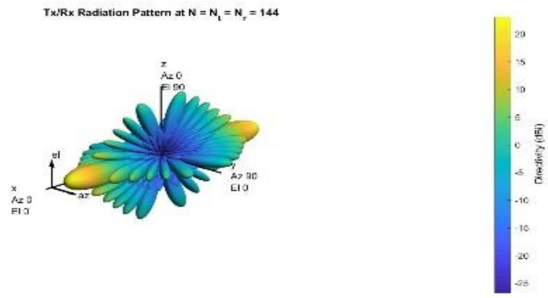
(s)



(t)



(u)



(v)

Figure B.1. Antenna array and radiation pattern of Massive MIMO system at both transmitting (Tx) and receiving (Rx) end for (a) antenna array at $N_t = N_r = 4$ (b) radiation pattern at $N_t = N_r = 4$ (c) antenna array at $N_t = N_r = 9$ (d) radiation pattern at $N_t = N_r = 9$ (e) antenna array at $N_t = N_r = 16$ (f) radiation pattern at $N_t = N_r = 25$ (g) antenna array at $N_t = N_r = 4$ (h) radiation pattern at $N_t = N_r = 25$ (i) antenna array at $N_t = N_r = 36$ (j) radiation pattern at $N_t = N_r = 36$ (k) antenna array at $N_t = N_r = 49$ (l) radiation pattern at $N_t = N_r = 49$ (m) antenna array at $N_t = N_r = 64$ (n) radiation pattern at $N_t = N_r = 64$ (o) antenna array at $N_t = N_r = 81$ (p) radiation pattern at $N_t = N_r = 81$ (q) antenna array at $N_t = N_r = 100$ (r) radiation pattern at $N_t = N_r = 100$ (s) antenna array at $N_t = N_r = 121$ (t) radiation pattern at $N_t = N_r = 121$ (u) antenna array at $N_t = N_r = 144$ (v) radiation pattern at $N_t = N_r = 144$.

Appendix C

The antenna technology is most important part in any communication system to transmit and receive the signals. Today, mobile technology used advanced antenna systems to use of multiple antenna technology. SISO, SIMO, MISO, MIMO and Massive MIMO are the classification of antenna systems. The key difference between SISO, SIMO, MISO, MIMO and Massive MIMO is the use of number of antennas at the transmitting and receiving ends. These classifications are described in the *table C.1*.

Table C.1. SISO, SIMO, MISO, MIMO and Massive MIMO: Antenna Systems.

Antenna System	Transmitter	Receiver
SISO (Single Input Single Output)	One Antenna	One Antenna
SIMO (Single Input Multiple Output	One Antenna	Multiple Antennas (Two or More)
MISO (Multiple Input Multiple Output)	Multiple Antennas (Two or More)	One Antenna
MIMO (Multiple Input Multiple Output)	Multiple Antennas (Two to Seven Approximately)	Multiple Antennas (Two to Seven Approximately)
Massive MIMO (Massive Multiple Input Multiple Output)	Multiple Antennas (Approximately Eight or More)	Multiple Antennas (Approximately Eight or More)

The advantages of SISO, SIMO, MISO, MIMO and Massive MIMO antenna systems are discussed in *table C.2*.

Table C.2. SISO, SIMO, MISO, MIMO and Massive MIMO: Benefits

Particular/ Parameter	SISO	SIMO	MISO	MIMO	Massive MIMO
Transmitting antenna	Single	Single	Multiple	Multiple	Multiple
Receiving antenna	Single	Multiple	Single	Multiple	Multiple
BER	Lower BER due to Single Antenna	Better than SISO	Better than SIMO	Optimized value of BER due to multiple antennas at both ends	Better than MIMO
Throughput	Much less	Better than MISO	Better than SISO	Better than MISO	Better than all others
Transmitting signals	Point to Point	Maximum ratio combining due to multiple antenna	Transmitted using beamforming and space division coding	Diversity due to multiple antennas at both ends	More diversity due to high number of antennas at both ends
Quality of received signals	Weak	Concept of switched diversity to select stronger antenna	Implemented by Space Division Coding and received with enhanced gain	Transmitted using Spatial Multiplexing, so gives best signal quality and high diversity gain	Better than MIMO
Channel Capacity	Least	Greater than SISO and MISO	Greater than SISO	Greater than SIMO	Greatest
Coverage	Least	Greater than SISO and MISO	Greater than SISO	Greater than SIMO	Greatest
Generation	1G-2G	2G-3G	3G-4G	3G-5G	4G-5G

Appendix D

The purpose of digital filters is to separate signals that have been combined and to restore signals that have been distorted in some way. Signal separation is required when a signal has been contaminated with interference, noise, or other signals whereas restoration is used when a signal has been distorted in some way. Broadly the basic digital filters are classified as FIR (Finite Impulse Response) and IIR (Infinite Impulse Response) filters. The FIR filters are stable but IIR filters are unstable in behaviour due to their open-loop and closed-loop structures. Therefore, FIR filters are more useful as compared to IIR filters. The Weiner, Kalman and Adaptive filters are advanced digital filters. The adaptive filters are most advanced digital filters as compared to all other filters.

A Wiener filter is a digital filter, which is designed to reduce the mean square difference between some desired signal and the filtered output. It is occasionally called a minimum mean square error filter. A Wiener filter can be FIR filter or an IIR filter.

Generally, the formulation of an FIR Wiener filter results in a set of linear equations and has a closed-form solution whereas the formulation of an IIR Wiener filter results in a set of non-linear equations.

The Kalman filter is a mathematical power tool which plays an important role in computer graphics as we include sensing of the real world in our systems. The Kalman filter can also be termed as a set of mathematical equations that implement a predictor-corrector type estimator which is optimal in the sense that it minimizes the estimated error covariance when some presumed conditions are met. For the past decade the Kalman filter has been the active area of research and application, particularly in the area of autonomous or assisted navigation. The Kalman filter and its variants such as the extended Kalman filter and unscented Kalman filter is one of the most popular data fusion algorithms in the field of information processing.

An adaptive filter is a system with a linear filter which consists of transfer function restrained by variable parameters and a means to adjust those parameters according to an optimization algorithm. Adaptive linear filters are linear dynamical system with adaptive or variable structure and parameters and have the property to transform the values of their parameters, i.e. their transfer function, during the processing of the input signal, in order to generate signal at the output which is without undesired components, noise, degradation and interference signals. An adaptive algorithm is driven by the error signal which generates the filter coefficients in a manner that minimizes the error signal. Unlike from the fixed filter design, here the filter coefficients are tunable, are adjusted in dependency of the environment that the filter is operated in, and can therefore track any potential changes in his environment. Using this concept, adaptive filters can be tailored to the environment set by these signals. However, if the environment changes filter through a new set of factors, adjusts for new features. The adaptive filter constitutes a vital part of the statistical signal processing. The application of an adaptive filter offers a smart solution to the problem wherever there is a need to process signals that result from operation in an environment of unknown statistics, as it typically provides a significant enhancement in performance over the use of a fixed filter designed by conventional methods. The adaptation adjusts the characteristics of the filter through an interaction with the environment in order to reach the desired values. Contrary to the conventional filter design techniques, adaptive filters do not have constant filter coefficients and no priori information is known, such a filter with adjustable parameters are called an adaptive filter. Adaptive filter adjusts their coefficients to minimize an error signal and may be termed as FIR, IIR, lattice and transform domain filter. Generally adaptive digital filters consist of two separate units: the digital filter, with a structure determined to achieve desired processing (which is known with an accuracy to the unknown parameter vector) and the adaptive algorithm for the update of filter parameters, with an aim to guarantee fastest possible convergence to the optimum parameters from the point of view of the adopted criterion. Majority of adaptive algorithms signify modifications of the standard iterative procedures for the solution of the problem of minimization of criterion function in real time. The most common form of adaptive filters is the transversal filter using LMS algorithm. Adaptive algorithms have been extensively studied in the past few decades and the most popular adaptive algorithms are the LMS algorithm and the RLS algorithm. Attaining the best performance of an adaptive filter requires usage of the best adaptive algorithm with low computational complexity and a fast convergence rate.

A very straightforward approach in noise cancelling is the use of LMS algorithm. This algorithm uses a gradient descent to estimate a time varying signal. The gradient descent method finds a minimum, if it exists, by taking steps in the direction negative of the gradient and it does so by adjusting the filter coefficients in order to minimize the error. The gradient is the del-operator and is applied to find the divergence of a function, which is the error with respect to the n^{th} coefficient in this case. The LMS algorithm has been accepted by several researchers for hardware implementation because of its simple structure. In order to implement it, modifications have to be made to the original LMS algorithm because the recursive loop in its filter update formula prevents it from being pipelined.

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