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Optimized Beam-forming for Massive MIMO- OFDM System

Nelly M. Shafik
Doctor of philosophy Degree in electrical engineering, Cairo University, Egypt,
nelly_mohammed@yahoo.com

Hazem H. El-Banna
Doctor of philosophy Degree in electrical engineering, MTC, Cairo, Egypt

All thanks to Allah and my partner Dr. Hazem who supported me in my researches

CASE STUDY

Optimized Beam-forming for Massive MIMO-OFDM System

Hazem H. El-Banna, Nelly M. Shafik*

Department of Electronics Engineering and Communications Technology, Modern Academy for Engineering and Technology, Cairo, Egypt

Abstract

Massive Multiple-Input Multiple-Output (MIMO) wireless communication systems, achieved by large number of antennas, is the main secrete of Fifth Generation (5G) wireless communication networks powerful. In this paper, novel active antennas selection algorithm is proposed with resulted in efficient system performance with only half number of antenna elements. In order to gain optimum performance of massive MIMO wireless communication systems, it is vital to well analyze channel models which is glory indication for massive MIMO system characteristics. Linear antenna array is mounted on High-Speed Train (HST) and we proposed simple algorithm for determining of beams number each time the train changes its position. In this paper, MIMO system is simulated in bad frequency selective fading channel which is considered the most matching channel in case of HST situation therefor optimization for antenna array directivity and optimum selection for the number of active elements is applied with simple algorithm. Massive MIMO OFDM transceiver was simulated using MATLAB code and analyzed in the last sections of the paper.

Keywords: Antenna array, Directivity, High-speed train, Long term evolution

1. Introduction

Revolution of 5G wireless communication arises from the fact that 5G can provide service for capacity thousand times larger than the Fourth Generation (4G) Long Term Evolution (LTE)/LTE-Advanced (LTE-A) wireless communication system Patil, Patel (Patil et al., 2014; Fakeeh, 2015; Patel). The second advantage of 5G with respect to 4G is enhancement of spectral efficiency to be hundred times of 4G spectral efficiency at 1 Gb/s data rate for fast moving users and 10 Gb/s for slow moving users Patil, Patel (Patil et al., 2014; Fakeeh, 2015; Patel).

Improvement of bit rate at worst channel conditions enables users of 5G to control huge number of devices even on distance. In addition to multiple Radio Access Technologies (multi-RATs) which is inevitable in 5G wireless communication networks Theodore, Lui and colleagues (Theodore, 2017; Dahlman et al., 2014; Wang et al., 2018; Soszka, 2022; Liu et al., 2018). Many other technologies can be supported by 5G wireless communication such as High-Speed Train (HST) communications, Machine-to-Machine (M2M) communications, and low power massive machine communication. The powerful secrete of 5G wireless communication is coming from applying efficient multiple access technique like OFDM and customized multi-input multi-output antennas system (MIMO) Dahlman and colleagues, Wang and colleagues, Soszka (Dahlman et al., 2014; Wang et al., 2018; Soszka, 2022).

Massive (MIMO) is the main technique distinguishes 5G system that improves spectral efficiency of transmitted signal Andrews and colleagues, Boccardi and colleagues (Andrews et al., 2014; Boccardi et al., 2014) by combining multiplexing and diversity gain in addition to beam-forming which is applied to minimize interference Gao and colleagues (Gao et al., 2016). Many researches Chen and colleagues, Lu and colleagues, Li and colleagues (Chen et al., 2015a; Lu et al., 2016; Li et al., 2013)

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* Corresponding author.
E-mail address: nelly_mohammed@yahoo.com (N.M. Shafik).

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were introduced in field of beam-forming techniques in high-speed moving users. Most beam-forming techniques results in performance improvement by customization of antenna array radiation directivity. Most of previous work did not consider implementation complexity of beam-forming for massive MIMO system especially in high-speed train (HST) scenario and with blind channel estimation. Usually, mobile system with high-speed moving users requires efficient and fast channel estimation more than slow moving case. In this paper, HST is considered as an extreme example for fast moving mobile user. The proposed system considers uplink from mobile array (MA) mounted on fast moving train and mobile base station (BS). There will be large fluctuation in the received signal power seen at MA resulted from fast fading channel situation especially at the edge end of BS coverage area. When combining massive MIMO technique with fast moving mobile user, as considered in the proposed HST system, as shown in Fig. 1, there should be one of beam-forming techniques; adaptive beam-forming Cheng and colleagues (Cheng et al., 2012) or switched beam-forming Chen and colleagues (Chen et al., 2015b) in order to optimize antenna array directivity and to experience more channel characteristics diversity.

In this paper, both beam-forming techniques, mentioned before, will be applied in case of linear antenna array.

When analyzing channel environment of HST we will find traversing diverse terrains and many other scatter obstacles resulting in difficult and complicated channel estimation needed at the receiving end since channel characteristics will be fast time-varying represented in channel impulse response and transfer function. Complexity of channel characteristics in rapid mobility manner as in our case doesn't match traditional beam-forming techniques therefore, in this paper we introduce a novel fast technique for adaptive beam-forming based on selection of beams number according to train position. (Massive MIMO Beam).

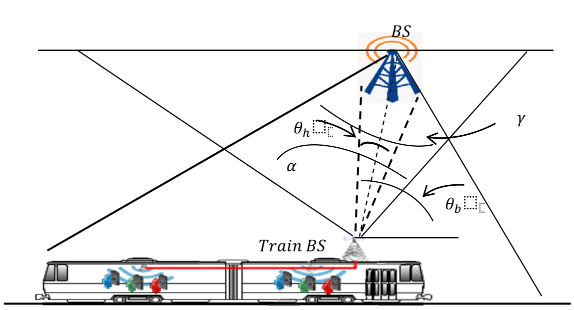

Fig. 1. "Geometry between HST and BS".

Speed of moving train, however, never exceed signaling rate (especially in 5G rates) due the safety guarantee for high-speed vehicles. Actually, there is strong relation between train position and corresponding antenna array beamwidth and consequently antenna array directivity. Therefore, we will handle in the first subsection of paper, in quick view, relationships between antenna array beamwidth, directivity, and proposed equations for antenna array weights under consideration. One of the main targets of antenna array design is to maximize directivity therefor, in the proposed massive MIMO OFDM transceiving system we focused on directivity maximization by selection of optimum number of beams while steering antenna radiation. Proposed algorithm of directivity optimization is based on pre-assumed probability of detection in order to guarantee efficient transmission with least beam steering angle. Novelty of this paper is coming from combination of two techniques.

(1) Directivity optimization with simple algorithm that matches high mobility of proposed HST system.
(2) Antenna array switching in Massive MIMO system located on HST after applying simple received pilot threshold test.

2. Beamforming fundamentals and architectures

In order to enhance wireless communication system directivity, the antenna beam is should be steered to cover a large communication sector. Electronically beam steering is realized by using phased array antenna that could be placed in many configurations, as linear or planner arrays. In this paper linear array is the used configuration with non-uniform excitations of elements for the purpose of beamforming. In linear array, M antenna elements are linearly located with uniform distance d from each other as shown in Fig. 1. Spacing between elements results in phase shifting between received or transmitted signals given as follows:

$$\Delta\Phi = \frac{\omega_o d \operatorname{Cos}(\theta_b)}{c} \tag{1}$$

(Elliott, 1981).

Where, θ_b is the angle between antenna array axis (z-direction) mounted on the train and BTS direction as shown in Fig. 2, c is speed of light, and ω_o is the angular frequency.

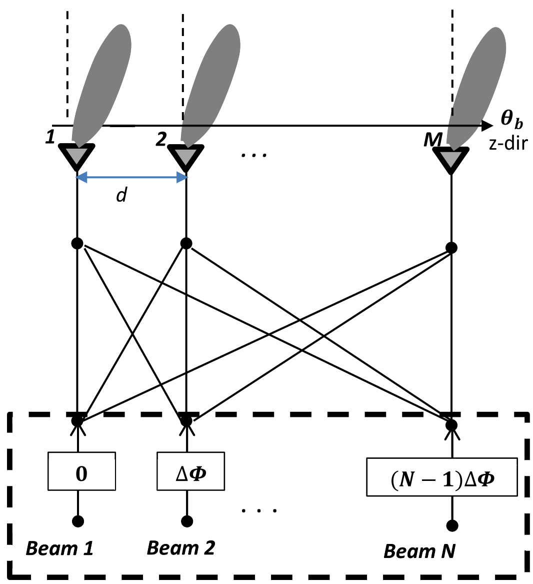

Fig. 2. "Linear antenna array structure".

Array feeding network generates N beams with different weights which could be expressed in matrix form as follows:

$$W = \begin{bmatrix} W_1 \\ \vdots \\ W_N \end{bmatrix} = \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1M} \\ \vdots & \vdots & & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NM} \end{bmatrix} \tag{2}$$

(Elliott, 1981).

Where:

$$W_n = \left[I_1 \, I_2 e^{j(kdcos\theta_b + \beta_1)} \ldots \, I_M e^{j(M-1)(kdcos\theta_b + \beta_M)}\right] \ldots \tag{3}$$

(Elliott, 1981). Where: W_n is weights vector of nth beam, I_m is the excitation amplitude for mth antenna, and $k = 2\pi/\lambda$. In this paper, antenna array mounted on the train is steered in order to enhance directivity continuously at each time the train changes its position. This means that value of θ_b is variable but known and precalculated by transmitter.

3. Massive MIMO OFDM system model

Proposed OFDM transceiving system considers uplink between HST and BTS where massive antenna array is supposed to be mounted on the train with M elements in linear array configuration. Main objective of proposed massive MIMO OFDM transceiver is to obtain optimum array directivity with minimum number of active array elements. Array directivity optimization is executed by applying iterative algorithm that maximizing probability of detection. (Massive MIMO Beam) For each value of θ_b simple iterative algorithm is applied with following steps:

(1) Set optimum number of beams $N^* = 1$

(2) Assume maximum detection angle (i.e. field of view angle) is between left − right bounds given as follows:

$$\gamma_l = \frac{[\pi + 2S\theta_h - 2\theta_b]h}{2\sin(\theta_b)} \tag{4}$$

(Massive MIMO Beam).

and

$$\gamma_r = \frac{[2\theta_b - \pi - 2(S-1)\theta_h]h}{2\sin(\theta_b)} \tag{5}$$

(Massive MIMO Beam).

Where: θ_h is the beam width of antenna array mounted on train BTS

$$S = \left\lfloor \frac{2\theta_b - \pi}{2\theta_h} \right\rfloor \tag{6}$$

(Massive MIMO Beam).

(3) Calculate beam-forming probability P_i given as follows:

$$P_i = 1 - \frac{Q\left(\frac{\gamma_l}{\sigma}\right) + Q\left(\frac{\gamma_r}{\sigma}\right)}{2} \tag{7}$$

(Massive MIMO Beam).

Where:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(\frac{-t^2}{2}\right) dt$$

(4) If $P_i > P_{th}, let\ N^* = 2N^*$

(5) Go to stpe-2

(6) Else $Output \ N^*$

Selection of active antennas number is based on channel coefficients estimated at receiving end. Stage of channel coefficients estimation will be executed before every signaling interval by the aid of pilot signal transmission through down link. Now let us display stages of presignaling, channel estimation, beam forming and real data transmission.

3.1. Pre-signaling and channel estimation stage

Before real data transmission through uplink, pilot signal is emitted from BS, as well seen in Fig. 3, in order to enable train BS monitoring channel characteristics seen by each antenna element. Pilot signal is usually a single tone with the same operating frequency so that in the frequency domain it's constant amplitude spectrum. For mathematical analysis simplifying, we will display all equations in matrix form and baseband signal modeling will be

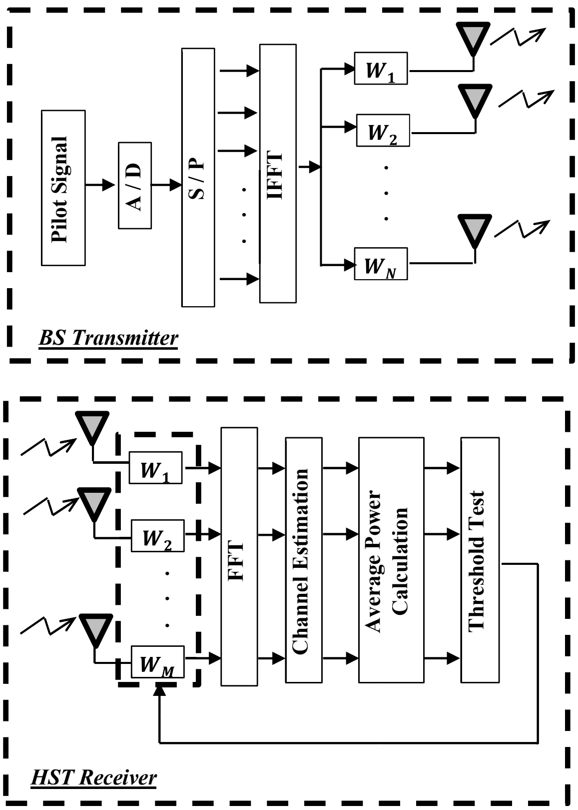

Fig. 3. "Transceiver stages for selecting active antennas".

handled. Considering received vector seen by antenna element m after pilot transmission, it can be represented as follows:

$$\underline{R}_p^{(m)} = \sqrt{A}\,H^{(m)}W^{(m)}\,\underline{P} + \underline{N}^{(m)} \tag{8}$$

(Elliott, 1981).

Where:

$\underline{R}_p^{(m)}$: is the received vector ($1\times M_{OFDM}$) seen by antenna element m after pilot vector transmission, M_{OFDM}: is defined as OFDM symbol length, A: is the average power of HST transmitted signal, $H^{(m)}$: is fast fading channel transfer function coefficient at current signaling interval and seen by antenna element m with Rayleigh distribution $W^{(m)}$: is the weight of antenna element m illustrated before in equ.3, $\underline{P}$: is pilot vector in frequency domain which contains all ones with length $= M_{OFDM}$, and $\underline{N}^{(m)}$: is AWGN coefficient with unit variance, A simple received power test will be applied at each element of BS antenna array in order to decide what will be active antennas group at current signaling interval as follows: (Also illustrated in flow chart shown in Fig. 12):

(1) Define empty array B = [ ];
(2) for m = 1: M
determine $\underline{R}_p^{(m)}$
if $\left|\underline{R}_p^{(m)}\right| \geq C_{TH}$
$B = [B \quad 1]$
else.
$B = [B \quad 0]$
end
end

At the end of that algorithm, B will contain pattern of 1's and 0's with length = M determining status of each antenna element; ON or OFF. In Fig. 4, simple example of active elements selected based on channel r.m.s. threshold test was simulated using MATLAB code in which channel characteristics were changed twice and correspondingly, positions and number of active elements were changed at the same value of channel detection threshold. In system simulation we assume channel transfer function is time invariant for time duration = OFDM symbol time duration.

In addition of selecting active group of antennas, pilot sequence transmission has another vital function which is estimation of channel characteristics that have fast time variation manner as a result of rapid motion of receiver. An example for obtained group of active antenna array elements is illustrated in Fig. 4 which displays only half elements could be active which results in reduction of channel equalization complexity at receiver. In the block diagram shown in Fig. 3, an accurate estimate for channel transfer function $\widehat{H}_{ch}(f)$ can be obtained at the output of FFT processor inside HST BS which will be needed in real data transmission step as will be described in coming subsection.

3.2. Real data transmission

Now we consider up link performance in which HST will transmit sequence of OFDM frames to BS

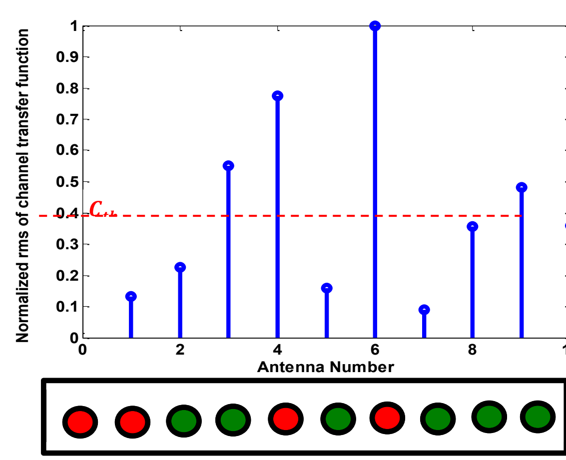

Fig. 4. "Antenna selection algorithm result at time interval: t = t$_o$: Active elements are represented by Green spots and sleep elements are represented by Red spots".

emitted by only activated antenna elements determined before. At the same time steering of array beams is applied in order to achieve directivity optimization at different positions of train. Stages of transmitter and receiver in real data transmission is shown in Fig. 5.

We can define received sequence seen by antenna element i (at BS) as follows:

$$\underline{R}^{(i)} = \begin{bmatrix} R^{i1}.A^{(1)} \\ R^{i2}.A^{(2)} \\ . \\ . \\ . \\ R^{iM}.A^{(M)} \end{bmatrix} \tag{9}$$

(Dahlman et al., 2014).

Where: $\underline{R}^{(i)}$: is received matrix with size $M\times M_{OFDM}$ in frequency domain (i.e. after FFT process) and $A^m \in \{0,1\}$.

Now it is required to eliminate fading channel distortion by applying one of equalization techniques by the aid of estimated channel transfer function $\widehat{H}_{ch}^{(m)}, 1 \leq m \leq M$ obtained before in pre-signaling stage. Equalized data received sequence could be expressed as follows:

$$R_{eq}^{i}(m) = R^{i}(m).conj\left(\widehat{H}_{ch}^{(m)}\right) \tag{10}$$

(Dahlman et al., 2014).

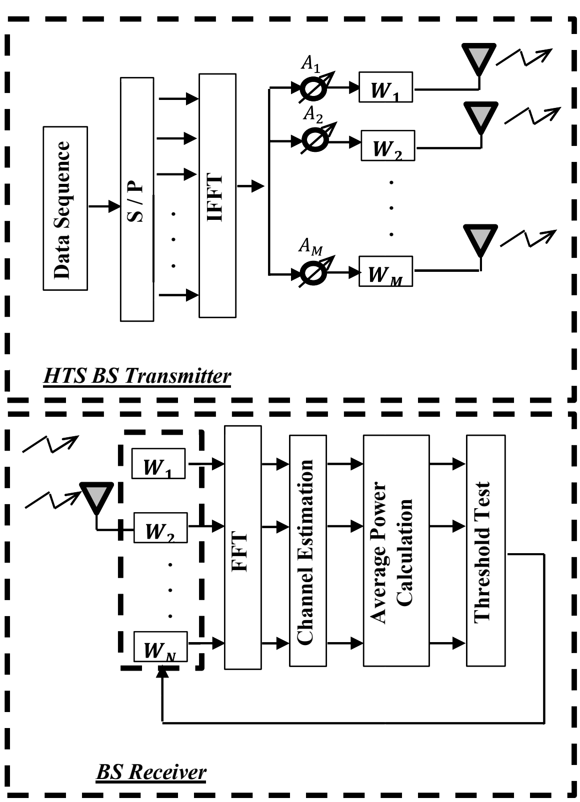

Fig. 5. "Up link transceiving stages in Real data transmission ".

4. Proposed system simulation

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4.1. Parameters affecting on active antennas number

The objective of the first group of simulation results shown in figure-is to study effect of channel multi-path number on the average number of active elements. It is expected that when the train enters region contain much more reflectors or obstacles, more active elements are needed. But actually, proposed MIMO system simulation using Matlab showed that increment in the required number of active elements is not linear with channel paths number so that in very bad channel situation (i.e. Np = 45) only 14 from 30 elements of train array should be active, as shown in Fig. 6.

As expected, relationship between threshold of channel detection C_{th} and number of active elements is inverse proportionality as well illustrated in the next set of results, shown in Fig. 6. The aim of this part of simulation is to determine optimum value of C_{th} requited to obtain specific number of active elements. And by knowledge of fading

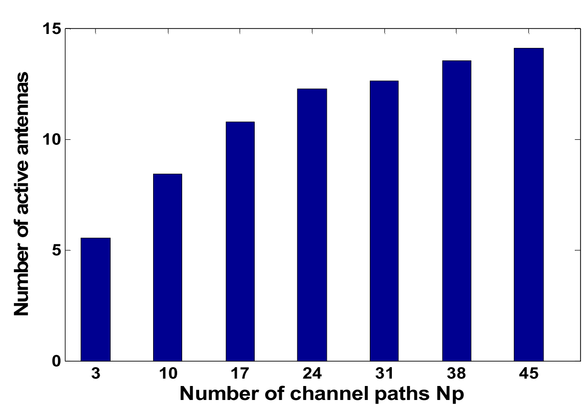

Fig. 6. "Number of active elements at different situations of multi-path channels at $M = 30$, $SNR = -10$ dB, $T = 4$, $M_{OFDM} = 32$, $P_{th} = 0.95$, and $C_{th} = 50$".

channel multi-path number, corresponding number of active elements could be known from Fig. 7.

As mentioned before, speed of channel detection and correspondingly determination of active elements number depends on duration of OFDM symbol. Therefore, it was worthwhile to study effect of OFDM length M_{OFDM} on the active elements number as shown in Fig. 7. In case of fast fading channel, it's recommended to use small value of M_{OFDM} in order to make channel detection more rapid since in fast fading calculation process should be executed in time less than $\frac{M_{OFDM}}{f_b}$ whereas in slow fading case, large values for M_{OFDM} could be applied without fearing of lsoing time and at the same time we can gain benefits of using large value of M_{OFDM} for pupose of BER reduction. When channel is fast fading type, more array elements are to be activated and this is improved by simulation results in Fig. 8.

4.2. BER performance of proposed system

Now it is required to examine performance of complete MIMO transceiving system applying proposed array steering technique and active elements selection method. Channel conditions considered here is multi-path frequency selective Rayleigh fading channel. In digital wireless communication system, the most effective parameter to be measured that reflect quality of received data is BER therefor in the coming groups of results

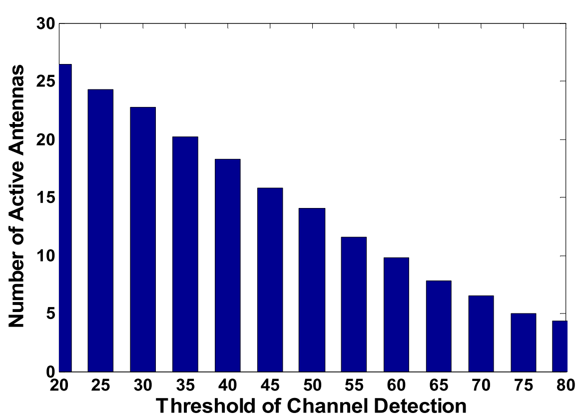

Fig. 7. "Number of active elements at different values of channel detection threshold using: M = 30, SNR = −5 dB, T = 4, M_{OFDM} = 32, Pth = 0.95, and Np = 20".

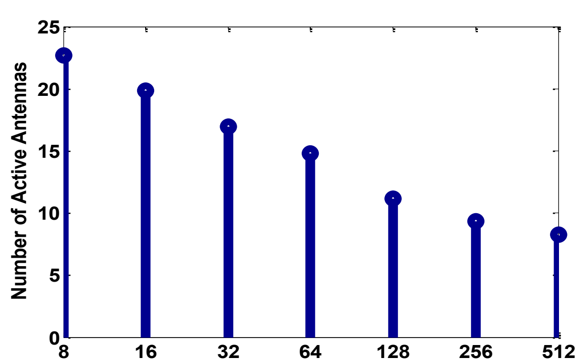

Fig. 8. "Number of active elements at different values of OFDM symbol length using: M = 40, SNR = −5 dB, T = 4, Pth = 0.95, Np = 20, and Cth = 40".

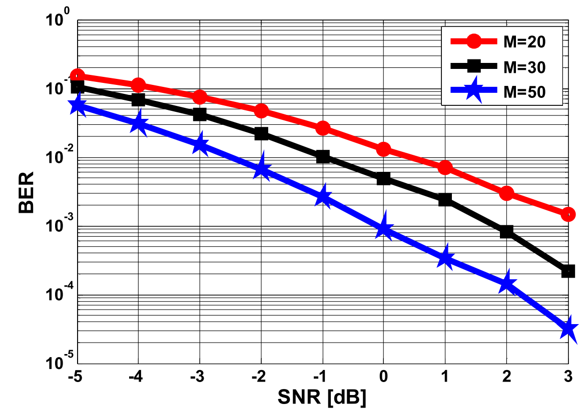

Fig. 9. "BER performance at different values of array elements using: T = 4, M_{OFDM} = 32, Pth = 0.95, Np = 5, and Cth = 16".

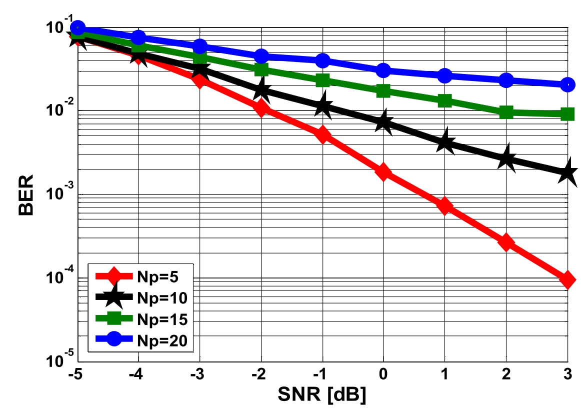

Fig. 10. "BER performance at different values of channel paths using: M = 40, T = 4, M_{OFDM} = 32, P_{th} = 0.95, and C_{th} = 16".

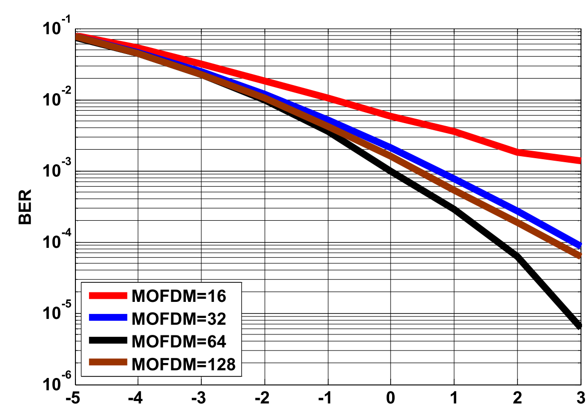

Fig. 11. "BER performance at different values of OFDM symbol length using: M = 40, Np = 5, Cth = 80, and Pth = 0.95".

we will display effect of different system parameters on BER performance versus variation of SNR from −5 dB to 3 dB which is the standard range of uplink SNR seen by BTS.

In the set of curves shown in Fig. 9, effect of array elements number M on BER performance to be studied where three values of M were adjusted resulting in three curves and the rest system parameters were kept constant as follows: end-fire array (T = 4), OFDM symbol length $M_{OFDM} = 32$, probability of detection Pth = 0.95, number of fading channel paths NP = 5, and threshold of channel detection Cth = 16. As expected, BER is inversely proportional with number of antenna elements. The contribution here is that only half of antenna elements will be activated at each signaling interval using proposed threshold test which means more power saving.

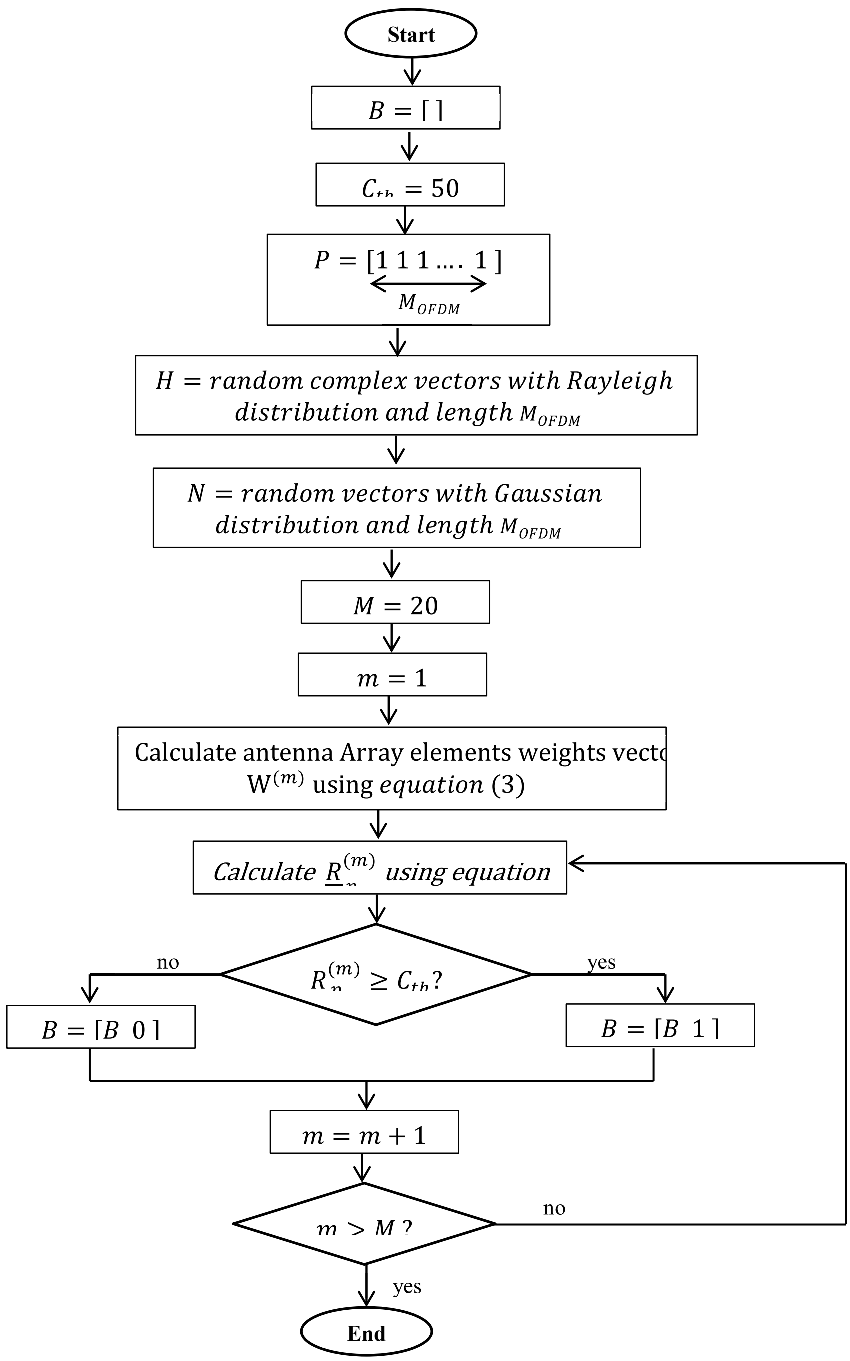

Fig. 12. "Flow chart of proposed active elements selection algorithm".

In the next set of results curves, shown in Fig. 10, we will study effect of fading channel paths number NP on BER performance in which four values we assumed in simulation program NP = 5, 10, 15, and 20. Whereas, rest of system parameters were kept constant as follows: in-fire array (T = 4), number of array elements M = 40, OFDM symbol length $M_{OFDM} = 32$, probability of detection Pth = 0.95, and threshold of channel detection Cth = 16.

In the last set of curves, shown in Fig. 11, effect of OFDM symbol length M_{OFDM} on BER performance was considered. Where, BER performance was compared in case of four values of $M_{OFDM} = 16, 32, 64$, and 128 in order to determine optimum value for OFDM symbol length matching fading channel characteristics under consideration. Rest of system parameters were kept constant as follows: in-fire array (T = 4), number of array elements M = 40, fading channel number of paths Np = 5, probability of detection Pth = 0.95, and threshold of channel detection Cth = 80. As well seen in Fig. 10 and summarized in table- 3, the optimum value for OFDM symbol length matching our channel condition is = 64 since it will result in lowest BER level w.r.t. other three values. Although we know this important conclusion about OFDM symbol length, we didn't apply during simulation process and we preferred to apply another sub-optimum value $M_{OFDM} = 32$ due to time delay of simulation program run.

5. Conclusion

Massive (MIMO) HST can be effectively operated with minimum number of antenna elements when applying elements selection algorithm based on threshold test applied to equalized received vector in using OFDM technology. Also, number of active beams in massive MIMO array feeder can be optimized using proposed algorithm dependent on current position of HST. Simulation results showed that we can reach BER equals to order of 10^{-5} at SNR = 3 dB seen at receiving end of the Uplink while using only half number of antenna elements when total number of antenna elements $M = 50$. This paper is considered extended work to paper referred in (Massive MIMO Beam) with overlap in part of antenna array model and algorithm of detecting number of antenna beams. When considering previus work mentioned in papers Lu and colleagues, Liand colleagues, Cheng and colleagues, Chen and colleagues, Griffiths and Jim (Lu et al., 2016; Li et al., 2013; Cheng et al., 2012; Chen et al., 2015b; Griffiths and Jim, 1982) we can say that our paper has main contribution in proposed algorithm for selecting number of active antenna elements.

Author contribution

Through this paper, we introduce efficient algorithm to obtain optimum number of beams steered by BTS antenna array mounted on high speed train (HST) and also optimum power saving by activating limited number of antenna elements at each time the train changes its position. Simulation results using MATLAB code showed satisfying bit error rate level that could be obtained at receiving end considering Massive OFDM system in spite of applying very bad channel conditions (frequency selective fast fading channel).

Role of each author: 1. Nelly M. Shafik prepared and revised OFDM transceiver parameters, fading channel modeling, MATLAB code writing and simulating results analysis. 2. Hazem H. El-Baanna prepared and revised subsections of paper related to antenna array steering and directivity optimization.

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Availability of data and material

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

Code availability

Simulation code was designed and installed using MATLAB R2021a application.

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