doi: 10.17586/2226-1494-2022-22-1-206-216

A comparative analysis of computational intelligence algorithms for estimation of LTE channels

Siraj Pathan[1]✉, Ajit Noonia[2], Mujib Tamboli[3], Sunil Pathak[4]

[1,2,4] Amity University Rajasthan, Jaipur, 303006, India
[3] Anjuman-I-Islam's Kalsekar Technical Campus, Panvel, 410206, India

[1] sirajpathan404@gmail.com✉, https://orcid.org/0000-0002-1728-3030
[2] ajit009noonia@gmail.com, https://orcid.org/0000-0002-3110-4908
[3] mujibtamboli@yahoo.co.in, https://orcid.org/0000-0002-5891-3713
[4] sunilpath@gmail.com, https://orcid.org/0000-0001-7409-9814

Abstract
Precise modelling and accurate estimation of long-term evolution (LTE) channels are essential for numerous applications like video streaming, efficient use of bandwidth and utilization of power. This deals with the fact that data traffic is increasing continuously with advances in Internet of things. Previous works were focused mainly on designing models to estimate channel using traditional minimum mean square error (MMSE) and least squares (LS) algorithms. The proposed model enhances LTE channel estimation. The designed model combines LS and MMSE methods using Taguchi genetic (GE) and Particle Swarm Intelligence (PSO) algorithms. We consider LTE operating in 5.8 GHz range. Pilot signals are sent randomly along with data to obtain information about the channel. They help to decode a signal in a receiver and estimate LS and MMSE combined with Taguchi GA and PSO, respectively. CI-based model performance was calculated according to the bit error rate (BER), signal-to-noise ratio and mean square error. The proposed model achieved the desired gain of 2.4 dB and 5.4 dB according to BER as compared to MMSE and LS algorithms, respectively.

Keywords
genetic algorithm (GA), particle swarm intelligence (PSO), long term evolution (LTE), minimum mean square error (MMSE), least squares (LS)

Acknowledgements
We thank Amity School of Engineering & Technology of Amity University, Jaipur, India for providing material and resources for our study, we also thank Anjuman-I-Islam's Kalsekar Technical Campus of Mumbai University Navi Mumbai, India for providing laboratory to do research.

For citation: Pathan S., Noonia A., Tamboli M., Pathak S. A comparative analysis of computational intelligence algorithms for estimation of LTE channels. *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, 2022, vol. 22, no. 1, pp. 206–216. doi: 10.17586/2226-1494-2022-22-1-206-216

УДК 621.396.946

Сравнительный анализ алгоритмов вычислительного интеллекта для оценки канала LTE

Сирадж Патан[1]✉, Аджит Нуния[2], Муджиб Тамболи[3], Сунил Патхак[4]

[1,2,4] Амити Университет Раджастана, Джапур, 303006, Индия
[3] Технический кампус Анджуман-и-Ислам в Калсекаре, Панвел, 410206, Индия

[1] sirajpathan404@gmail.com✉, https://orcid.org/0000-0002-1728-3030
[2] ajit009noonia@gmail.com, https://orcid.org/0000-0002-3110-4908
[3] mujibtamboli@yahoo.co.in, https://orcid.org/0000-0002-5891-3713
[4] sunilpath@gmail.com, https://orcid.org/0000-0001-7409-9814

Аннотация

Выполнение моделирования и точной оценки канала беспроводной связи в стандарте Long-Term Evolution (LTE) необходимо для работы многочисленных приложений, таких как потоковое видео, а также для эффективного использования полосы пропускания и энергии. Это связано с постоянным увеличением трафика данных и развитием интернета вещей. Существующие исследования в основном направлены на изучение моделей оценки канала с использованием традиционных алгоритмов вычисления минимальной среднеквадратичной ошибки Minimum Mean Square Error (MMSE) и наименьших квадратов Least Square (LS). Предложенная модель позволяет улучшить оценку канала в мобильных сетях стандарта LTE. Модель основана на объединении методов наименьших квадратов и наименьшей среднеквадратической ошибки с применением Тагучи-генетического алгоритма и алгоритма оптимизации роя частиц Particle Swarm Intelligence (PSO). Приведен пример сети LTE, работающей в диапазоне 5,8 ГГц. Случайные пилотные сигналы следуют вместе с данными для получения сведений о канале, помогают декодировать сигнал в приемнике и оценивать LS и MMSE за счет сочетания Тагучи-генетического алгоритма и PSO соответственно. Выполнена оценка эффективности модели по частоте битовых ошибок Bit Error Rate (BER), отношению сигнал/шум и среднеквадратической ошибки. С учетом величины BER представленная модель на основе искусственного интеллекта обеспечивает лучшие результаты по сравнению с MMSE на 2,4 дБ и с LS – на 5,4 дБ.

Ключевые слова

генетический алгоритм, GA, алгоритм оптимизации роя частиц, PSO, мобильная сеть LTE, минимальная среднеквадратическая ошибка, MMSE, метод наименьших квадратов, LS

Благодарности

Авторы благодарят Школу инженерии и технологий Университета Амити в Джайпуре, Индия, за предоставление учебных материалов и ресурсов. Также благодарны за предоставление лаборатории для проведения исследований Техническому кампусу Анджуман-и-Ислам в Калсекаре, Университет Мумбаи, Нави Мумбаи, Индия

Ссылка для цитирования: Патан С., Нуния А., Тамболи М., Патхак С. Сравнительный анализ алгоритмов вычислительного интеллекта для оценки канала LTE // Научно-технический вестник информационных технологий, механики и оптики. 2022. Т. 22, № 1. С. 206–216 (на англ. яз.). doi: 10.17586/2226-1494-2022-22-1-206-216

Introduction

LTE means Long Term Evolution, and it began as a project in early 2005 by the 3rd Generation Partnership Project, a telecommunications organization. The corresponding evolution of 3G packet network is System Architecture Evolution (SAE). LTE is a term that stands for the combination of LTE and SAE [1, 2].

The Universal Mobile Telecommunication System (UMTS) is one of the branches of Global System for Mobile Communications and Evolved UMTS Terrestrial Radio Access network, whereas E-UTRAN is the air interface in an LTE Cellular Network. LTE is the first version.

Fig. 1 shows the evolution of LTE and how different version of LTE added new technologies for better services. The 3rd Generation Partnership Project has been working

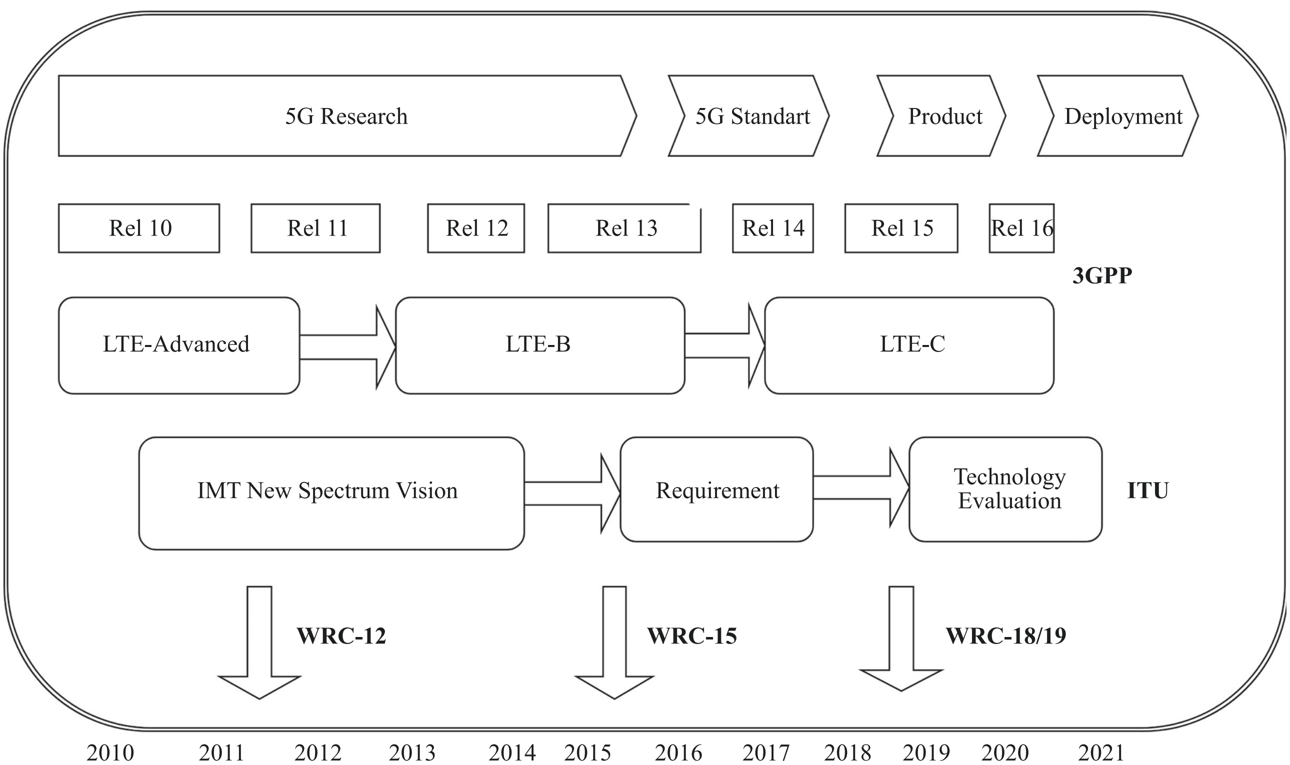

Fig. 1. Evolution of LTE

on LTE on the path to the fourth generation mobile due to the increase in mobile devices data usage and the advent of new applications for Internet of Things devices [3, 4].

LTE's major aim is to form a high-data-rate, low error, packet-optimized wireless radio technology that allows for changing capacity deployments. LTE network architecture was created to perform switched traffic while maintaining high quality of service and mobility.

The most significant parameter in wireless communications is channel state information (CSI). This information aids in understanding signal propagation via the channel, as well as the distortion and delay created by the signal from the transmitter side to the receiver side.

The LTE channel estimation depends on present information that is shared between the sending and LTE receiving side. This approach of channel estimation aids in signal reconstruction at the receiver end. At the receiver, the LTE channel impulse response can be estimated by using inserted pilot symbols, which are familiar to both the sending and receiving side, and which apply various interpolation types to estimate the LTE channel response of the subcarriers between the pilots [5, 6].

Although blind channel estimate has a lower overhead, it requires a lot of signals received from antenna to reconstruct the desired signal. The efficiency of the channel estimation can be improved by utilizing the semi-blind channel estimating system, which uses pilot and data symbols.

This method employs the signal tracked as a feedback mechanism to track the performance of the channel, as well as the tracked signal as reference signal for future data prediction. Although based on symbols, channel prediction delivers the best performance, above the described pilot symbols, which are transmitted with data symbols, reduce transmission efficiencies. When we use training symbols, the channel estimation is done using Least Square (LS) and Minimum Mean Square Error (MMSE) algorithms, which improve system performance by lowering the Bit Error Rate (BER) [7, 8].

Optimization deals with the process of creating a system with the goal of lowering production costs or increasing production efficiency. The procedure for algorithms of optimization is to run them continuously while comparing alternative answers until the optimal one is found.

A genetic algorithm reflects the process of natural selection of fittest particle for reproduction in order to produce offspring of next generation.

Particle Swarm Optimization (PSO) is nothing but finding the best solution in space. It works on the objective function and is not affected by any differential shape of the objective [9, 10].

Using pilot signals, this work approximates the noised mixed, faded signal in the system at the receiver side. The random pilot signals are subjected to the optimization technique, which is then compared to the fixed pilot signals subjected to the LS algorithm and MMSE algorithms [11, 12].

Related Work

One of the applications that received much attention is data-driven channel estimation. In [13], a channel prediction technique for LTE was suggested. To increase the performance of a LTE system that consists of Millimeter wave connected with N Multiple-Input Multiple-Output (MIMO) users, this strategy was integrated with hybrid LS techniques.

The researchers proposed a CI-Model which uses Orthogonal Frequency Division Multiplexing (OFDM) as receiver that applies a Computational Intelligence (CI) algorithm to collect channel state information (CSI) and find out transmitted symbols [14].

Montgomery [15] investigated a MIMO based huge LTE system that estimated the channel matrix using an LS and MMSE. However, a major disadvantage of utilizing LS and MMSE for channel estimation is that it necessitates a significant amount of training channel data, which may be impractical for time-changing channels.

The medium in a Frequency-Division-Duplex system was estimated using a bi-direction recurrent Genetic Algorithm (GA) in conjunction with pilot samples in [16].

In addition, the authors suggested a CI-included channel evaluating idea for MIMO antenna system that consists of a MIMO base interacting with many single-antenna points in [17]. Instead of evaluating the medium coefficients using the Least Square (LS) approach, this work applied computational intelligence to denoise the received signal.

In [18], the author introduced a joint GA and LS-based channel estimation for the transmitter that takes advantage of the receiver's Signal to Noise Ratio (SNR) received from output side to derive MIMO wireless channel coefficients.

CI implementation was suggested to overcome difficulties of predicting a mixed selective wireless channel [19]. In this study, the researcher focused on using a CI to calculate channel coefficients during the training phase.

Contributions

A deep examination of the works discussed in the previous section shows that the vast majority of authors have primarily concentrated on using LS and MMSE to acquire the CSI. Processing intelligence algorithms has significant computational needs and requires a lot of data to train. This feature prompted us to study the feasibility of introducing a low-complexity CI-based method specifically tailored for channel estimation. The contribution of our research is as follows.

We present a powerful CI algorithm for estimating and monitoring difficult time changing and frequency selective multipath channels. The parameters are optimised and the Channel Impulse Response (CIR) is obtained using stochastic gradient descent in this algorithm.

To calculate the impulse response of the channel whose time is changing continuously, the proposed CI algorithm is combined with the OFDM based transmission technique.

The performance of the designed technique is compared to that of the well-known least squares and MMSE channel estimation algorithms for a variety of pilot sample numbers. Even with minimal pilot samples for each symbol of OFDM, the suggested approach performs better than LS and MMSE algorithms, according to the obtained findings. The designed CI-Algorithm based wireless medium evaluating complexity is assessed in terms of drifting numbers operations. Our approach has a lower complexity than the usual MMSE and LS, according to the complexity evaluation.

Finally, the suggested algorithm's convergence is studied by determining the number of iterations required for the designed approach to meet the best feasible estimation channel.

Organization of the paper

The paper is organised as follows. The first section explains a system model with the help of mathematical expression. The subsections describe the transmitter and the designed channel model and their implementation with LS and MMSE technique. The next section deals with the CI based channel estimation explaining the receiver. The section on results considers all parameters and the paper is concluded with the achieved results.

System model

We analyse a basic LTE communication system shown in Fig. 2 in which Multiple Antenna at sending and receiving sides communicate over a changing frequency channel with a changing time frequency. We use the OFDM bock to reduce ISI and a multiplexing (OFDM) method.

In the LTE system, Downlink and Uplink Transmission are organized in frames. Data for Transmission are modulated using M-ary Quadrature Amplitude Modulation (QAM) scheme to get frame of N-subcarrier symbols, i.e. $X(k)$. OFDM signals, i.e. $x(n)$ to be send, are received by applying the Inverse Discrete Fourier Transform on $X(k)$ such that

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\Pi k \frac{n}{N}}.$$

In practice, N is a power of two, and IDFT is carried out with the help (IFFT) inverse-fast-Fourier transform. Actually, we consider an OFDM data with N sub-carriers that are split into N_P pilots to calculate p (number of pilot subcarrier) and track impulse response, as well as payload, N_D stand for data samples, D is number of Data Samples; j is imaginary unit used to indicate complex component in alternating current circuits; k is wavenumber. $X(k)$ is the Discrete Fourier Transform of $x(n)$.

Transmitter. The data is initially coded and then mapped with QAM on the transmitter side, using the block of Modulation. We shall consider system sends data in T time slots, with the QAM symbols at time slot t, $t = 1, \ldots, T$ are combined to Data Vector $x(t) \in C^N$ as

$$x(t) = [x_1(t), x_2(t), x_3(t), \ldots, x_N(t)],$$

where N is symbol of modulation. Following that, the encoded information is divided into N_T vectors that correspond to the Transmit antenna N_T as given below

$$x_i(t) = [x_i(t), x_{i+N_T}(t), x_{i+2N_T}(t), \ldots],$$

where $i = 1, 2, \ldots, N_T$.

Each antenna will send data in serial to parallel form, and pilot symbols are inserted to acquire knowledge of Transmitter and receiver side as shown in Fig. 3. We define $x_a(t)$ and $a = 1, \ldots, N_T$. $x_a(t)$ is a vector for signal which is inserted between pilots. After that the block of inverse fast Fourier transform is applied to $x_a(t)$, transforming the signals from frequency domain to time domain defined by $\tilde{x}_a(t)$ as follows:

$$\tilde{x}_a(t) = IFFT\{x_a(t)\}.$$

Then, we use cyclic prefix insertion of length N_G as a guard interval to remove the inter-symbol interference.

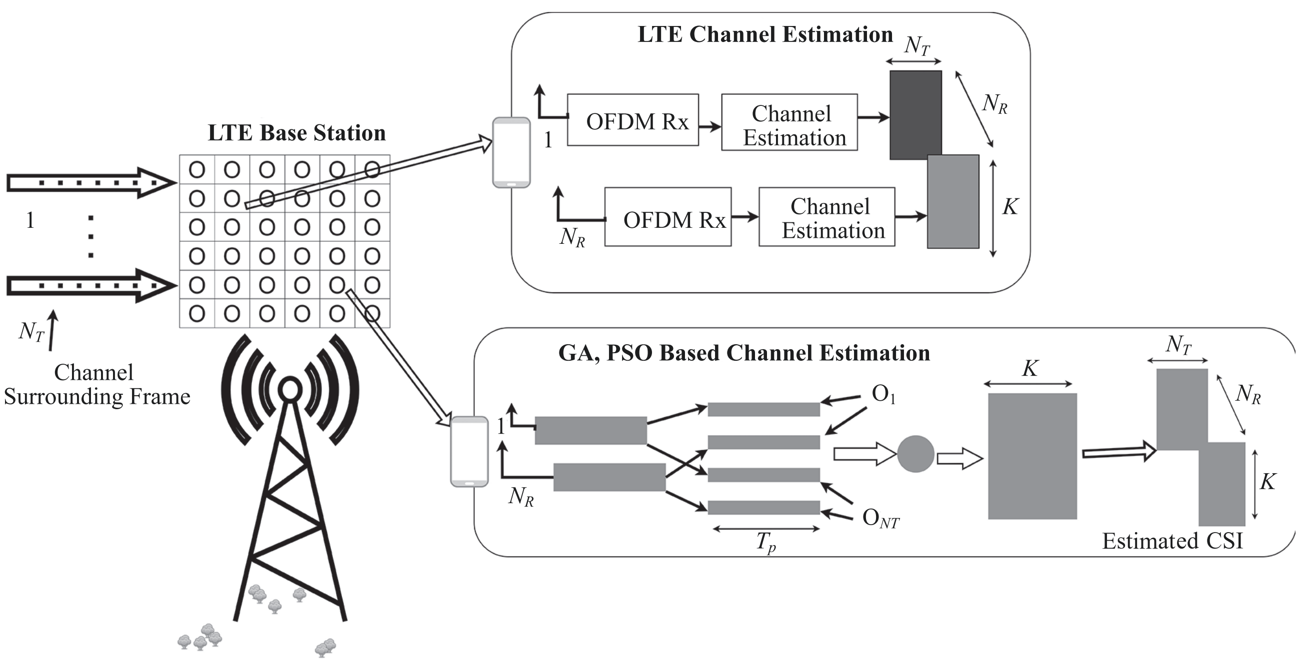

Fig. 2. Overview of the Computational Intelligence algorithm based Channel Estimation for LTE.

K is Number of Subcarriers, N_T is Number of transmit antenna, N_R is Number of receiver antennas, O_{NT} is Orthogonal Sequence of length N_T, T_p is Number of time Domain samples in the channel sounding frame

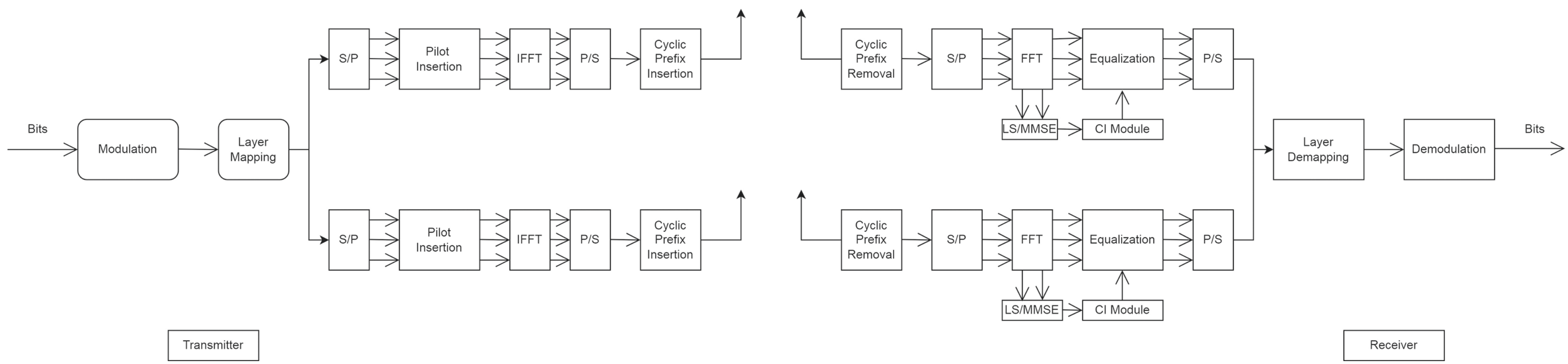

Fig. 3. Illustration of the considered LTE Model with the proposed CI Based Algorithm Module

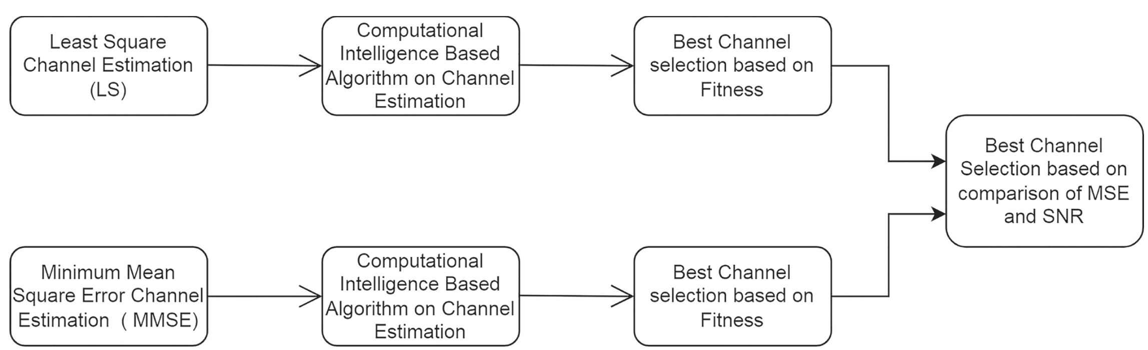

Fig. 4. Block Diagram of Computational Intelligence Based LS and MMSE Channel estimation

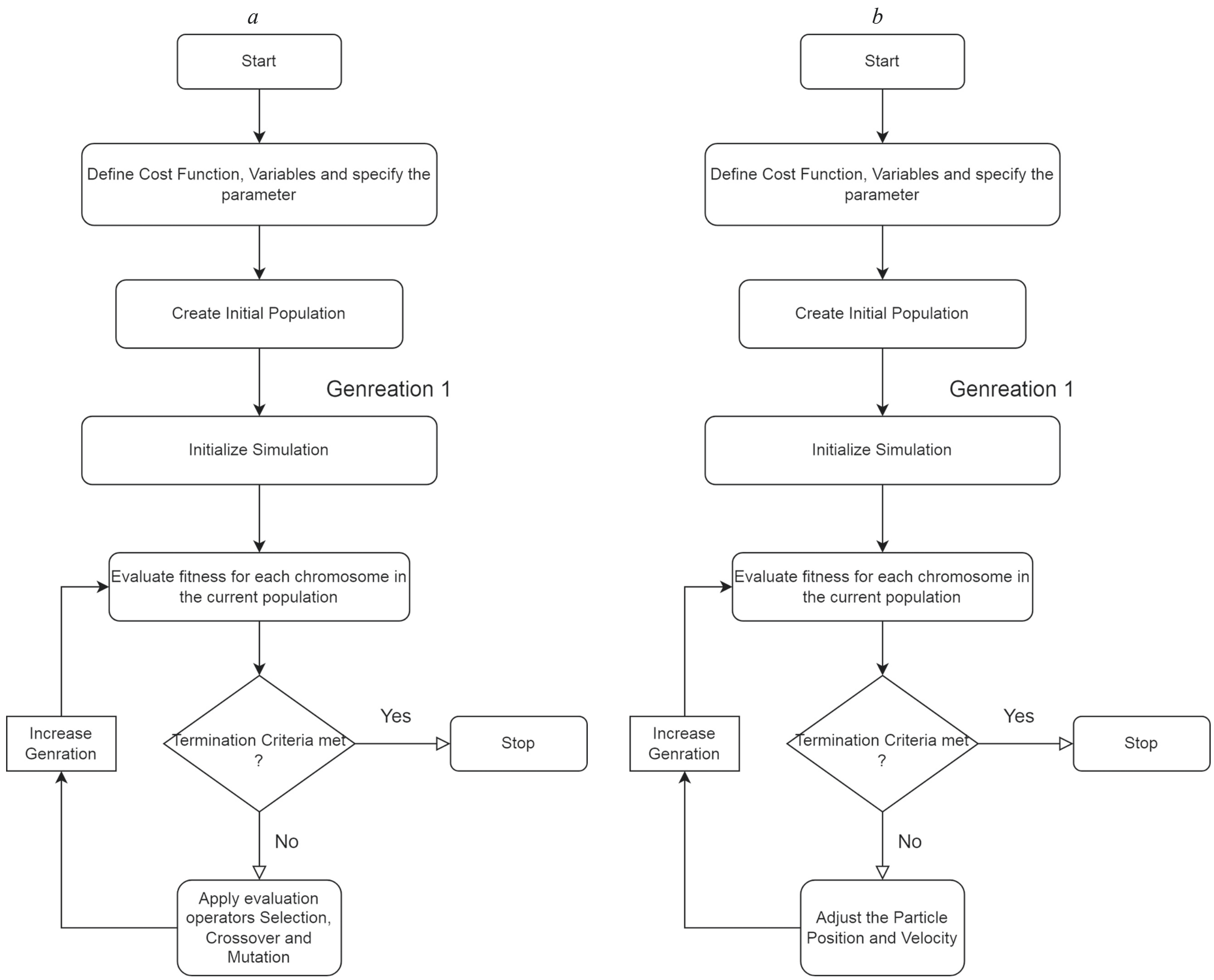

Fig. 5. Flow chart of Computational Intelligence based GA (*a*) and PSO (*b*) Algorithm

Fig. 4 represents CI-based and MMSE channel estimation. The GA is an automatic search algorithm for determining the lowest cost function and maximizing fitness. This algorithm is defined by parameters as mutation, cross over, and process of selection. If number of variables is more used in MIMO-OFDM based LTE system, GA provides the best solution. This method, which is one of the best, provides the best answer to the problem and is utilized in a variety of applications, including mobile communication systems. GA consists of three components: reproduction, mutation, and crossover. These components are used to calculate the Fitness value to select the best channel. The fitness formula is as follows:

$$fitness = \left(\frac{H - H_{GA}}{H}\right)^2.$$

Each particle is referred to as an agent in PSO, and it is kept in the search area to locate the objective function from the present location (Fig. 5). Every particle in the solution search space adjusts its velocity to find the optimum spot.

$$fitness = \left(\frac{H - H_{PSO}}{H}\right)^2.$$

The fitness function helps to optimize the problem and identify the best answer.

Designed Channel Model. Received Output Signal is defined as

$$y = xh + n,$$

where n is the zero mean complex Gaussian noise with variance, x defines the frame of modulated N-length *IFFT*, h shows CIR, which is designed and considered as Length **L** vector, * represents convolution operation.

Noise with variance is given by the following formula:

$$N_0 = 2\Sigma_w.$$

The time varying model which uses Jakes's model is described as follows:

$$h_{jake}(t) = \sum_l A_l e^{j[\Theta_L + 2\Pi f_{D\max}\cos(\Phi_L)t]}.$$

Arrival angle, and phase of the lth path are represented by A_l, Θ_L, and Φ_L, respectively. It is worth noting that Θ_l and Φ_L are mutually independent and distributed uniformly between [–Π, Π]. Furthermore, $f_{D\max}$ specifies the highest possible Doppler frequency.

CI based channel estimation

Least Squares Estimation

The LS channel estimation technique assumes a block-type pilot configuration with pilots located at all subcarriers of the OFDM signal.

The received signal after FFT demodulation is as follows:

$$Y_{\rho} = H_P X_P + W_P,$$

when H_P denotes the Frequency Selective Channel's Frequency Response at pilot places, X_P and W_P defines pilot symbols of the transmitter and samples of additive white Gaussian noise, respectively.

To secure channel estimation after implementing LS, the cost function should be minimised

$$J(\hat{H}_{LS}) = ||Y_P - X_P \hat{H}_{LS}||. \quad (1)$$

Furthermore, the equation (1) should be calculated by considering $\hat{H}_{LS}$ and the output is set to zero to achieve the cost function's minimal value.

This expression will be further simplified to give channel estimation due to LS:

$$\hat{H}_{LS} = \frac{Y_P(k)}{X_P(k)}.$$

Minimum Mean Square Error Estimation

Minimum Means square estimation was first introduced in [20] as shown in Fig. 6.

By close analysis of the above described figure, the estimated channel obtained is

$$\hat{H}_{MMSE} = G\check{H}.$$

At pilot position $\check{H}$ is given as:

$$\check{H} = X_P^{-1} Y_P.$$

By minimising the below given cost function, MMSE estimate of the channel can be calculated as follows:

$$J\left(\check{H}_{MMSE}\right) = E\{||e||^2\} = E\left\{\left\|H - \check{H}_{MMSE}\right\|^2\right\}.$$

Receiver

To acquire $\tilde{y}_b(t)$ vector of length N_{FFT} on side of receiver, the cyclic prefix is detached from the collected signal $\tilde{y}_{gb}(t)$ on every received antenna by the module for removing cyclic prefix. The FFT block then converts the signal to parallel form and transforms it into the frequency domain, yielding a frequency domain signal $\tilde{y}_b(t)$:

$$y_b(t) = FFT\{\tilde{y}_b(t)\}.$$

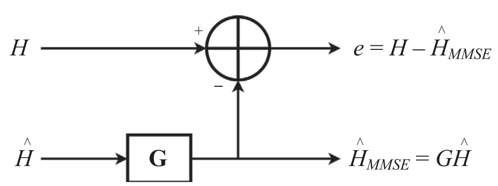

Fig. 6. MMSE System

For channel estimation, the pilot signal is extracted from the domain of the frequency signal. The layer demapping module equalizes and congregates the received signal $y_b(t)$ from all the reception antennas into a serial sequence after calculating the channel.

The signal is subsequently demodulated using the demodulation scheme, which is the same as the transmitter's approach. The final binary data sequence is obtained as the output of the LTE system model.

Results

This section presents the results as well as their discussion. The simulation results in this part were achieved using Spyder (anaconda3) and Google Colab on a core 3 GHz processor with 20 GB RAM and 1053 GPU.

Furthermore, the suggested Computational Intelligence-based channel estimation technique was implemented on a node that receives information through a time changing frequency channel model using Jake's model. In addition, Table 1 shows the simulation and channel model settings, while Table 2 shows the algorithm parameters.

The frame period T_{fp} is set to become shorter than the coherence time of channel T_{Ch} because the channel is believed to be twice selective and frequency-selective. Nonetheless, the channel response varying from frame to frame, the system must collect a correct CIR for every frame. To successfully estimate the CIR and keep track of the CIR variation, we designed the CI-based estimation algorithm at the output side.

We consider a period of training to receive the CIR before the start of data transmission. Once data transmission starts, the CI-based system will use define samples of pilot, inserted before each signal OFDM, to keep track of the impulse response change with respect to time. The presented innovative CI-based channel estimation's mean square error (MSE) performance was examined for a

Table 1. Simulation settings

FFT size	512
Number of symbols	100
No of Pilots	4
Carrier Frequency	3.7 GHZ
Mode of Modulation	16-QAM
Sub-carriers	2052
MaxVelocity	85 m/s
Doppler Shift	33–973 Hz
Per user Bandwidth	20 MHz
Channel type	AWGN

Table 2. CI Network Parameters

Input layer Size	2L
Output Layer Size	1
Number of Layers	2
Learning rate	0.001

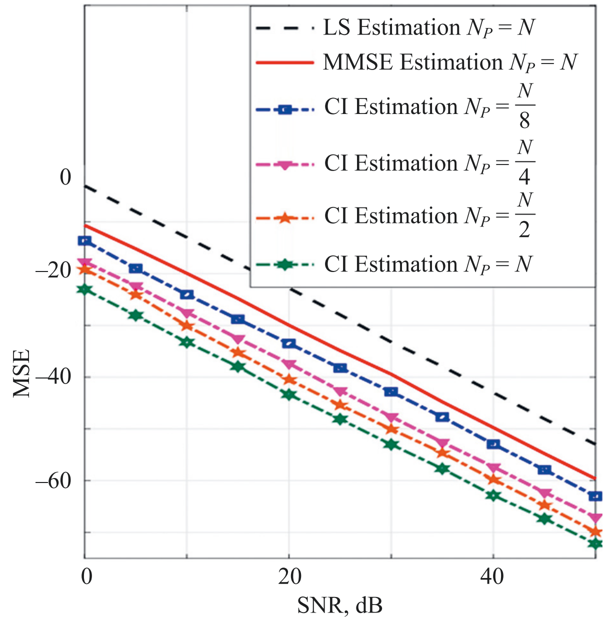

Fig. 7. MSE performance Comparison

different number of blocks of pilot in each block as shown in Fig. 7.

The pilots are considered as follows:

$$N_P = \frac{N}{8}, \frac{N}{4}, \frac{N}{2} \text{ and } N.$$

Mean square error performance of the designed model is compared with LS and MMSE channel estimation algorithm.

After the detailed analysis of Fig. 7, the designed algorithm outperforms MMSE and LS algorithm even when the number of pilots is small.

For $\frac{N}{8}$ data samples, the designed model gives 3.6 dB and 9.9 dB over MMSE and LS channel estimation algorithms. For $\frac{N}{4}$ data samples the designed model has a gain of 8.1 dB and 14.6 dB over MMSE and LS.

For $\frac{N}{2}$ samples, the model attained 11.3 dB and 17.9 dB compared with MMSE and LS.

For a variable number of pilots, we explored how the performance of MSE for CI-based channel estimate algorithm is turned into performance of BER at the receiving point. Fig. 8, *a* depicts the bit error rate performance for different four channel state information scenarios (CSI), including perfect or ideal CSI, CSI derived using the LS method, MMSE algorithm, and the suggested innovative CI-based algorithm.

A close analysis of Fig. 8, *a* reveals that BER performance of the designed model matches with perfect and ideal CSI. This match shows the effectiveness of the designed model.

Then we evaluate the MSE performance of the designed model against the number of pilot samples. Fig. 8, *b* shows the impact of increasing the number of pilot samples when SNR is fixed at 15 dB and 20 dB.

Similarly, BER outcome is evaluated against the number of pilot samples. Fig. 9, *a* shows that the performance of BER is proportional to the number of blocks of pilots. Performance of BER for CI-dependent estimator reaches of the evaluated values for BER of ideal CSI.

Fig. 9, *b* shows the convergence behaviour of the CI-based algorithm. We calculated MSE performance for different iterations to get the lowest MSE when SNR value is 10 dB, 15 dB and 20 dB, respectively. The designed model achieves the lowest MSE in between 17 and 19, respectively.

The analysis of Table 3 (Ô is Complexity constant and *L* is Floating point operations) shows that complexity of CI-model is less than LS and MMSE (Fig. 10, *a*).

Table 3. Complexity analysis

Estimator	Complexity
LS	Ô (Np)
MMSE	Ô $(N^2\text{p})$
CI-based estimator	Ô (L^2Np)

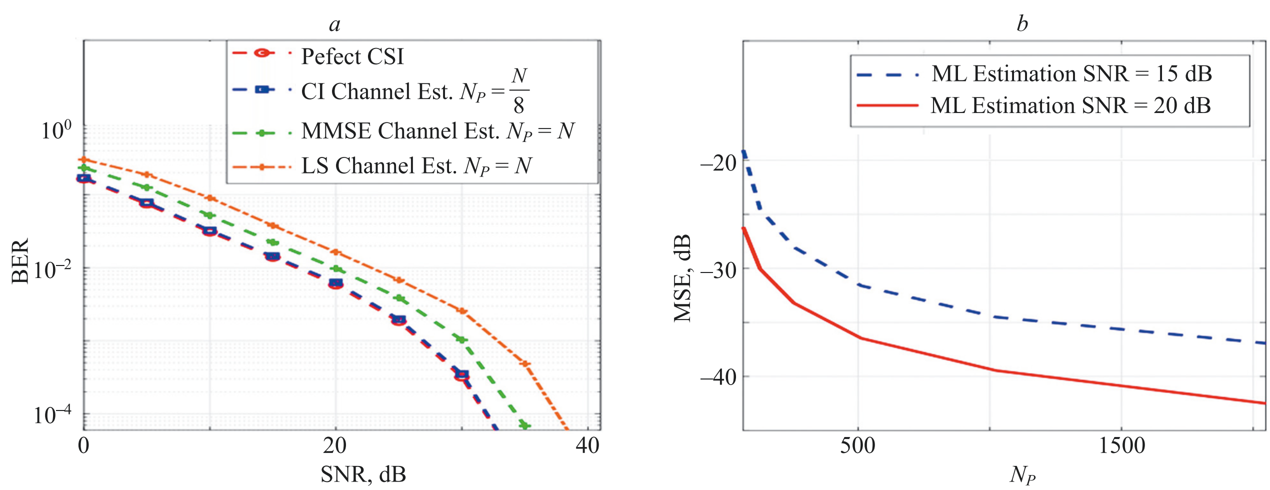

Fig. 8. BER performance comparison (*a*) and MSE performance vs pilots samples (*b*)

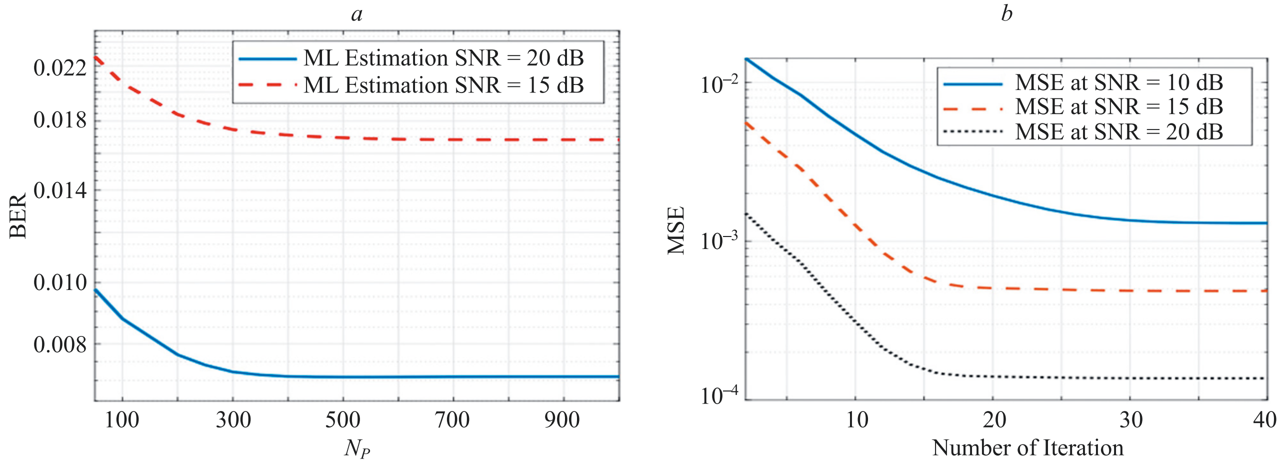

Fig. 9. BER Performance vs pilots samples (*a*) and MSE performance vs number of iterations (*b*)

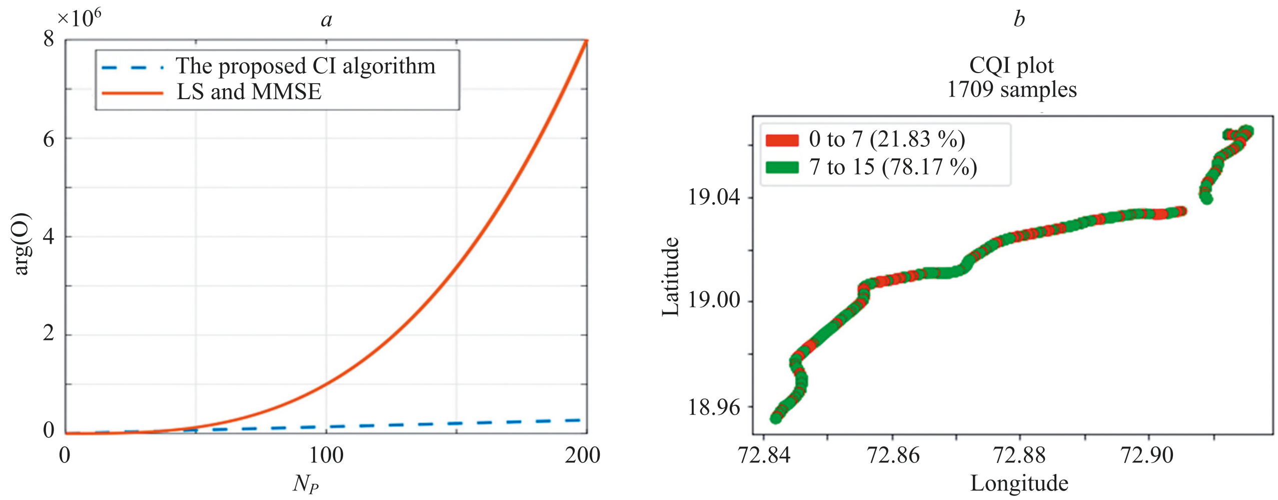

Fig. 10. Complexity comparison (*a*) and CQI analysis (*b*)

The proposed estimator converge the best CIR estimation if L is between 3 to 10 times less than the number of samples N_P.

Finally, Fig. 10, *b* shows the analysis of the channel quality indicator for the designed model taking into account different longitude and latitude for 1,709 drive test data samples.

Conclusion

This paper introduced a straightforward but an effective computational intelligence-depended approach for channel evaluation. We investigated an unmarked OFDM-depended LTE system that receives data across a frequency selective channel that changes over time. The designed algorithm was then applied to this OFDM depended system to evaluate this time changing channel and follows its changes from block to block. First, the suggested algorithm's performance was assessed in terms of MSE channel evaluation performance and differentiated from LS and MMSE channel estimation methods. Even with a modest number of pilot samples used to estimate and track the CIR, the obtained findings showed that the presented approach beat the LS and MMSE algorithms. The suggested CI-based technique performs far better than MMSE and LS channel estimation algorithms by 2.4 dB and 5.4 dB, respectively, in terms of BER. Furthermore, we tested the robustness of the proposed approach against a variety of different maximum Doppler frequency values, and the findings proved the effectiveness of our system in time-changing CIR, as the change in frequency caused only a modest outcome decrease of 0.19 dB.

References

1. Bobde S., Phalnikar R. Software restructuring models for object oriented programming languages using the fuzzy based clustering algorithm. *Scientific and technical journal of information technologies, mechanics and optics*, 2021, vol. 21, no. 5, pp 738–747. https://doi.org/10.17586/2226-1494-2021-21-5-738-747
2. Bothra S.K., Singhal S. Nature-inspired metaheuristic scheduling algorithms in cloud: a systematic review. *Scientific and technical journal of information technologies, mechanics and optics*, 2021, vol. 21, no. 4, pp. 463–472. https://doi.org/10.17586/2226-1494-2021-21-4-463-472
3. Farrokhi F.R., Lozano A., Foschini G.J., Valenzuela R.A. Spectral efficiency of FDMA/TDMA wireless systems with transmit and receive antenna arrays. *IEEE Transactions on Wireless Communications*, 2002, vol. 1, no. 4, pp. 591–599. https://doi.org/10.1109/TWC.2002.804078
4. Balanis C. *Antenna theory: Analysis and design*. 4rd ed. New York, John Wiley & Sons, 2016, pp. 900–908.
5. Durrani S., Bialkowski M.E. Effect of mutual coupling on the interference rejection capabilities of linear and circular arrays in CDMA systems. *IEEE Transactions on Antennas and Propagation*, 2004, vol. 52, no. 4, pp. 1130–1134. https://doi.org/10.1109/TAP.2004.825640
6. Piazza D., Kirsch N.J., Forenza A., Heath R.W., Dandekar K.R. Design and evaluation of a reconfigurable antenna array for MIMO systems. *IEEE Transactions on Antennas and Propagation*, 2008, vol. 56, no. 3, pp. 869–881. https://doi.org/10.1109/TAP.2008.916908
7. Lozano A., Tulino A.M. Capacity of multiple-transmit multiple-receive antenna architectures. *IEEE Transactions on Information Theory*, 2002, vol. 48, no. 12, pp. 3117–3127. https://doi.org/10.1109/TIT.2002.805084
8. Oyman Ö., Nabar R.U., Bölcskei H., Paulraj A.J. Tight lower bounds on the ergodic capacity of Rayleigh fading MIMO channels. *Proc. of the Conference Record / IEEE Global Telecommunications Conference*. V. 2, 2002, pp. 1172–1176. https://doi.org/10.1109/GLOCOM.2002.1188380
9. Du J., Li Y. Optimization of antenna configuration for MIMO systems. *IEEE Transactions on Communications*, 2005, vol. 53, no. 9, pp. 1451–1454. https://doi.org/10.1109/TCOMM.2005.855002
10. Waheed U.A., Kishore D.V. Uplink spatial fading correlation of MIMO channel. *IEEE Vehicular Technology Conference*, 2003, vol. 58, no. 1, pp. 94–98. https://doi.org/10.1109/VETECF.2003.1284985
11. Tsai J.-A., Woerner B.D. The fading correlation function of a circular antenna array in mobile radio environment. *Proc. of the IEEE Global Telecommunications Conference*. V. 5, 2001, pp. 3232–3236. https://doi.org/10.1109/GLOCOM.2001.966023
12. Li X., Nie Z.-P. Spatial fading correlation of circular antenna arrays with Laplacian PAS in MIMO channels. *Proc. of the IEEE Antennas and Propagation Society International Symposium*. V. 4, 2004, pp. 3697–3700. https://doi.org/10.1109/APS.2004.1330149
13. Recioui A., Bentarzi H. Genetic algorithm based MIMO capacity enhancement in spatially correlated channels including mutual coupling. *Wireless Personal Communications*, 2012, vol. 63, no. 3, pp. 689–701. https://doi.org/10.1007/s11277-010-0159-5
14. Recioui A., Azrar A. Use of genetic algorithms in linear and planar array synthesis based on Schelkunoff method. *Microwave and Optical Technology Letters*, 2007, vol. 49, no. 7, pp. 1619–1623. https://doi.org/10.1002/mop.22510
15. Montgomery D. C. *Design and Analysis of Experiments*. New York, Wiley, 1991, pp. 28–39.
16. Ross P.J. *Taguchi Techniques for Quality Engineering*. McGraw-Hill. 2013, pp. 43–52.
17. Weng W.C., Yang F., Elsherbeni A.Z. Linear antenna array synthesis using Taguchi's method: A novel optimization technique in electromagnetic. *IEEE Transactions on Antennas and Propagation*, 2007, vol. 55, no. 3, pp. 723–730. https://doi.org/10.1109/TAP.2007.891548
18. Wu Y. *Taguchi Methods for Robust Design*. ASME Press, 2012.
19. Gen M., Cheng R. *Genetic algorithms and engineering design*. Wiley, 2000, pp. 29–37.
20. Khlifi A., Bouallegue R., Performance analysis of LS and LMMSE channel estimation techniques for LTE downlink systems. *International Journal of Wireless & Mobile Networks (IJWMN)*, 2011, vol. 3, no. 5, pp. 141–149. https://doi.org/10.5121/ijwmn.2011.3511

Литература

1. Bobde S., Phalnikar R. Software restructuring models for object oriented programming languages using the fuzzy based clustering algorithm // Научно-технический вестник информационных технологий, механики и оптики. 2021. Т. 21. № 5. С. 738–747. https://doi.org/10.17586/2226-1494-2021-21-5-738-747
2. Bothra S.K., Singhal S. Nature-inspired metaheuristic scheduling algorithms in cloud: a systematic review // Научно-технический вестник информационных технологий, механики и оптики. 2021. V. 21. № 4. С. 463–472. https://doi.org/10.17586/2226-1494-2021-21-4-463-472
3. Farrokhi F.R., Lozano A., Foschini G.J., Valenzuela R.A. Spectral efficiency of FDMA/TDMA wireless systems with transmit and receive antenna arrays // IEEE Transactions on Wireless Communications. 2002. V. 1. N 4. P. 591–599. https://doi.org/10.1109/TWC.2002.804078
4. Balanis C. Antenna theory: Analysis and design. 4rd ed. New York: John Wiley & Sons, 2018. P. 900–908.
5. Durrani S., Bialkowski M.E. Effect of mutual coupling on the interference rejection capabilities of linear and circular arrays in CDMA systems // IEEE Transactions on Antennas and Propagation. 2004. V. 52. N 4. P. 1130–1134. https://doi.org/10.1109/TAP.2004.825640
6. Piazza D., Kirsch N.J., Forenza A., Heath R.W., Dandekar K.R. Design and evaluation of a reconfigurable antenna array for MIMO systems // IEEE Transactions on Antennas and Propagation. 2008. V. 56. N 3. P. 869–881. https://doi.org/10.1109/TAP.2008.916908
7. Lozano A., Tulino A.M. Capacity of multiple-transmit multiple-receive antenna architectures // IEEE Transactions on Information Theory. 2002. V. 48. N 12. P. 3117–3127. https://doi.org/10.1109/TIT.2002.805084
8. Oyman Ö., Nabar R.U., Bölcskei H., Paulraj A.J. Tight lower bounds on the ergodic capacity of Rayleigh fading MIMO channels // Proc. of the Conference Record / IEEE Global Telecommunications Conference. V. 2. 2002. P. 1172–1176. https://doi.org/10.1109/GLOCOM.2002.1188380
9. Du J., Li Y. Optimization of antenna configuration for MIMO systems // IEEE Transactions on Communications. 2005. V. 53. N 9. P. 1451–1454. https://doi.org/10.1109/TCOMM.2005.855002
10. Waheed U.A., Kishore D.V. Uplink spatial fading correlation of MIMO channel // IEEE Vehicular Technology Conference. 2003. V. 58. N 1. P. 94–98. https://doi.org/10.1109/VETECF.2003.1284985
11. Tsai J.-A., Woerner B.D. The fading correlation function of a circular antenna array in mobile radio environment // Proc. of the IEEE Global Telecommunications Conference. V. 5. 2001. P. 3232–3236. https://doi.org/10.1109/GLOCOM.2001.966023
12. Li X., Nie Z.-P. Spatial fading correlation of circular antenna arrays with Laplacian PAS in MIMO channels // Proc. of the IEEE Antennas and Propagation Society International Symposium. V. 4. 2004. P. 3697–3700. https://doi.org/10.1109/APS.2004.1330149
13. Recioui A., Bentarzi H. Genetic algorithm based MIMO capacity enhancement in spatially correlated channels including mutual coupling // Wireless Personal Communications. 2012. V. 63. N 3. P. 689–701. https://doi.org/10.1007/s11277-010-0159-5
14. Recioui A., Azrar A. Use of genetic algorithms in linear and planar array synthesis based on Schelkunoff method // Microwave and Optical Technology Letters. 2007. V. 49. N 7. P. 1619–1623. https://doi.org/10.1002/mop.22510
15. Montgomery D. C. Design and Analysis of Experiments. New York: Wiley, 1991. P. 28–39.
16. Ross P.J. Taguchi techniques for quality engineering. McGraw-Hill. 2013. P. 43–52.
17. Weng W.C., Yang F., Elsherbeni A.Z. Linear antenna array synthesis using Taguchi's method: A novel optimization technique in electromagnetics // IEEE Transactions on Antennas and Propagation. 2007. V. 55. N 3. P. 723–730. https://doi.org/10.1109/TAP.2007.891548
18. Wu Y. Taguchi Methods for Robust Design. ASME Press, 2012.
19. Gen M., Cheng R. Genetic algorithms and engineering design. Wiley, 2000. P. 29–37.
20. Khlifi A., Bouallegue R., Performance analysis of LS and LMMSE channel estimation techniques for LTE downlink systems // International Journal of Wireless & Mobile Networks (IJWMN). 2011. V. 3. N 5. P. 141–149. https://doi.org/10.5121/ijwmn.2011.3511

Authors

Siraj Pathan — MEng, Research Scholar, Amity University Rajasthan, Jaipur, 303006, India, https://orcid.org/0000-0002-1728-3030, sirajpathan404@gmail.com

Ajit Noonia — PhD, Assistant Professor, Amity University Rajasthan, Jaipur, 303006, India, SC 57221779854, https://orcid.org/0000-0002-3110-4908, ajit009noonia@gmail.com

Mujib Tamboli — PhD, Assistant Professor, Anjuman-I-Islam's Kalsekar Technical Campus, Panvel, 410206, India, https://orcid.org/0000-0002-5891-3713, mujibtamboli@yahoo.co.in

Sunil Pathak — PhD, Associate Professor, Amity University Rajasthan, Jaipur, 303006, India, SC 57194562539, https://orcid.org/0000-0001-7409-9814, sunilpath@gmail.com

Авторы

Патан Сирадж — исследователь, магистр, Амити Университет Раджастана, Джапур, 303006, Индия, https://orcid.org/0000-0002-1728-3030, sirajpathan404@gmail.com

Нуния Аджит — PhD, доцент, доцент, Амити Университет Раджастана, Джапур, 303006, Индия, SC 57221779854, https://orcid.org/0000-0002-3110-4908, ajit009noonia@gmail.com

Тамболи Муджиб — PhD, доцент, доцент, Технический кампус Анджуман-и-Ислам в Калсекаре, Панвел, 410206, Индия, https://orcid.org/0000-0002-5891-3713, mujibtamboli@yahoo.co.in

Патхак Сунил — PhD, доцент, Амити Университет Раджастана, Джапур, 303006, Индия, SC 57194562539, https://orcid.org/0000-0001-7409-9814, sunilpath@gmail.com

Received 21.11.2021
Approved after reviewing 13.01.2022
Accepted 29.01.2022

Статья поступила в редакцию 21.11.2021
Одобрена после рецензирования 13.01.2022
Принята к печати 29.01.2022