Received 28 May 2023, accepted 14 June 2023, date of publication 23 June 2023, date of current version 10 July 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3288898

RESEARCH ARTICLE

Performance of Downlink NOMA for a Massive IoT Network Over a Nakagami-*m* Fading Channel With Optimized Power Allocation

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This work was supported by the Directorate of Research and Development Universitas Indonesia, under Postgraduate International Indexed Publication (PUTI) Research Grant, contract No. NKB-316/UN2.RST/HKP.05.00/2022.

ABSTRACT Non-orthogonal multiple access (NOMA) is a multiple access technology that can provide efficient spectrum utilization and increased channel capacity on Internet of Things (IoT) networks. One factor affecting NOMA system performance in the IoT network is the allocation of power for each NOMA user. To improve the channel capacity of the system, this paper presents a method for optimizing power allocation for NOMA in an IoT network with a Lagrange multiplier using the Karush-Kuhn-Tucker (KKT) condition. The optimization will result in an optimal power allocation solution to maximize the system channel capacity with the maximum transmit power constraint function and the minimum data rate for NOMA users. The channel capacity achieved by the system was observed in the Nakagami-*m* fading channel with imperfect successive interference cancellation (imp-SIC). The proposed power allocation method was compared with orthogonal multiple access (OMA) and the conventional NOMA (C-NOMA) power allocation techniques. The results show that the proposed power allocation coefficient optimization solution with the Lagrange multiplier using the KKT conditions significantly increases the channel capacity of the system compared to the OMA and C-NOMA methods.

INDEX TERMS Non-orthogonal multiple access (NOMA), massive IoT, Nakagami-*m* fading, capacity, power allocation, successive interference cancellation (SIC).

I. INTRODUCTION

One of the important goals for the next generation of Internet of Things (IoT) wireless technology is to provide massive connectivity massive with high throughput. IoT allows remote users to access connected multimedia devices [1]. Various studies have been conducted to support the application of IoT wireless technology; however, meeting the needs of future IoT applications that can serve hundreds of billions of connected devices is still a challenge [2]. In general, there are two types of multiple access techniques, namely, the orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA) schemes. The OMA technique, in which each user is provided with different resources, thus eliminating interference between IoT devices, has been widely used in the development of large-scale wireless networks [2]. However, the OMA technique has limitations in massive IoT networks in terms of its ability to support an increasing number of users due to the exclusive utilization of orthogonal resources. With an increasing number of users, limited spectrum resources and multiple access interference can result in a failure to increase system capacity [3], also resulting in a scarcity of wireless resources and an inefficient use of wireless resources for massive connectivity. Non-orthogonal multiple access (NOMA) techniques have been widely studied as a multiple access scheme to increase the use of the

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Feng.

same power spectrum for multiple users on an IoT network. In this regard, NOMA has an important role in increasing network capacity in the future. The NOMA access scheme allows one resource block to be used by more than one user to share the same time and frequency block, with different transmit power allocations between users [4]. NOMA, as a multiple access scheme for sharing resources in IoT networks utilizes superposition coding (SC) on the transmitter to support signals from multiple users before transmitting them. To separate the signal and reduce the interference of the shared channel, successive interference cancellation (SIC) is performed at the receiver. SIC is performed by users with better channel conditions so that the receiver can recover the desired information from the signal received [5], [6].

The performance of NOMA is affected by the power allocation to each user in the IoT network, and by the sequence of decoding processes within the user [7]. An improper power allocation will reduce NOMA's performance. Therefore, to ensure the performance and fairness for NOMA users, the power allocation to each user must be optimized. In this study, a power allocation optimization technique was used with a Lagrange multiplier using the KKT conditions to determine the optimal power allocation subject to the total transmission power in the NOMA group and the user's minimum data rate. We assume that Nakagami-*m* fading occurs in the channel. The Nakagami-*m* fading channel is the most common channel that can model the fading conditions of different environments using different parameter values.

A. RELATED WORKS

NOMA technology is one of the technologies that promises to increase the channel capacity of the IoT network system [8], [9], [10]. NOMA's channel capacity will decrease as the number of NOMA users served increases due to the decrease in the SINR value at the receiver. Various studies have been carried out to increase the channel capacity and resource efficiency on an IoT network using power-domain NOMA (PD NOMA). The power allocation technique has an important role that has been widely studied to improve the performance of the interference cancellation process in the NOMA system network [11], [12], [13], [14], [15]. Alghasmari and Nassef [11] proposed a resource allocation algorithm for several NOMA downlink users; the performance of three power allocation schemes, namely, fixed power allocation (FPA), fractional transmit power allocation (FTPA) and full search power allocation (FSPA), is compared. The FPA scheme is considered inefficient because the power level is set without taking into account the channel conditions and target rate requirements from the users. The results show that the NOMA capacity increase was higher than that of OMA, and FSPA showed better performance than the FPA and FTPA methods. In the FTPA scheme, the transmit power allocation for $U_{n,k}$ in subchannel k is allocated according to the channel gain of all the users multiplexed in subchannel [12]. Ahmed et al. [13] observed intracell interference with joint dynamic user scheduling and the power allocation techniques. Optimization was performed by minimizing the total power consumption limit of the entire network with the dynamic user scheduling and power allocation (DUSPA) algorithm. The results showed that the DUSPA algorithm could minimize the energy consumed compared to several other algorithms. In [14], the author proposed a dynamic power allocation method by determining the power allocation based on the channel state information (CSI) on the Rayleigh fading channel. The results show that the achievable rate changed dynamically while maintaining the target rate at the expected value. The proposed method was applied only to two users and did not take user mobility into account. The influence of imperfect SIC with fixed power allocation (FPA) and dynamic power allocation (DPA) on the capacity of the NOMA channels was observed in [15]. The capacity of the NOMA channels with DPA is greater than that of the FPA because the FPA does not consider far users' target level requirements.

The optimization problem with the Lagrange multiplier using the Karush-Kuhn-Tucker (KKT) conditions was studied in [3], [16], [17], [18], [19], [20], [21], and [22]. The authors in [3] observed the problem of maximizing the energy efficiency in a two-tier NOMA heterogeneous network on the Rayleigh fading channel by the optimizing transmit power and user association. The initial nonconvex problem is converted into a convex problem using the Dinkelbach method approach. Then, the closed-form solution is obtained with the dual approach of using the Lagrange and Karush-Kuhn-Tucker (KKT) conditions. The simulation results showed that the proposed resource allocation algorithm had good reliability. In [16], the authors proposed an optimization problem to increase the sum capacity with several constraints, namely, the transmission power for the BS, power allocation for users, and the user's minimum data rate. An efficient PA strategy is proposed in NOMA's downlink network to obtain an optimal PA with iterative local optimal solutions that meet KKT conditions. The simulation results show that the proposed optimal NOMA scheme with an optimal PA strategy can significantly increase the sum capacity. In [17], the authors proposed a power allocation technique with Lagrange multiplier KKT conditions using the DKL algorithm. The sum rate maximization problem is first formulized, then the optimal power allocation in a closed-form solution for multiplex users is derived using KKT conditions. The global optimal power allocation solution is not guaranteed in the formulation, so the optimal power allocation solution is obtained using the Dinkelbach (DKL) algorithm. User pairing was performed with the Hungarian (HNG) algorithm, which pairs 2 users in 1 cluster over the Rayleigh fading channels. In [18], power allocation optimization for NOMA users is performed by grouping users into clusters and then optimizing the power allocation of each in the proposed cluster by exploiting the difference in channel gain among the users in the NOMA cluster. A power allocation to maximize throughput per cluster while maximizing the overall system throughput is derived by using KKT optimization. Reference [19] applied the technique of determining the optimal power allocation factor with the Lagrange function and KKT conditions in cooperative relay networks. To obtain the optimal power allocation factor, an expression of the Lagrangian function with KKT conditions is used, and through the iterative Lagrangian multiplier, the capacity of the system is maximized. In [20], the authors observed the energy efficiency problem by applying effective user clustering and power allocation methods on the Rayleigh fading channel. The optimal power allocation for each user in each cluster was calculated by using the Lagrange multiplier method with KKT conditions. To obtain maximum energy efficiency, a dynamic programming algorithm between the clusters was developed. Spectrum efficiency and optimal power allocation methods were carried out by taking into account the quality of service (QoS) requirements and the successful operation of the SIC. With the proposed algorithm, the performance of the NOMA system was better than that of the OMA system. The authors in [21] investigated a resource management scheme to maximize the total spectral efficiency of a multioperator IoT network for two PD NOMA users on a Rayleigh fading channel. This study proposed a new NOMA technique with a sequential quadratic programming (SQP) approach to solve the KKT-based power control problem, which was treated as a benchmark in which the power allocation of the SIC decoding process was completed. In [22], the authors examine the EE-based power allocation algorithm for IoT devices on the CR-NOMA network. The power allocation ratio for IoT devices is developed using a Lagrange multiplier based on the KKT conditions according to the minimum QoS requirements of each user. The authors in [5] used resource management to maximize the sum capacity by considering the minimum capacity requirements of each user on a Rayleigh channel with only two users. The authors proposed two algorithms that were designed based on the user's channel conditions and the user's minimum capacity requirements. By applying duality theory, the optimal power allocation for each subchannel was calculated. The results show that the proposed method is more efficient than the NOMA benchmark scheme.

The performance of IoT networks with NOMA over Rayleigh fading channels has been investigated in various studies. The authors in [3] obtained a closed-form solution of the power allocation technique and user association with the Lagrange function using the KKT conditions from the NOMA enabled heterogeneous network on the Rayleigh fading channel. To simplify the analysis, the NOMA network was implemented with a perfect interference cancellation (SIC) process. The impact of an imperfect SIC in NOMA has been investigated in various studies, in which the SIC process to eliminate errors mainly depends on the channel gain and power allocation factors. The authors in [23] introduced reversed decode-forwards relaying NOMA (R-DFNOMA) to improve user fairness by taking into account imperfect SIC processes. The NOMA downlink cooperative network with imperfect CSI through the Nakagami-*m* fading channel was observed in [24], in which the system performance was evaluated based on the outage probability value.

Various studies have extensively discussed power allocation optimization for KKT-based NOMA transmission on Rayleigh fading channels [3], [17], [20], [21]. However, none of them discussed the Nakagami-*m* fading channel by taking into account imperfect SIC. Therefore, this study observes the power allocation optimization technique on a massive IoT network on the Nakagami-*m* fading channel and imperfect SIC. This study also examines the problem of maximizing channel capacity and analysing outage probabilies for NOMA downlinks with a limit on the total transmission power in the NOMA group and the minimum data rate requirements of the user.

Previous studies in simplifying IoT network analyses with NOMA assumed that the interference cancellation (SIC) process was perfect, yet an imperfect SIC process could occur. As a result, the receiver cannot cancel out interference from other users' signals, that have poorer channel gain. An increased number of NOMA users affects the number of SIC processes, and most of the existing studies use a scenario with only two NOMA users. Only using two NOMA users is assumed to be inadequate to connect the large amount of IoT equipment on the network. Serving a large number of IoT networks using conventional power allocation methods will result in decreased system performance. Existing studies have observed the NOMA function in the Rayleigh fading channel model with the assumption that interference cancellation was perfect; however, the effect of NOMA in the Nakagami-*m* fading channel model with imperfect interference cancellation has not been studied. Table 1 shows the related survey article, which also highlights the research gaps in comparison to the proposed survey.

We have summarized the main contributions of the paper as follows.

- We propose an access scheme design for a NOMA-based IoT network that aims to increase channel capacity in downlink over the Nakagami fading channel by optimizing the power allocation. The fading channel model applied was Nakagami-*m*, which is the most common fading distribution [25].
- we determine the optimal power allocation for users by the optimization method using a Lagrange multiplier with KKT conditions subject to the individual QoS requirements and maximum transmit power allocation at BS.
- We analyze the channel capacity and outage probability of the proposed system according to the SINR value assuming an imperfect SIC.

B. PAPER ORGANIZATION

This paper is structured as follows. Section II introduces the NOMA downlink system model on a massive IoT network. Section III shows the formulation of the mathematical model for the observed channel capacity with the application of

TABLE 1. Comparison of the proposed NOMA methods in terms of the pros and cons.

Reference	Proposed method	Pros	Cons
[3]	Optimization of the power allocation and user association algorithm based on the Lagrange dual method and KKT conditions.	1) The impact of imperfect CSI error on the user's outage probability is provided for insight into the performance of the proposed algorithm. 2) Considering the QoS measurement of each user, the maximum transmits the power constraint of BS. 3) The proposed algorithm had good robustness and can reduce the OP of macrocell users.	1) Observed in the Rayleigh fading channel. 2) Deterministic and convex optimization problem by using the worst-case approach and Dinkelbach's method
[5]	Efficient resource management to maximize capacity by duality theory	1) Considers each user's minimum capacity, requirement optimization with Lagrange multiplier. 2) More efficient when compared with the benchmark NOMA schemes.	1) Observed in the Rayleigh fading channel. 2) Considers 2 users in the subchannel.
[9]	Optimal Power Allocation Schemes for OFDM-NOMA-based UDN IoT Network	1) Guarantees the QoS 2) The throughput of NOMA is far greater than the OMA system. 3) The optimal PA schemes solved by jointly employing a channel-state sorting-pairing algorithm, water filling algorithm, and convex optimization theory.	1) Observed in the Rayleigh fading channel. 2) No error propagation
[11]	Different approaches for the power allocation and user pairing schemes: FSPA, FPA, and FTPA.	1) Compared the performance of three algorithms for resource allocation. 2) FSPA obtains a higher performance than FPA and FTPA.	1) Random user pairing and channel state sorting-based user pairing are studied. 2) FSPA has a higher complexity, especially with the increased number of users sharing the same subchannel.
[15]	Dynamic Power Allocation (DPA) for power domain NOMA with user mobility.	PA coefficient for DPA dynamically adjusted based on target rate requirement and imperfect SIC.	Observed in the Rayleigh fading channel.
[16]	Proposed an efficient PA strategy to maximize the sum capacity under various practical constrains.	1) Considers practical constraints: power budgets for BSs, PA for user, and minimum rate requirements per user. 2) A local optimal solution is obtained to solve the optimization problem with KKT conditions.	The power allocation problem observes in the multicell multiuser (MCMU) over the Rayleigh fading channel.
[17]	Optimization to maximize the sum rate and energy efficiency using a local optimal solution with KKT conditions.	1) Considers practical constraints: maximum available transmission power at the BS and minimum acceptable data rate. 2) NOMA-PDKL-HNG achieves a high sum rate and provides more fairness.	1) To obtain the optimal sum rate in NOMA using PDKL-HNG algorithm. 2) Observed in the Rayleigh fading channel.
[18]	Optimization to obtain optimal power allocations for any cluster size using KKT optimality conditions.	1) Considers practical constraints: transmission power at the BS, minimum rate requirements of the users, and SIC. 2) Proposes user grouping and power allocation solutions for throughput maximization.	Formulate throughput maximization problem for both uplink and downlink NOMA.
[20]	Optimization of user clustering and power allocation by employing the Lagrange multiplier method with KKT optimality conditions.	Considers practical constraints: maximum transmission power at the BS, maximum transmission power of each cluster, minimum data rate requirements of each user and is power for efficient SIC.	Develops an intercluster dynamic programming algorithm to achieve the overall energy efficiency maximization.
[21]	Resource optimization for maximizing the spectral efficiency (SE) of the IoT networks	1) Considers practical constraints: SIC complexity, minimum gap of received power among different IoT equipment, QoS requirements, IoT equipment's transmit powers. 2) The proposed technique significantly outperforms the benchmark NOMA schemes based on the KKT conditions and conventional OMA.	1) The paper designs a suboptimal algorithm for efficient frequency block assignment for assignment and to solve the nonconvex power control problem. 2) More suitable for large-scale IoT networks.
[23]	Introduce reversed decode-forwards relaying NOMA (R-DFNOMA)	1) The proposed method is to improve user fairness and is investigated with the imperfect SIC effect and CSI errors. 2) R-DFNOMA provides better user fairness than C-DFNOMA.	1) Observed in the Rayleigh fading channel. 2) R-DFNOMA allocates more power to near users than to far users.

TABLE 1. *(Continued.)* **Comparison of the proposed NOMA methods in terms of the pros and cons.**

[24]	The outage performance of cooperative NOMA network with DF relaying.	1) Observed in the Nakagami-*m* fading channel. 2) OP of FU with direct link much better than that of FU without direct link. 3) Performance of C-NOMA with ipCSI is superior to OMA	This paper has investigated the downlink cooperative NOMA network without PA optimization
[26]	A spectrum-efficient scheme to achieve better SE for NOMA-based Coordinated direct and relay transmission (CDRT) systems.	1) Observed in the Nakagami-*m* fading channel with both perfect and imperfect SIC. 2) Derive the close-form expressions of the Ergodic Capacity (EC), average SE, user fairness index, and energy efficiency (EE) with both perfect an imperfect SIC	Investigated a CDRT in NOMA network.
[27]	Sum rate capacity of NOMA with optimal PA, where the outage probability (OP) has been derived for ordered NOMA through the cumulative density function-based approach.	1) SINR are measured corresponding to the decoded symbols of the far user and near users. 2) The capacity in terms of sum rates can be maximized if optimal power levels are chosen. 3) The OP reduces with an increase in SNR	The simulation scenario only considers two-users in a single cell over the Rayleigh fading channel.

KKT conditions to obtain the optimal power allocation coefficient. In Section IV, the analysis is presented. The NOMA access technique has been widely studied as a multiple access scheme to increase the use of a shared power spectrum for multiple users on an IoT network. The performance of the system with the Lagrange multiplier using the KKT conditions is discussed, and characterized by channel capacity and outage probability. Then, the simulation results are presented in Section V. Finally, the summary in this paper is provided in Section VI.

The flowchart of the research is shown in Fig. 1.

II. SYSTEM MODEL

The downlink NOMA access scheme system model proposed in this study is shown in Fig. 1, consisting of one base station (BS) transmitting its signals to N users, with the total bandwidth B divided into M subchannel frequencies and the bandwidth for each subchannel is b_{sc}. In Fig. 2, $U_{1,k}$ and $U_{N,k}$ are the strogest and weakest users, respectively. The total transmission power of the BS for the downlink NOMA is evenly divided into subchannels with the power for each subchannel is $P_k = P_t/M$, where P_t and P_k are, respectively, the total transmitted power of the BS and the allocated power on the k-th subchannel.

In the transmission process, the system undergoes fading, which is modelled as an independent and identically distributed (iid) Nakagami fading channel. The Nakagami-m fading channel approach uses the Nakagami distribution. The estimated channel coefficients $h_{n,k}$ = Z represent the Nakagami-m distribution, so the estimated channel gain of $U_{n,k}$ at BS $|h_{n,k}|^2 = |Z|^2$ follows the Gamma distribution with the fading parameter m_z and the estimated link mean power Ω_z. The form of the probability density function (PDF) of the channel with power gain $z = \left|h_{n,k}\right|^2$, $n = 1, 2, \ldots$ from Nakagami-m fading with an average channel power of $z = E\{|Z|^2\}$ is obtained from [24] and [26].

$$f_{|Z|^2(x)} = \frac{m^m}{\Omega^m \Gamma(m)} x^{m-1} exp\left(\frac{-m}{\Omega}x\right), \quad \forall x > 0 \qquad (1)$$

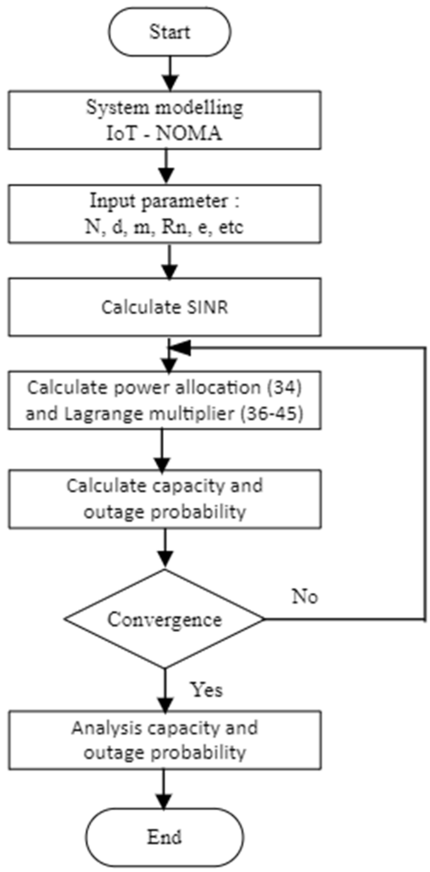


FIGURE 1. **The flowchart of the research.**

The CDF for Nakagami-m fading is expressed as

$$F_{|Z|^2(x)} = 1 - exp\Big(-\frac{mx}{\Omega}\Big) \sum\nolimits_{b=0}^{m-1} \frac{1}{b!} \left(\frac{mx}{\Omega}\right)^b \qquad (2)$$

where $\Gamma(.)$ denotes the gamma function. The Nakagami distribution is a generalized formula to model the fading conditions of different environments using different parameter values. If m = 1/2, it will model the Gaussian fading

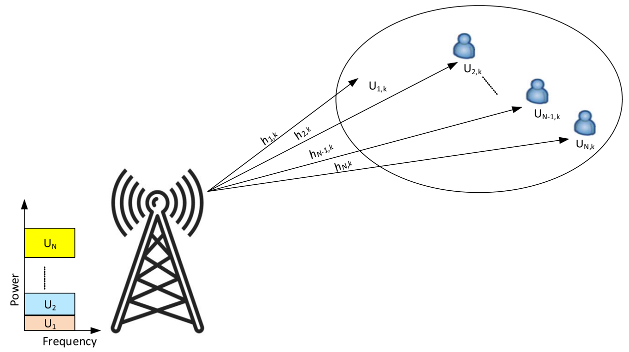


FIGURE 2. The proposed downlink NOMA system model.

channel. If m = 1, then the channel will have Rayleigh fading characteristics, while for very large m, then the channel will be nonfading [28].

Without loss of generality, the channel gains of all the users in the k-th subchannel are sorted in descending order by $|h_{1,k}|^2 > |h_{2,k}|^2 \ldots. > |h_{N-1,k}|^2 > |h_{N,k}|^2$. For users in the k-th subchannel, the power allocation coefficient is selected and sorted by user channel gain $\alpha_{1,k} < \alpha_{2,k} \ldots. < \alpha_{N-1,k} < \alpha_{N,k}$. Because the BS allocates more power to transmit the $U_{N,k}$ signal, the $U_{N,k}$ user has the largest power allocation coefficient, so it can directly decode the signal. The superimposed signal transmitted by the BS on the k-th subchannel is expressed as

$$x_k = \sqrt{\alpha_{1,k}P_k}s_{1,k} + \sqrt{\alpha_{2,k}P_k}s_{2,k} + \ldots + \sqrt{\alpha_{N-1,k}P_k}s_{N-1,k} + \sqrt{\alpha_{N,k}P_k}s_{N,k} \quad (3)$$

$S_{n,k}$ and P_k are information signals that are transmitted by the BS for the n-th user through the k-th subchannel and the total transmit power of the BS for each subchannel, respectively. The power allocation coefficient for the n-th user in the k-th subchannel is denoted by $\alpha_{n,k}$, with $\alpha_{1,k} + \alpha_{2,k} + \ldots. + \alpha_{N-1,k}, + \alpha_{N,k} = 1$.

The signal that user $U_{n,k}$ receives on the k-th subchannel after passing through the channel is given as

$$y_{n,k} = h_{n,k}\sum_{i=1}^{n-1}\sqrt{\alpha_{i,k}P_k}s_{i,k} + h_{n,k}\sqrt{\alpha_{n,k}P_k}s_{n,k} + n_{n,k} \quad (4)$$

in which $h_{n,k}$ is the fading channel coefficient from the BS to user $U_{n,k}$ on the k-th subchannel, and $n_{n,k}$ is additive white Gaussian noise (AWGN) at $U_{n,k}$ with zero mean and noise variance σ^2. Interference cancellation at each receiver is used to decode weaker users before decoding the signal itself. User $U_{1,k}$ uses SIC to decode its signal from $y_{1,k}$ so the signal that user $U_{1,k}$ receives after SIC is given as

$$\widehat{y_{1,k}} = h_{1,k}\sqrt{\alpha_{1,k}P_k}s_{1,k} + n_{1,k} \quad (5)$$

The SIC process at the user utilizes the SINR to detect the signal of each user. However, in practical systems, decoding errors may be unavoidable. As a result, interference cannot be eliminated completely, i.e., the SIC process is imperfect (impSIC). Decoding errors will cause residual interference, where the residual interference will reduce the performance of the system, especially in massive access systems. The SINR that the $U_{n,k}$ user receives to decode its own signal with impSIC conditions is given as

$$\gamma_{n,k}^{impSIC} = \frac{\alpha_{n,k}P_k\left|h_{n,k}\right|^2}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left|h_{n,k}\right|^2 + \sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2 + \sigma^2} \quad (6)$$

where ϵ is the value of the interference residual level with $0 \leq \epsilon \leq 1$. The denominator of the first term of Equation (6), $\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left|h_{n,k}\right|^2$, is the signal from a user with more power allocation that after cancellation cannot be cancelled. Residual interference is mainly caused by amplitude, phase, and channel estimation errors, thus causing imperfect regeneration of the received signal. The second term is the signal from a user with a lower power allocation, which represents a signal that is not cancelled.

The SINR of user $U_{n,k}$ after SIC is expressed by the following formula [28].

$$\gamma_{n,k}^{pSIC} = \frac{\alpha_{n,k}P_k\left|h_{n,k}\right|^2}{\sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2 + \sigma^2} \quad (7)$$

III. PERFORMANCE METRIC

The aim of this study is to maximize the channel capacity of the NOMA-based massive IoT network by determining the optimal user power allocation coefficient. The parameters used to measure the communication performance of the proposed system model are based on the channel capacity and outage probability parameters.

A. CHANNEL CAPACITY PERFORMANCE EVALUATION

Channel capacity is the effective transmission rate of a signal in a wireless communication system; it is measured in bits per second (bps). To ensure fairness among users, the minimum rate for each user is determined [29]. The channel capacity is evaluated for a number of N NOMA users with one subcarrier, minimum user constraint rate and P_t limit as the total transmission power. The channel capacity of IoT users assuming impSIC is represented mathematically as [23],

$$C_{n,k}^{impSIC} = b_{sc}\log_2\left(1 + \gamma_{n,k}^{impSIC}\right) \quad (8)$$

Substituting Equation (6) into Equation (8),

$$C_{n,k}^{impSIC} = b_{sc}\log_2\left(1 + \frac{\alpha_{n,k}P_k\left|h_{n,k}\right|^2}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left|h_{n,k}\right|^2 + \sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2 + \sigma^2}\right) \quad (9)$$

where b_{sc} is the bandwidth for the k-th subcarrier. In the first user pair with the k-th subcarrier, the channel capacity of user $U_{1,k}$ is expressed as

$$C_{1,k}^{impSIC} = b_{sc}\log_2\left(1+\gamma_{1,k}\right) = b_{sc}\log_2\left(1+\frac{\alpha_{1,k}P_k\left|h_{1,k}\right|^2}{\epsilon\sum_{j=2}^{N}\alpha_{j,k}P_k\left|h_{1,k}\right|^2+\sigma^2}\right) \tag{10}$$

$\left|h_{1,k}\right|^2\sum_{j=2}^{N}\alpha_{j,k}P_k$ is the interference for user $U_{1,k}$, so to obtain the signal itself, SIC is performed. After the SIC, the rate of $U_{1,k}$ users with perfect SIC ($\epsilon = 0$) is based on the equation

$$C_{1,k}^{pSIC} = b_{sc}\log_2\left(1+\frac{\alpha_{1,k}P_k\left|h_{1,k}\right|^2}{\sigma^2}\right) \tag{11}$$

The sum capacity of the NOMA user group is obtained by adding the channel capacity of each user as

$$C_{sum}^{ImpSIC} = \sum_{k=1}^{K}\sum_{n=1}^{N}C_{n,k}^{impSIC} \tag{12}$$

B. OUTAGE PROBABILITY

One of the parameters used to determine the good or bad performance of a wireless communication system is the outage probability (OP). OP is defined as the probability of an outage on the system, which states the probability of a failure of the information sent to the destination. OP occurs when the transmission rate of the system drops below the minimum required data rate in bits/sec/Hz [30].

In accordance with NOMA provisions, users can share the same bandwidth, so the data rate of each user must be within the channel capacity limit. An outage will occur if the user's achievable rate exceeds Shannon's capacity, which will result in the user failing to receive data [27]. Suppose the minimum data rate required by the BS with channel $U_{n,k}$ is $R_{n,k}$; then, the OP of the system can be mathematically expressed as [31]

$$(OP)_{n,k} = \Pr\left(C_{n,k} < R_{n,k}\right) \tag{13}$$

By substituting Equations (9) to (13), the OP for far user $(U_{n,k})$ occurs on

$$log_2\left(1+\frac{\alpha_{n,k}P_k\left|h_{n,k}\right|^2}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left|h_{n,k}\right|^2+\sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2+\sigma^2}\right) < R_{n,k} \tag{14}$$

with $\left|h_{n,k}\right|^2 = Z_{n,k}$, and $\rho_k = \frac{P_k}{\sigma^2}$, then

$$\frac{\alpha_{n,k}\rho_k Z_{n,k}}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}\rho_k Z_{n,k}+\sum_{i=1}^{n-1}\alpha_{i,k}\rho_k Z_{n,k}+1} < 2^{R_{n,k}}-1 = \delta_{n,k}) \tag{15}$$

where $\delta_{n,k}$ is the target SINR for the n-th user who has target rate $R_{n,k}$.

$$Z_{n,k} < \frac{\delta_{n,k}}{\rho_k\left(\alpha_{n,k}-\delta_{n,k}\sum_{i=1}^{n-1}\alpha_{i,k}\right)} \tag{16}$$

By substituting Equation (16) into Equation (13), then

$$(OP)_{n,k} = Pr\left(Z_{n,k} < \frac{\delta_{n,k}}{\rho_k\left(\alpha_{n,k}-\delta_{n,k}\sum_{i=1}^{n-1}\alpha_{i,k}\right)}\right) \tag{17}$$

Outage on the near user $(U_{1,k})$ is affected by SIC, and the symbol $S_{1,k}$ is decoded in advance at the terminal, where the outage can occur when the data rate of $U_{2,k}$, $U_{3,k}$,….., $U_{n,k}$ exceeds Shannon's capacity.

IV. POWER ALLOCATION COEFFICIENT OPTIMIZATION

To improve NOMA performance, one of the issues widely researched is the power allocation solution for the NOMA group. In this paper, the optimal power allocation coefficient solution for each user was obtained with Lagrange multipliers using the KKT conditions. Mathematically, the power allocation coefficient optimization problem can be simplified to (18)–(20), as shown at the bottom of the next page. where C1 is a function of the maximum transmitting power constraint according to the NOMA protocol, and C2 is the minimum data rate constraint of each user. Optimization was carried out to maximize the sum capacity of the network in Equation (18) as the objective function. The constraint functions considered were the total transmission power in the NOMA group and the user's minimum data rate functions, which are convex functions [32]. A solution to obtain the optimal power allocation coefficient for NOMA users in the subchannel is given using the KKT condition [17]. The suitable Lagrange function of the observed problem can be represented as (21), shown at the bottom of the next page. The Lagrange function formed is the objective function supplemented with the total constraint, with λ and τ_n being Lagrange multipliers. By simplifying Equation (21), we obtain (23), as shown at the bottom of the next page.

The KKT conditions are expressed as

$$\lambda \geq 0 \tag{24}$$

$$\tau_n \geq 0, \quad n = 1, 2, \ldots.., N \tag{25}$$

By differentiating the objective function in Equation (21) with respect to $\alpha_{n,k}$, λ and τ_{n} of the KKT conditions can be achieved.

- Limitation of the maximum transmission power allocation coefficient of the subchannel,

$$\frac{\partial F\left(\alpha_{n,k},\lambda,\tau_n\right)}{\partial\alpha_{n,k}} = \frac{b_{sc}\left(1+\tau_n\right)\left(P_k\kappa_n\right)}{ln2\left(1+\alpha_{n,k}\left(P_k\kappa_n\right)\right)} - \lambda P_k = 0, \quad \forall n \in N \tag{26}$$

- Limitation of the maximum transmission power allocation within the subchannel,

$$\frac{\partial F(\alpha_{n,k},\lambda,\tau_n)}{\partial \lambda} = \sum_{n=1}^{N} \alpha_{n,k}P_k - P_t = 0, \quad \forall n \in N \tag{27}$$

- Minimum data transmission rate for each user,

$$\frac{\partial F\left(\alpha_{n,k},\lambda,\tau_n\right)}{\partial \tau_n} = b_{sc}log_2\left(1+\alpha_{n,k}\left(P_k\kappa_n\right)\right) - R_{n,k} = 0, \quad \forall n \in N \tag{28}$$

The optimal power allocation coefficient can be derived according to the problem in Equation (28) by giving Lemma 1.

Lemma 1: According to the KKT condition, the optimal solution is obtained if λ and τ_n are greater than zero. Therefore, from Equations (27) and (28), we obtain

$$\sum_{n=1}^{N} \alpha_{n,k}P_k = P_t, \quad \forall n \in N \tag{29}$$

$$R_{n,k} = b_{sc}log_2\left(1+\alpha_{n,k}P_k\kappa_n\right), \quad \forall n \in N \tag{30}$$

The optimal power allocation for downlink NOMA in the subchannel is obtained from the objective function Equation (28) as stated in Equations,

$$b_{sc}log_2\left(1+\alpha_{n,k}P_k\kappa_n\right) - R_{n,k} = 0 \tag{31}$$

$$log_2\left(1+\alpha_{n,k}P_k\kappa_n\right) = \frac{R_{n,k}}{b_{sc}} \tag{32}$$

$$\alpha_{n,k}P_k\kappa_n = 2^{\frac{R_{n,k}}{b_{sc}}} - 1 \tag{33}$$

$$\boldsymbol{\alpha_{n,k}} = \left(\frac{1}{P_k\kappa_n}\right)\left(2^{\frac{R_{n,k}}{b_{sc}}} - 1\right), \quad \forall n \in N \tag{34}$$

According to Equation (29), the user power allocation coefficient $U_{1,k}$ is obtained by determining $n = 1$, so that

$$\alpha_{1,k} = \frac{1}{P_k}\left(P_t - \sum_{i=2}^{N} \alpha_{i,k}P_k\right) \tag{35}$$

The optimal λ value obtained from Equation (26) is expressed as

$$\frac{\partial F(\alpha_{n,k},\lambda,\tau_n)}{\partial \alpha_{n,k}} = \frac{b_{sc}(1+\tau_n)\left(P_k\kappa_n\right)}{ln2\left(1+\alpha_{n,k}\left(P_k n\right)\right)} - \lambda.P_k = 0 \tag{36}$$

$$\boldsymbol{\lambda} = \frac{\boldsymbol{b_{sc}(1+\tau_n)}\left(\kappa_n\right)}{ln2\left(1+\alpha_{n,k}\left(P_k\kappa_n\right)\right)} \tag{37}$$

Based on KKT conditions with $\lambda = 0$, then $\frac{\partial F(\alpha_{n,k},\lambda,\tau_n)}{\partial \alpha_{1,k}} = \frac{\partial F(\alpha_{n,k},\lambda,\tau_n)}{\partial \alpha_{2,k}} \ldots\ldots = \frac{\partial F(\alpha_{n,k},\lambda,\tau_n)}{\partial \alpha_{n,k}} = 0$. By substituting n = 1,

$$\max_{\alpha_{n,k}} \sum_{n=1}^{N} C_{n,k} = \max_{\alpha_{n,k}} b_{sc} \sum_{n=1}^{N} log_2\left(1+\frac{\alpha_{n,k}P_k\left|h_{n,k}\right|^2}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left|h_{n,k}\right|^2+\sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2+\sigma^2}\right) \tag{18}$$

$$\text{Subject to } C1: \sum_{n=1}^{N}\alpha_{n,k}P_k \le P_t, \alpha_{n,k}P_k \ge 0, \quad \forall n \in N \tag{19}$$

$$C2: b_{sc}log_2\left(1+\frac{\alpha_{n,k}P_k\left|h_{n,k}\right|^2}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left|h_{n,k}\right|^2+\sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2+\sigma^2}\right) \ge R_{n,k}, \quad \forall n \in N \tag{20}$$

$$\begin{aligned} F\left(\alpha_{n,k},\lambda,\tau_n\right) &= b_{sc}\sum_{n=1}^{N} log_2\left(1+\frac{\alpha_{n,k}P_k\left|h_{n.k}\right|^2}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left|h_{n,k}\right|^2+\sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2+\sigma^2}\right) \\ &- \lambda\left(\sum_{n=1}^{N}\alpha_{n,k}P_k - P_t\right) \\ &- \sum_{n=1}^{N}\tau_n\left(R_{n,k} - b_{sc}log_2\left(1+\frac{\alpha_{n,k}P_k\left|h_{n,k}\right|^2}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left|h_{n,k}\right|^2+\sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2+\sigma^2}\right)\right) \end{aligned} \tag{21}$$

Suppose

$$\kappa_n = \frac{\left|h_{n,k}\right|^2}{\epsilon\sum_{j=n+1}^{N}\alpha_{j,k}P_k\left\lceil h_{n,k}\right\rceil^2+\sum_{i=1}^{n-1}\alpha_{i,k}P_k\left|h_{n,k}\right|^2+\sigma^2} \tag{22}$$

$$F\left(\alpha_{n,k},\lambda,\tau_n\right) = b_{sc}\left(1+\tau_n\right)\sum_{n=1}^{N} log_2\left(1+\left(\alpha_{n,k}P_k\kappa_n\right)\right) - \lambda\left(\sum_{n=1}^{N}\alpha_{n,k}P_k - P_t\right) - \sum_{n=1}^{N}\tau_n R_{n,k} \tag{23}$$

2, 3, ... into Equation (27), we obtain

$$\frac{\partial F(\alpha_{n,k}, \lambda, \tau_n)}{\partial \alpha_{1,k}} = \frac{b_{sc}(1+\tau_1)(P_k\kappa_1)}{ln2\left(1+\alpha_{1,k}P_k\kappa_1\right)} - \lambda.P_k = 0 \quad (38)$$

$$\frac{\partial F(\alpha_{n,k}, \lambda, \tau_n)}{\partial \alpha_{2,k}} = \frac{b_{sc}\,(1+\kappa_2)(P_k\kappa_2)}{ln2\left(1+\alpha_{2,k}\,(P_{k2})\right)} - \lambda.P_k = 0 \quad (39)$$

$$\frac{\partial F(\alpha_{n,k}, \lambda, \tau_n)}{\partial \alpha_{3,k}} = \frac{b_{sc}\,(1+\tau_3)(P_k\kappa_3)}{ln2\left(1+\alpha_{3,k}\,(P_k\kappa_3)\right)} - \lambda.P_k = 0 \quad (40)$$

Then, the relationship between τ_2 and τ_1 can be expressed as

$$\frac{b_{sc}(1+\tau_2)(P_k\kappa_2)}{ln2\left(1+\alpha_{2,k}\,(P_k\kappa_2)\right)} = \frac{b_{sc}(1+\tau_1)(P_k\kappa_1)}{ln2\left(1+\alpha_{1,k}\,(P_k\kappa_1)\right)} \quad (41)$$

then:

$$\tau_2 = 1 - \frac{\left(1+\alpha_{2,k}\kappa_2\right)(1+\tau_1)\,\kappa_1}{\left(1+\alpha_{1,k}\kappa_1\right)\kappa_2} > 0 \quad (42)$$

Likewise, since $\frac{\partial L(\alpha_{n,k},\lambda,\tau_n)}{\partial \alpha_{3,k}} = \frac{\partial L(\alpha_{n,k},\lambda,\tau_n)}{\partial \alpha_{1,k}} = 0$, the relationship between τ_3 and τ_1 can be expressed as

$$\frac{b_{sc}\,(1+\tau_3)(P_k\kappa_3)}{ln2\left(1+\alpha_{3,k}\,(P_k\kappa_3)\right)} = \frac{b_{sc}(1+\tau_1)(P_k\kappa_1)}{ln2\left(1+\alpha_{1,k}P_k\kappa_1\right)} \quad (43)$$

$$\tau_3 = 1 - \frac{\left(1+\alpha_{3,k}\kappa_3\right)(1+\tau_1)\,\kappa_1}{\left(1+\alpha_{1,k}\kappa_1\right)\kappa_3} > 0 \quad (44)$$

thus:

$$\tau_n = 1 - \frac{\left(1+\alpha_{n,k}\kappa_n\right)(1+\tau_1)\,\kappa_1}{\left(1+\alpha_{1,k}\kappa_1\right)\kappa_n} > 0 \quad (45)$$

The closed-form solution of the optimal power allocation BS within the N-user NOMA can be given as [32].

$$\alpha_{i,k} = \frac{1}{P_k\kappa_n} 2^{\frac{\sum_{j=i+1}^{n} R_{j,k}}{b_{sc}}}\left(2^{\frac{R_{i,k}}{b_{sc}}} - 1\right), \quad i = 2, \ldots, \text{n}, \ldots \quad (46)$$

Based on Lemma 1, to ensure that the user data rate with the worst channel gain is the same as the minimum required target data rate, power is first allocated to all the users with the worst channel. After that, the difference in the total transmission power from the BS is allocated to the user who has the highest channel gain. Thus, the channel capacity of the users can be maximized in accordance with the total transmission power constraints and the minimum rate requirements of each user.

V. RESULTS AND PERFORMANCE EVALUATION

In this subsection, the performance of the power allocation is presented by considering the imperfect SIC through the Nakagami-*m* fading channel. The NOMA system bandwidth was 1 MHz with the IoT devices in the cell randomly and evenly distributed. The results of testing the performance of the NOMA system on the proposed massive IoT network were compared with the conventional NOMA (NOMA without power allocation optimization) and the OMA schemes. In the simulation, tests were carried out to observe the effect of the number of users served on the subcarrier, the fading coefficient, the user target rate and the residual interference value in determining the amount of channel capacity and outage probability of the system. The test parameters are shown in Table 2.

TABLE 2. List of parameter specifications used in the test.

Parameters	Values
Bandwidth	1 MHz
Transmit Power of BS, P_t	40 dBm
Channel type	Nakagami-*m* fading
Distance BS with UEs	Random
Noise Power	No = -174 + 10log$_{10}$(BW) (dBm)
Target rate, $R_{n,k}$	0.5, 1.5, 2.0 (bps/Hz)
Channel Fading Coefficient, *m*	0.5, 1, 3
Spectral Density AWGN	−174 dBm/Hz

The system performance test was performed by providing a target rate of 1.5 bps/Hz, and the number of active IoT devices in the subchannel was 6. The system's channel capacity was evaluated versus variations in the transmission power, as shown in Fig. 3.

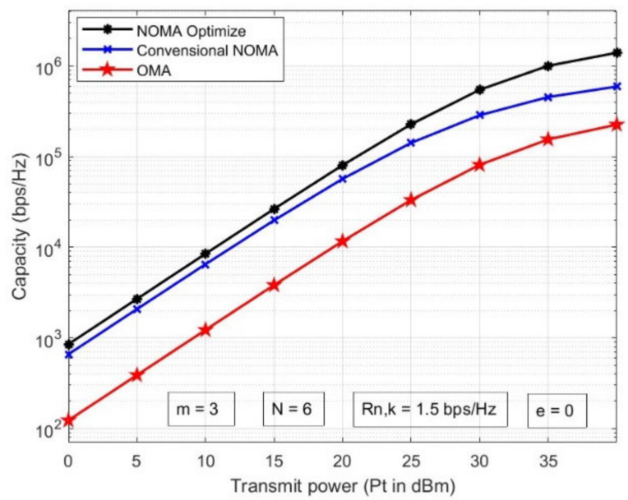


FIGURE 3. Channel capacity with transmission power at m = 3, $R_{n,k}$ = 1.5 bps/Hz, N = 6, and ϵ = 0.

The results were compared with the power allocation schemes for conventional NOMA (C-NOMA) and OMA. Based on Fig. 3, a higher channel capacity was given by the NOMA optimization scheme with KKT conditions. This indicates that NOMA can share a subchannel with more than one user. OMA limits bandwidth usage to only one user, thereby reducing the ability to maximize the use of available bandwidth. The test results show that the optimal power allocation provided better system capacity. Fig. 3 also shows that the capacity of both the OMA and NOMA multiple access schemes increases as the transmission power of the BS increases. When the transmit power of BS Pt is greater, more power will be allocated to the subchannel, SINR reception of the users will be increased and the channel capacity will increase.

Fig. 4 shows the performance of channel capacity on transmission power for different numbers of multiplexed users (N = 2, 4, and 6) with fading coefficients (m = 0.5, 1, and 3).

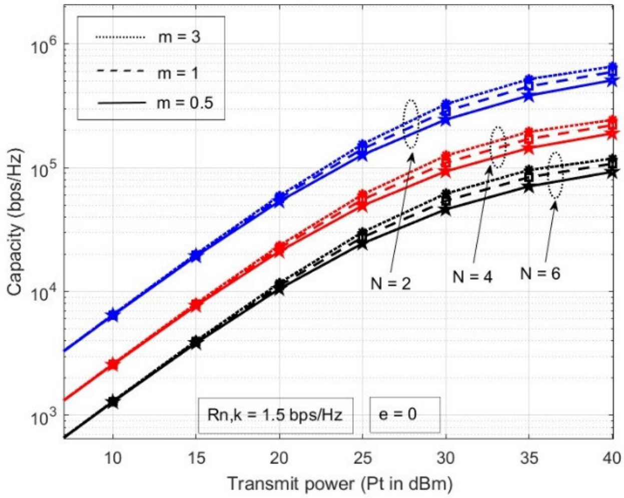


FIGURE 4. Channel capacity with variations of Pt for different number of users.

The results show that channel capacity increases with increasing transmission power and that channel capacity decreases with an increasing number of users of the NOMA group. The channel capacity for 4 NOMA users in a subchannel was better than that for 6 NOMA users in a subchannel. This was due to the increasing number of NOMA users; there was a possibility of error detection and decoding because the near user has to decode all signals of the far users. This error detection will reduce the performance of the system. Another possibility is that increasing users in the subchannel means less power allocation to the users, whereas reduced power allocation increases the possibility of interference.

Based on Fig. 4, it can also be seen that for the channel capacity with different fading parameters, the channel capacity increases with the increase in the value of m. Higher values of m indicate better channel conditions and increased channel capacity.

SIC errors are caused by the channel experiencing deep fading or an improper allocation of communication resources for the NOMA users. The effect of the SIC error on the NOMA system is simulated with different error values ($\epsilon = 0, \epsilon = 0.5$ and $\epsilon = 1$) by determining the target rate of far user $R_{n,k} = 1.5$ bps/Hz. The number of IoT devices observed was 6 users in one NOMA group, and the simulation results under perfect SIC conditions are shown in Fig. 5. The simulation results show that in perfect SIC ($\epsilon = 0$), the system performance is better than that in impSIC. In the case of impSIC, an increase in the value of ϵ indicates an increase in residual interference, so that the system performance decreases. The presence of residues in the SIC process has an impact on

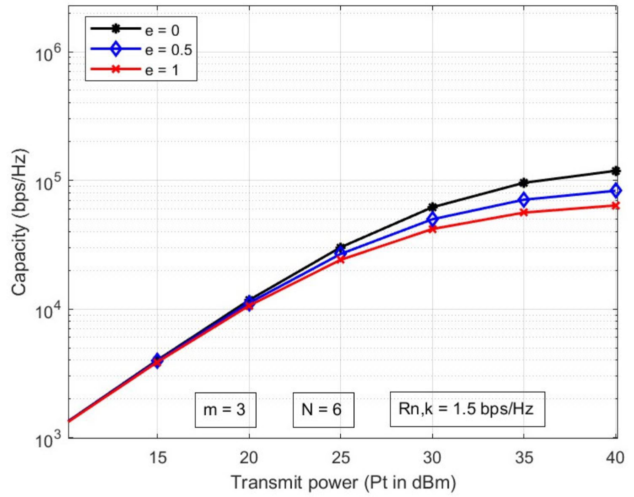


FIGURE 5. Channel capacity with variations of Pt to different error values.

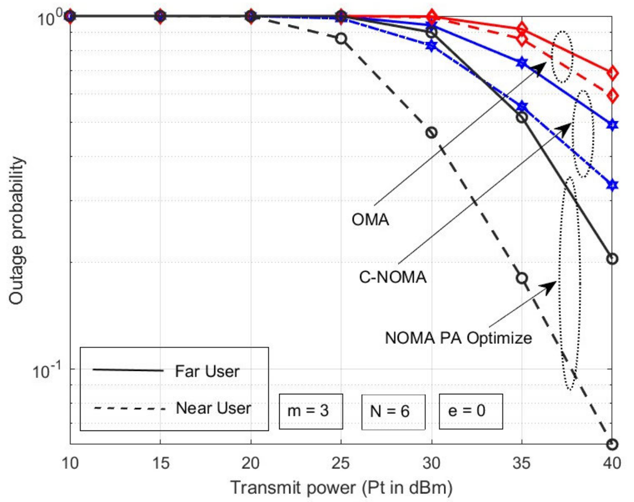


FIGURE 6. OP with variation of transmission power for NOMA power allocation optimization and C-NOMA.

decreasing the capacity obtained by the system because these residues will be considered signal interference, so they affect the SINR value, which also affects the capacity gain.

The evaluation of the outage probability with variations in transmission power is shown in Fig. 6. The results show that the outage probability value for near and far users decreases with increasing transmit power. The greater the transmit power used by the BS, the better the quality of the signal received at the destination. For example, for the NOMA power allocation optimization scheme, when the transmit power is 35 dBm, the resulting outage probability is 0.516. However, when the transmit power is 40 dBm, the resulting outage probability is 0.205. The smaller the outage probability value is, the smaller the failure rate of information transmission from source to destination. The outage probability performance of the proposed NOMA PA optimization scheme is evaluated compared to the conventional NOMA

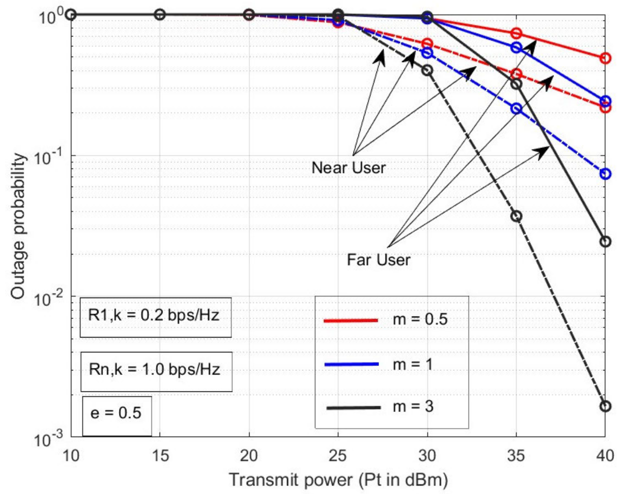


FIGURE 7. Outage probability with variation of transmission power for different fading parameter, $m = 0.5, 1, 3$.

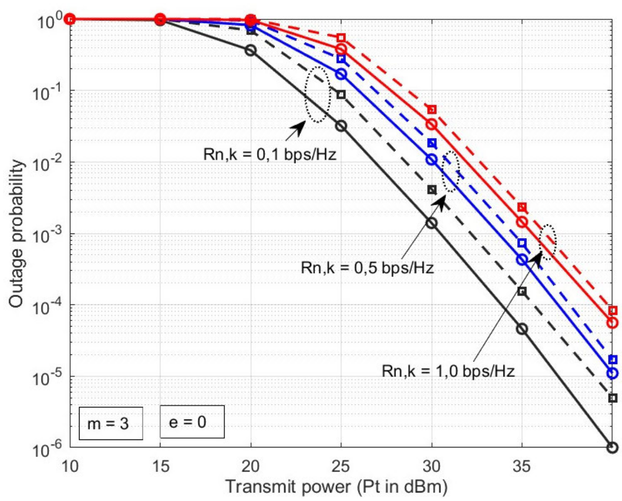


FIGURE 8. Outage probability with variation of transmit power for different target rates.

(C-NOMA) and the OMA scheme. The proposed NOMA PA optimization scheme provides better outage probability performance for near and far users.

Fig. 7 shows that the outage performance is better with a higher fading parameter value. A higher value of m indicates a better channel condition that can reduce the probability of an outage. At $m = 1$, the channel acts as a Rayleigh model where the line of sight between the transmitter and receiver is nonexistent. Conversely, when m is larger ($m = 3$), the dominant line of sight becomes clearer, and the outage probability decreases.

The effect of user target rates ($R_{n,k}$) on OP performance is shown in Fig. 8. By specifying $m = 3$ and $\epsilon = 0$, different $R_{n,k}$ values are assigned. Observations show that the OP performance of users worsened with increasing target rate values; this is due to more power being used to support larger target rates.

VI. CONCLUSION

This paper discusses the performance of downlink NOMA on a massive IoT network by optimizing the power allocation coefficient in the system. Optimization of the power allocation coefficient for the NOMA multiuser is conducted with a Lagrange multiplier for KKT conditions on the Nakagami fading channel. Taking into account the impSIC, the performance of the system for channel capacity and outage probability are evaluated. The evaluation results show that the channel capacity and outage probability are affected by the number of users served on the subcarrier, the fading coefficient, target rate users and residual interference value. The performance of the proposed system was evaluated by comparing it with the conventional NOMA and OMA power allocation methods.

REFERENCES

[1] N. A. Khan, A. Awang, and S. A. A. Karim, "Security in Internet of Things: A review," *IEEE Access*, vol. 10, pp. 104649–104670, 2022.

[2] I. Budhiraja, N. Kumar, S. Tyagi, S. Tanwar, Z. Han, M. J. Piran, and D. Y. Suh, "A systematic review on NOMA variants for 5G and beyond," *IEEE Access*, vol. 9, pp. 85573–85644, 2021.

[3] X. Wang, Y. Xu, J. Wang, and S. Fu, "Joint user association and power allocation in heterogeneous NOMA networks with imperfect CSI," *IEEE Access*, vol. 8, pp. 47607–47618, 2020.

[4] Z. Mlika and S. Cherkaoui, "Massive IoT access with NOMA in 5G networks and beyond using online competitiveness and learning," *IEEE Internet Things J.*, vol. 8, no. 17, pp. 13624–13639, Sep. 2021.

[5] A. Ali, A. Baig, G. Awan, W. Khan, Z. Ali, and G. A. Sidhu, "Efficient resource management for sum capacity maximization in 5G NOMA systems," *Appl. Syst. Innov.*, vol. 2, no. 3, p. 27, Aug. 2019.

[6] X. Sun, L. Yu, and Y. Yang, "Jointly optimizing user clustering, power management, and wireless channel allocation for NOMA-based Internet of Things," *Digit. Commun. Netw.*, vol. 7, no. 1, pp. 29–36, Feb. 2021.

[7] A. Tregancini, E. E. B. Olivo, D. P. M. Osorio, C. H. M. de Lima, and H. Alves, "Performance analysis of full-duplex relay-aided NOMA systems using partial relay selection," *IEEE Trans. Veh. Technol.*, vol. 69, no. 1, pp. 622–635, Jan. 2020.

[8] A. Akbar, S. Jangsher, and F. A. Bhatti, "NOMA and 5G emerging technologies: A survey on issues and solution techniques," *Comput. Netw.*, vol. 190, May 2021, Art. no. 107950.

[9] Y. Gao, F. Yu, H. Zhang, Y. Shi, and Y. Xia, "Optimal downlink power allocation schemes for OFDM-NOMA-based Internet of Things," *Int. J. Distrib. Sensor Netw.*, vol. 18, no. 1, 2022, Art. no. 15501477211064741.

[10] S. R. Islam, M. Zeng, O. A. Dobre, and K. S. Kwak, "Nonorthogonal multiple access (NOMA): How it meets 5G and beyond," in *Wiley 5G Ref: The Essential 5G Reference Online*. Hoboken, NJ, USA: Wiley, 2019, pp. 1–28.

[11] W. F. Alghasmari and L. Nassef, "Power allocation evaluation for downlink non-orthogonal multiple access (NOMA)," *Int. J. Adv. Comput. Sci. Appl.*, vol. 11, no. 4, pp. 1–7, 2020.

[12] F. Fang, H. Zhang, J. Cheng, and V. C. M. Leung, "Energy-efficient resource allocation for downlink non-orthogonal multiple access network," *IEEE Trans. Commun.*, vol. 64, no. 9, pp. 3722–3732, Sep. 2016.

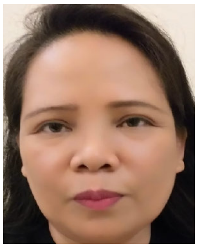
[13] M. A. Ahmed, A. Baz, and C. C. Tsimenidis, "Performance analysis of NOMA systems over Rayleigh fading channels with successive-interference cancellation," *IET Commun.*, vol. 14, no. 6, pp. 1065–1072, Apr. 2020.

[14] R. Seetharaman, D. Rahul, H. M. Lakshmanan, K. Anandan, and S. Gayathri, "Analysis of power allocation for non-orthogonal multiple access," *J. Phys., Conf. Ser.*, vol. 1916, no. 1, 2021, Art. no. 012059.

[15] R. Sirait and G. Wibisono, "Capacity analysis of non-orthogonal multiple access (NOMA) network over Rayleigh fading channel with dynamic power allocation and imperfect SIC," in *Proc. 4th Int. Seminar Res. Inf. Technol. Intell. Syst. (ISRITI)*, Dec. 2021, pp. 7–11.

[16] W. U. Khan, Z. Yu, S. Yu, G. A. S. Sidhu, and J. Liu, "Efficient power allocation in downlink multi-cell multi-user NOMA networks," *IET Commun.*, vol. 13, no. 4, pp. 396–402, Mar. 2019.

[17] Z. J. Ali, N. K. Noordin, A. Sali, F. Hashim, and M. Balfaqih, "Novel resource allocation techniques for downlink non-orthogonal multiple access systems," *Appl. Sci.*, vol. 10, no. 17, p. 5892, Aug. 2020.
[18] M. S. Ali, H. Tabassum, and E. Hossain, "Dynamic user clustering and power allocation for uplink and downlink non-orthogonal multiple access (NOMA) systems," *IEEE Access*, vol. 4, pp. 6325–6343, 2016.
[19] L. Hu, R. Shi, S. Huang, Q. Wu, W. Hu, and Z. Chen, "Research on throughput optimization of NOMA system with cooperative full duplex relay," in *Proc. IEEE 5th Inf. Technol., Netw., Electron. Autom. Control Conf. (ITNEC)*, vol. 5, Oct. 2021, pp. 651–655.
[20] R. Chen, F. Shu, K. Lei, J. Wang, and L. Zhang, "User clustering and power allocation for energy efficiency maximization in downlink non-orthogonal multiple access systems," *Appl. Sci.*, vol. 11, no. 2, p. 716, Jan. 2021.
[21] W. U. Khan, J. Liu, F. Jameel, V. Sharma, R. Jäntti, and Z. Han, "Spectral efficiency optimization for next generation NOMA-enabled IoT networks," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 15284–15297, Dec. 2020.
[22] G. Wu, W. Zheng, Y. Li, and M. Zhou, "Energy-efficient power allocation for IoT devices in CR-NOMA networks," *China Commun.*, vol. 18, no. 4, pp. 166–181, Apr. 2021.
[23] F. Kara and H. Kaya, "Improved user fairness in decode-forward relaying non-orthogonal multiple access schemes with imperfect SIC and CSI," *IEEE Access*, vol. 8, pp. 97540–97556, 2020.
[24] X. Gong, X. Yue, and F. Liu, "Performance analysis of cooperative NOMA networks with imperfect CSI over Nakagami-m fading channels," *Sensors*, vol. 20, no. 2, p. 424, Jan. 2020.
[25] A. Tregancini, C. H. M. Lima, E. E. B. Olivo, and H. Alves, "Performance analysis framework for NOMA systems over non-identical Nakagami-m fading channels," in *Proc. 16th Int. Symp. Wireless Commun. Syst. (ISWCS)*, Aug. 2019, pp. 150–154.
[26] Y. Xu, B. Li, N. Zhao, Y. Chen, G. Wang, Z. Ding, and X. Wang, "Coordinated direct and relay transmission with NOMA and network coding in Nakagami-m fading channels," *IEEE Trans. Commun.*, vol. 69, no. 1, pp. 207–222, Jan. 2021.
[27] L. Bhardwaj, R. K. Mishra, and R. Shankar, "Sum rate capacity of non-orthogonal multiple access scheme with optimal power allocation," *J. Defense Model. Simul., Appl., Methodol., Technol.*, vol. 19, no. 4, pp. 759–769, Oct. 2022.
[28] T. Chulajata and P. Sedtheetorn, "Theoretical analysis on spectral efficiency of non orthogonal multiple access in Nakagami fading," in *Proc. IEEE Int. Conf. Control Syst., Comput. Eng. (ICCSCE)*, Nov. 2015, pp. 146–149.
[29] X. Wang, J. Wang, L. He, and J. Song, "Outage analysis for downlink NOMA with statistical channel state information," *IEEE Wireless Commun. Lett.*, vol. 7, no. 2, pp. 142–145, Apr. 2018.
[30] T. M. Hoang, B. C. Nguyen, and X. N. Tran, "Outage probability and ergodic capacity of user clustering and beamforming MIMO-NOMA relay system with imperfect CSI over Nakagami-*m* fading channels," *IEEE Syst. J.*, vol. 15, no. 2, pp. 2398–2409, 2020.
[31] Ashish, I. Kumar, and R. K. Mishra, "Performance analysis for wireless non-orthogonal multiple access downlink systems," in *Proc. Int. Conf. Emerg. Frontiers Elect. Electron. Technol. (ICEFEET)*. IEEE, 2020, pp. 1–6.
[32] H. Zuo and X. Tao, "Power allocation optimization for uplink non-orthogonal multiple access systems," in *Proc. 9th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2017, pp. 1–5.



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