NON-ORTHOGONAL MULTIPLE ACCESS FOR UNMANNED AERIAL VEHICLE COMMUNICATION SYSTEM

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DEDICATION

I dedicate this thesis to all the affectees of Covid-19 in the world. May Allah bless us with His greatest mercy and safeguard humanity in these catastrophic times of loss and suffering. Ameen.

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ABSTRACT

The Unmanned Aerial Vehicle (UAV) assisted communication systems provide users a unique connectivity platform to support high data traffic demand of the future. However, the practical proliferation of the aerial nodes is highly involved in finding solutions to the challenges of low spectral efficiency and limited energy reserves of the system. In spite of the fact that the power domain Non-Orthogonal Multiple Access (NOMA) has established its proficiency for the next generation terrestrial wireless networks, the design and validation of NOMA's performance are still needed in the new perspective of an aerial Base Station (BS) deployment. Hence, the thesis investigates the capability of NOMA as a promising candidate for future aerial communication systems with the objectives to maximize jointly data-rate, coverage, and energy efficiency of the system. First, NOMA's feasibility is established by formulating the problem of achievable sum-rate constituting a joint function of power allocation and UAV-BS altitude. Then, a constrained coverage expansion methodology, facilitated by the increase of NOMA user-rate is proposed. Next, a swarm intelligence based user-pairing strategy jointly optimized with UAV altitude and user power allocation is devised to minimize the transmission power of the aerial system. Finally, the formulated non-linear fractional programming problem of energy efficiency maximization is solved using a nested Dinkelbach's structure. Taken together, the presented results manifest that NOMA performs better than the baseline scheme of Orthogonal Multiple Access (OMA). Particularly, the proposed NOMA schemes achieve 30% coverage radius expansion, 18% spectral efficiency enhancement, and 25% transmission power reduction compared to OMA. In addition, two times improvement in energy efficiency is observed for the NOMA system as it achieves 3 bps/joule compared to 1.5 bps/joule of OMA in dense-urban deployment. In conclusion, the research findings prove the proficiency of NOMA for future aerial communication systems.

ABSTRAK

Sistem komunikasi yang dibantu Pesawat Tanpa Pemandu (UAV) menyediakan pengguna satu platform kebersambungan yang unik untuk menyokong permintaan lalu lintas data tinggi pada masa depan. Walau bagaimanapun, pengembangbiakan praktikal nod aerial sangat bergantung kepada pencarian penyelesaian terhadap cabaran kecekapan spektrum rendah dan tenaga simpanan sistem yang terhad. Walaupun Capaian Berbilang Bukan Ortogon (NOMA) domain kuasa telah mem-buktikan kecekapannya untuk rangkaian daratan wayarles generasi akan datang, reka bentuk dan pengesahan prestasi NOMA masih diperlukan dalam perspektif baru penggunaan Stesen Asas (BS) udara. Oleh itu, tesis ini menyiasat kemampuan NOMA sebagai calon untuk sistem komunikasi aerial masa depan dengan objektif untuk memaksimumkan bersama kadar data, liputan, dan kecekapan tenaga sistem. Pertama, kebolehlaksanaan NOMA diwujudkan dengan merumuskan masalah jumlah kadar yang dapat dicapai sebagai fungsi peruntukan kuasa dan altitud UAV-BS. Kemudian, metodologi pengembangan liputan terhad yang dipermudah oleh kenaikan kadar pengguna NOMA dicadangkan. Seterusnya, strategi berpasangan pengguna berdasarkan kecerdasan kerumunan dioptimumkan bersama dengan altitud UAV dan peruntukan tenaga pengguna direka untuk meminimumkan kuasa penghantaran sistem aerial. Akhirnya, pemaksimuman kecekapan tenaga yang dirumuskan sebagai masalah pengaturcaraan pecahan tidak linear diselesaikan dengan menggunakan teknik struktur Dinkelbach yang bersarang. Secara keseluruhan, hasil kajian yang dibentangkan menunjukkan bahawa NOMA mempunyai prestasi yang lebih baik daripada skim garis tapak Capaian Berbilang Ortogon (OMA). Khususnya, skim NOMA yang dicadangkan mencapai pengembangan jejari liputan sebanyak 30%, peningkatkan kecekapan spektrum sebanyak 18% dan pengurangan kuasa penghantaran sebanyak 25% dibandingkan dengan OMA. Tambahan pula, peningkatan kecekapan tenaga sebanyak 2 kali diperhatikan bagi sistem NOMA yang mencapai 3 bps/joule jika dibandingkan dengan 1.5 bps/ joule yang dicapai oleh OMA di aturan kedudukan bandar padat. Secara kesimpulan, dapatan kajian membuktikan kecekapan NOMA untuk sistem komunikasi aerial masa depan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3-D	–	Three-Dimensional
3GPP	–	3rd Generation Partnership Project
4G	–	Fourth Generation
5G	–	Fifth Generation
A2A	–	Air To Air
A2G	–	Air To Ground
B5G	–	Beyond Fifth Generation
BS	–	Base Station
CDC	–	Counts of Dimensions to be Changed
CR	–	Cognitive Radio
CSI	–	Channel State Information
CSO	–	Cat Swarm Optimization
D2D	–	Device-to-Device
DL	–	DownLink
HAP	–	High Altitude Platform
IoT	–	Internet of Things
ITU	–	International Telecommunication Union
LAP	–	Low Altitude Platform
LOS	–	Line Of Sight
MIMO	–	Multiple Input Multiple Output
MINLP	–	Mixed Integer Non-Linear Programming
mmWave	–	millimeter Wave
MR	–	Mixture Ratio
NLFP	–	Non-Linear Fractional Programming

NLOS	–	Non-Line Of Sight
NOMA	–	Non-Orthogonal Multiple Access
OMA	–	Orthogonal Multiple Access
PSO	–	Particle Swarm Optimization
PU	–	Primary User
QoS	–	Quality of Service
RAT	–	Radio Access Technology
ROI	–	Region Of Interest
SI	–	Swarm Intelligence
SIC	–	Successive Interference Cancellation
SM	–	Seeking Mode
SMP	–	Seeking Memory Pool
SNR	–	Signal to Noise Ratio
SRD	–	Seeking Range of the selected Dimensions
SU	–	Secondary User
TM	–	Tracing Mode
UAV	–	Unmanned Aerial Vehicle
UL	–	UpLink

LIST OF SYMBOLS

$\mathcal{N}_U$	–	Set of all the users in the coverage area
N	–	The number of users in the coverage area
R_c	–	Coverage radius
(x_0, y_0)	–	The Cartesian coordinates of the UAV-BS vertical projection in the coverage region
H	–	Altitude of the UAV-BS
H_O	–	Altitude of the OMA based UAV-BS
H_N	–	Altitude of the NOMA based UAV-BS
H_O^*	–	Optimum altitude of the OMA based UAV-BS
H_N^*	–	Optimum altitude of the NOMA based UAV-BS
H^{min}	–	The minimum allowed operational altitude for the UAV-BS
H^{max}	–	The maximum allowed operational altitude for the UAV-BS
D_j	–	Horizontal distance between the vertical projection of the UAV-BS and the $j\,th$ user
X_j	–	Distance between the UAV-BS and the $j\,th$ user
θ_j	–	Elevation angle between the UAV-BS and the $j\,th$ user
$Pr_j(LOS)$	–	Probability of having a Line of Sight communication channel between the UAV-BS and the $j\,th$ user
$Pr_j(NLOS)$	–	Probability of having a Non-Line of Sight communication channel between the UAV-BS and the $j\,th$ user
(α, β)	–	Environment scaling factors for the computation of probability of Line of Sight communication channel
$\varkappa_{LOS}$	–	Excessive path loss for LOS communication channel
$\varkappa_{NLOS}$	–	Excessive path loss for NLOS communication channel
L_j	–	Path loss between the UAV-BS and the $j\,th$ user

$\overline{L}_j$	–	Mean path loss between the UAV-BS and the jth user
h_j	–	Channel between the UAV-BS and the jth user
Ω	–	Free-space path loss exponent
P_T	–	Transmission power
δx_j	–	User message signal.
δy_j	–	Signal received at the jth user
n_j	–	Additive White Gaussian Noise
P_n	–	Noise power
γ	–	Signal to Noise Ratio
Δ	–	Multiplexing loss of OMA
m	–	Weight of the UAV-BS
g	–	Acceleration due to gravity of Earth.
P_{climb}	–	Minimum power of the UAV-BS motor
v_{climb}	–	Velocity of the UAV-BS to climb a given altitude
E_{climb}	–	Energy required by the UAV-BS to climb a given altitude
E_{hover}	–	Energy required by the UAV-BS to hover at a given altitude
t_{hover}	–	Hovering time of the UAV-BS at a given altitude
E_O	–	Energy required for OMA based UAV-BS
E_N	–	Energy required for NOMA based UAV-BS
ΔE	–	Difference between energies for OMA and NOMA based UAV-BSs
Δh	–	Difference between operational altitudes for OMA and NOMA based UAV-BSs
ψ	–	Minimum power needed by the UAV-BS to hover just above the ground
Γ	–	Motor speed multiplier
P^{max}	–	Maximum allowed transmission power per channel resource

P_r	–	Allocated transmission power to the $r\,th$ NOMA user
P_s	–	Allocated transmission power to the $s\,th$ NOMA user
ω_r	–	Transmission power allocation coefficient for the $r\,th$ NOMA user
ω_s	–	Transmission power allocation coefficient for the $s\,th$ NOMA user
Υ_r^N	–	The achievable data-rate by the $r\,th$ NOMA user
Υ_s^N	–	The achievable data-rate by the $s\,th$ NOMA user
Υ_r^O	–	The achievable data-rate by the $r\,th$ OMA user
Υ_s^O	–	The achievable data-rate by the $s\,th$ OMA user
(μ_1, μ_2)	–	Tuning coefficients
τ	–	Total coverage area of the UAV-BS
$\overline{\boldsymbol{P}}_T$	–	Power allocation vector for all user-pairs
$\boldsymbol{U}$	–	NOMA user-pairing matrix
$\boldsymbol{C}_k$	–	Positon matrix of the $k\,th$ cat
$\boldsymbol{V}$	–	Velocity matrix for each cat's position
(v_{min}, v_{max})	–	Minimum and maximum velocity limits, respectively
$\boldsymbol{F}$	–	Binary flag vector allocating operational modes to each cat
(w^{max}, w^{min})	–	Maximum and minimum inertia weights, respectively
η_{EE}	–	Energy efficiency of UAV-BS utilizing the sum of energy consumption during signal transmission and hover operation
$[a,b]_{Feasible}$	–	The range of feasible altitude range of the NOMA based UAV-BS given the constraints

CHAPTER 1

INTRODUCTION

1.1 Background and motivation

The future wireless networks promise to provide ubiquitous connectivity to a multitude of devices with diversified traffic patterns wherever and whenever needed. Particularly, an economically viable and agile multifaceted connectivity platform is the primary requisite for successful future generation wireless networks. Hence, a renewed interest in adopting the Unmanned Aerial Vehicle (UAV) assisted communication systems for a broad range of civil applications has been witnessed in the last few years [1]. Among many use cases of UAV communication systems such as coverage enhancing relays [2] and data disseminating flying nodes [3], a UAV Base Station (BS) deployment may also be necessitated by the presence of coverage holes in the absence of a terrestrial BS caused by a malfunctioning or a natural catastrophe [4]. The UAV-BS equips the means to swiftly deploy recovery networks, which connects the first responder personnel in a case of natural calamity when the terrestrial network is partially or entirely malfunctioning [5]. The UAV assisted communication systems, if appropriately designed, are envisioned to support the spatially as well as temporally volatile traffic surges in the coverage area without relying on the overly-engineered cellular network [6].

Irrespective of the deployment scenario, the flexible placement with dynamic adaptability to the changing communication scenarios and diversified user Quality of Service (QoS) requirements has set UAV communication systems to become an essential component of the ubiquitously connected Fifth Generation (5G) and Beyond Fifth Generation (B5G) wireless networks [7]. However, the incorporation for UAV communication system to reap all the captivating benefits for future wireless communication networks needs thoughtful deliberation over the many challenges diminishing this synergy. Notably, the issue of optimal deployment for the objectives of maximized coverage, capacity, and energy efficiency is of a paramount importance in the UAV realm. Though beneficial, the extra degree of freedom facilitated by the almost unrestricted mobility makes an optimal deployment of the UAV significantly more complicated compared to its terrestrial counterpart.

Particularly, the design and performance of UAV communication systems is highly characterized by the deployment objective and the environment profile of the coverage area. Furthermore, the spatial distribution of users as well as the Air To Ground (A2G) communication channel, defined by the UAV altitude are needed to be explicitly taken into account for the optimal deployment of the UAV communication system. In addition, the performance of the UAV systems is often limited by deficient onboard energy reserve. The energy reserve of a UAV is needed for flight operation, communication, and computation purposes, where an inefficient utilization of this reserve not only reduces the air operational time of the UAV, but also effects the performance of the wireless communication system [8]. Thus, it is imperative to even include energy efficiency as a critical parameter in the design of a UAV communication system.

On the other hand, the last few years have seen exceptional growth in the wireless data traffic demand that is contemplated to reach a staggering 77 Exabytes per month by 2022[1]. Classic Orthogonal Multiple Access (OMA) schemes such as Time Division Multiple Access in Second Generation, Code Division Multiple Access in Third Generation, and Orthogonal Frequency Division Multiple Access in Fourth Generation (4G), require each user to be served with a dedicated resource either in time, frequency, or code domain. This yields sub-optimal channel resource utilization and increased latency for the connected devices. Subsequently, the challenging massive spectral efficient connectivity requirements for the 5G/B5G wireless networks is often restricted by the available orthogonal channel resources.

Therefore, the high-density presence of users sharing the limited physical radio resources has motivated the development of 5G enabling technologies such as massive

[1]Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017-2022", Cisco public (2019).

Multiple Input Multiple Output (MIMO), millimeter Wave (mmWave), and Device-to-Device (D2D) communication [9]. Meanwhile, the same prognosis has directed investigations on a Radio Access Technology (RAT) called Non-Orthogonal Multiple Access (NOMA) that opportunistically serves multiple users within the same channel resource block utilizing a novel domain of power control, superposition coding, and Successive Interference Cancellation (SIC) [10–17]. NOMA has been proved to exhibit improved spectral efficiency as well as balanced and fair access as compared to OMA technologies which mostly benefits the user with more favourable channel condition [15, 16, 18]. Additionally, NOMA with the exploitation of a new dimension of power is an add-on technology that is able to operate in conjunction with other techniques in the multiple access paradigm. For instance, NOMA renders a meaningful reduction in interference by extending intra-cluster access for the users sharing the same orthogonal resource or beam for inter-cluster access [19, 20]. Undoubtedly, NOMA provides the means to meet the challenging 5G envisioned requirements of the Internet of Things (IoT) of ultra-low latency and ultra-high connectivity.

In contrast, the analyses of the potentials and challenges arising with the choice of RAT for UAV assisted communication systems have been conventionally constrained to OMA [21–23]. Specifically, NOMA is a promising solution to challenges encompassing the next generation wireless networks and finds its applications in technologies envisioned to support 5G/B5G key technologies [24] such as massive MIMO [13, 25, 26]. However, the incorporation of NOMA for UAV communication remained unexplored [27, 28] before the preliminary work by Sohail *et al.* reported in [29]. In view of fundamental differences in working principles of OMA and NOMA, current studies are not directly applicable to NOMA based UAV communication systems and several challenges must be addressed before gauging its effectiveness for the UAV communication systems. Henceforth, NOMA scheme with its share of benefits is investigated in the thesis for typical deployment scenario of an aerial BS, where the aspects of improved throughput, coverage, and energy efficiency are addressed.

1.2 Problem statement

As discussed, NOMA holds the key essence on the fruitful deployment of UAV communication systems for harmonized coverage and capacity in the 5G and B5G wireless networks [30]. Nonetheless, the aspects of power allocation and the corresponding user channel characteristics commonly associated to the performance gain of terrestrial NOMA wireless networks are to be viewed within the new perspective of an aerial BS deployment. Of particular interests are the characteristics of the A2G channel and its effect on the UAV-user link based on their respective location in the coverage region [31]. The following presents the problem statements associated with investigated case of NOMA based UAV-BS communication system.

1.2.1 The problem of UAV-BS altitude and NOMA user power allocation

According to the widely adopted A2G channel model [32], the increasing altitude of the UAV also increases the probability of establishing Line Of Sight (LOS) communication links between the UAV-BS and terrestrial users. However, the increment in altitude of the UAV-BS also results in increased path loss between the communicating nodes. Hence, an optimal vertical placement of the UAV-BS that balances between higher probability of LOS and path loss is to be computed for the attainment of specific objectives such as maximized throughput as presented in [21]. Conventionally, the methodologies presented in [21, 33] are primarily devised for OMA and propose to improve channel condition for the cell-edge user in the coverage region. The improvement of cell-edge user's channel condition generates minimum difference between channel state of the users in the coverage area, which is fundamentally different to the working principle of NOMA communication systems and further investigation regarding optimal altitude placement of an NOMA system need further investigation [34]. Thus, it may hamper the anticipated benefits of NOMA transmission [35]. Specifically, the performance of NOMA is highly dependent upon the asymmetric channel conditions of the users selected for NOMA transmission [36]. In contrast, the improvement of cell-center user channel condition through altitude optimization can be utilized to achieve maximum difference in the channel state of the

NOMA users for increased gains as compared to OMA based aerial nodes. In addition, NOMA relying on SIC and NOMA user power allocation holds a significant place to create balance between capacity and fair access of the system [37]. As an alternative to the fixed power allocation schemes [38, 39], the potential gains of NOMA for aerial communication system may be maximized by dynamically adjusting user power allocation in accordance to changing altitude of the UAV-BS. The dynamic NOMA power allocation schemes in [40], [41], and [42] were proposed to simultaneously meet the data-rate thresholds for both NOMA users. However, the devised methodologies cater for fixed altitude terrestrial wireless communication networks, which are not trivial to extend for the aerial NOMA communication systems. Therefore, the thesis investigates a novel altitude displacement scheme to generate distinctive channel conditions between the paired users that is jointly optimized with the dynamic power allocation for the objectives of maximal throughput and coverage. Particularly, a NOMA based aerial communication system is proposed to surpass the sum-rate of the system achievable by an equivalent OMA scheme as proposed in [23] and [33]. Moreover, a performance comparison of the proposed scheme is also presented with the a terrestrial NOMA system having fixed altitude and power allocation scheme [43].

1.2.2 The problem of NOMA user-pairing

To this end, the work in this thesis is proposed to establish the viability of NOMA UAV communication systems by tackling the problem of a two user deployment in the coverage region. However, the evaluation of the case with more than two users in the coverage area raises the question of appropriate user-pairing scheme for the aerial BS. Since the conception of NOMA, a significant number of studies have been conducted to investigate terrestrial NOMA user-pairing and its effect on various performance metrics of the network [44–46]. Nonetheless, the A2G channel gain for the case of aerial networks varies as a function of altitude and imposes an additional complexity of dynamic channel conditions for all users when adjusting altitude for better performance. Although the available literature on terrestrial NOMA user-pairing have laid a strong foundation, further investigations are still needed to determine the appropriate pairing scheme for a NOMA based aerial deployment [47]. Meanwhile, the energy-efficient operation for enhanced mission time has been recognized among the most pressing concerns in the UAV communication realm [48,49]. Consequently, a Particle Swarm Optimization (PSO) based user-pairing methodology was proposed to minimize the required transmission power for an aerial NOMA communication system [50]. However, the authors assumed simplification of fixed altitude for the proposed methodology and the mutual contribution of UAV-BS altitude and NOMA user-pairing optimization remains unexplored in the literature. Specifically, the reported analysis in [50] ignored the inter-dependency between various parameters such as user-pairing, power allocation, and altitude in the problem formulation. Although the presented work evaluates the effect of varying altitude of UAV-BS, no methodology was proposed for optimization of UAV-BS altitude for the considered utility function. Moreover, the user-pairing scheme in [50] failed to elaborate the effect of various environmental factors on the performance of NOMA based aerial systems and the presented analysis fails to compare the performance of the proposed scheme with other competing heuristic techniques. Thus, a novel problem of joint optimization of NOMA UAV-BS altitude, power allocation, and user-pairing needs to be investigated for achieving a reduction in the required transmission for the aerial NOMA systems. Moreover, a detailed investigation on the performance of the NOMA UAV-BS based on deployment environment and user-density needs to be conducted for an insightful knowledge.

1.2.3 The problem of NOMA UAV-BS energy efficiency

It is also noteworthy that a significant proportion of the available energy is consumed during the flight operation of a UAV [51]. For instance, Hua *et al.* in [52] and [53] examined iterative strategies to minimize total energy consumption and maximize the secrecy energy efficiency of a fixed-wing UAV-BS, respectively. However, the reported analyses assumed OMA with fixed altitude and the evaluation of secrecy energy efficiency was carried out by considering only the more prominent mobility related energy consumption of a fixed-wing UAV. Meanwhile, the energy efficiency defined as the ratio of achievable sum-rate to the total power consumption has been identified as a core performance metric for the NOMA based wireless networks [54–58]. Fang *et al.* in [54, 55] examined joint user-scheduling and power allocation for the cases of perfect and imperfect Channel State Information (CSI), respectively. A matching theory based channel allocation limited to two users per sub-channel was proposed in [54], whereas the same concept was extended in [55] for the general case of the arbitrary number of users per sub-channel given imperfect CSI. Zamani *et al.* [56] also studied a power allocation based energy efficiency maximization for imperfect CSI, where a value close to optimal total power allocation was computed by leveraging the concept of the difference of two concave functions programming and Dinkelbach's structure. On the other hand, a joint bandwidth and power allocation optimization was conducted by transforming the non-convex problem into a difference of two convex functions problem [58]. However, it is crucial to note the substantial difference between the UAV and terrestrial wireless communication systems in terms of their design and operational characteristics. Different from the terrestrial perspective, the total power consumption of the rotary-wing UAV-BS is computed considering the composite of powers required for the signal transmission and hover operation of the UAV-BS modeled as a linear function of altitude [59, 60]. Secondly, the optimization of UAV-BS specific parameters such as altitude, which is comparable to the problem of channel assignment, imposes an additional complexity of dynamic channel conditions for all users during the optimization. This is in contrast to the conventionally assumed static channel states while optimizing the channel allocation [54]. Furthermore, it is important to observe the tight coupling between altitude and power allocation for conflicting goals of maximized sum-rate, minimized transmission power, as well as efficient flight operation of the UAV-BS. Particularly, a low energy consumption during the hovering operation of the UAV-BS requires a low altitude flight while serving the ground users. On the other hand, the UAV-BS may be required to fly at a relatively higher altitude for lower transmission power allocation to fulfill the QoS thresholds of the users. Consequently, it is not trivial to maximize the information bits per unit energy consumption of the UAV-BS utilizing the existing work that is mainly focused on energy efficiency maximization for terrestrial NOMA based systems.

A summary of the most notable literature that influenced the directions of the thesis is presented as Table 1.1.

Table 1.1 Summary of the open problems in literature

Year	Ref.	Summary	Open problems
2014 2015 2016 2018	[32] [61] [23] [33]	A2G channel gains are dependent on the elevation angle and distance between the ground users and UAV-BS. The optimum altitude for minimum path loss for cell-edge user also maximizes the Signal to Noise Ratio for all OMA users within the coverage region.	An optimal vertical placement of the UAV-BS that balances between LOS and path loss needs further investigation for a NOMA aerial communication system. An altitude optimization methodology to maximize the channel distinctiveness between paired NOMA user for maximum gain needs to devised.
2016 2017 2020	[40] [41] [37]	A fixed power allocation scheme lacks the ability to cater for users with different QoS requirements. Thus, dynamic power allocation strategies are proposed to meet data-rate thresh-old set for all terrestrial NOMA users given a utility function.	A dynamic power allocation strategy is needed to tackle varying channel conditions for changing altitude of the UAV-BS for maximum NOMA gains in comparison to fixed and terrestrial communication system based power allocation strategies.
2019 2019 2019	[44] [47] [50]	The impact of user-pairing on the performance of terrestrial NOMA is highlighted for different utility functions. A PSO based user-pairing scheme is presented for fixed altitude aerial NOMA BS.	A joint optimization of user-pairing, power allocation, and altitude considering the prevailing A2G channel conditions is neglected in literature, which requires further investigation.
2018 2018 2019	[52] [57] [56]	The ratio of sum-rate to the total power consumption for fixed altitude terres-trial NOMA system is evaluated. The role of UAV flight energy consumption is highlighted.	The energy consumption during the flight operation of the UAV-BS needs to considered in the problem formula-tion. The joint altitude optimization and the corresponding power alloca-tion strategy is required for conflicting goals of energy efficiency maximiza-tion of the NOMA UAV-BS.

1.3 Research objectives

The main objectives of the thesis are listed as:

1. To propose the joint optimization of NOMA UAV-BS altitude and NOMA power allocation for improved throughput and coverage.
2. To propose the joint optimization of NOMA user-pairing and UAV-BS altitude to minimize the total transmission power allocation.
3. To propose the joint optimization of NOMA UAV-BS altitude and NOMA power allocation to maximize the energy efficiency.

1.4 Research Scope

The research work presented in the treatise focuses on establishing NOMA's viability for the UAV assisted communication systems. The identified performance metrics of throughput, coverage, and energy efficiency have been investigated by formulating for each metric of a constrained optimization problem. It is important to note that all the presented analyses have been conducted assuming a DownLink (DL) communication employing a single antenna aided low altitude rotary-wing UAV platform providing coverage to disc-shaped Region Of Interest (ROI). The radii of the ROI is fixed as 60 m, 120 m, and 180 m (unless otherwise stated), where the users in the ROI are also assumed to be equipped with single antenna devices. A single cell scenario has been assumed throughout the thesis, where the effect of co-located cellular network such as interference is excluded from the scope of the presented work. A widely adopted generic A2G channel model is employed to characterize the effect of altitude as well as the deployment environment (rural, urban, and dense urban) towards the performance of the UAV communication system in terms of various metrics under consideration [62, 63]. The channel gains between the UAV-BS and the ground users are dependent on the altitude of the UAV-BS and the position of the users on the ground. Hence, it is assumed that the knowledge of user position is known to the UAV-BS and corresponding channel gains can be computed using the adopted A2G channel model. The energy consumption of the

UAV-BS during the flight operation is modeled as a function of altitude following the work in [59, 60]. The formulated optimization problems in the thesis constrained by multi-QoS requirements pose fair analyses between the OMA and NOMA techniques by following a stringent benchmark for each NOMA user to meet the individual rate threshold attained by a conventional OMA UAV-BS deployment. The numerical analyses including Monte Carlo simulations have been conducted utilizing MATLAB software, where optimization tool such as *fminsearch* and *fmincon* have been applied to solve various unconstrained and constrained convex problems, respectively. The presented results are computed using numerical simulation by performing established models and no field measurement is performed.

1.5 Contributions

Chapter 4 presents a dynamic power allocation strategy for altitude optimized NOMA UAV-BS to maximize its capacity. The optimization problem is formulated as a function of the altitude of the UAV-BS, constrained to meet or exceed the individual user-rates set forth by OMA for the same deployment scenario and target area. The role of altitude for improved NOMA aerial system performance is highlighted, where a lower flight operation compared to an equivalent OMA system is proposed to generate greater throughput. Furthermore, a methodology is devised to render an expansion of the aerial cell coverage, which is facilitated by NOMA user-rate gains. Thus, the high dependency between various optimization parameters such as altitude, power allocation, and user-pairing is identified to influence the achievable gains of NOMA for the aerial system. The findings of Chapter 4 are published as [64].

The Chapter 5 further elaborates the complex inter-dependency of diverse optimization parameters on the overall performance of a NOMA aerial communication system. Thus, a novel scenario involving joint optimization of user-pairing, altitude, and the corresponding power allocation is investigated for optimizing transmission power requirements in terms of the multi-functional objective for a NOMA UAV-BS configuration. A novel hybrid optimization methodology invoking the provisions of the nature-inspired heuristic technique and convex optimization is proposed to solve the formulated Mixed Integer Non-Linear Programming (MINLP) problem. The proposed methodology is the first work to leverage a potential on Cat Swarm Optimization (CSO) in the field of NOMA communication systems. The evidenced reduction in the required transmission power for various communication environments and coverage areas compared to an OMA deployment scenario proves the efficacy of the proposed scheme. The findings of the Chapter 5 are under review process at the Journal of Vehicular Communications, Elsevier.

Finally, the implications of altitude to the overall energy expense during the hovering operation of the UAV-BS is emphasized in the Chapter 6. Henceforth, the effect of altitude is also incorporated in a novel formulation of total energy efficiency of the NOMA UAV-BS. The chapter evaluates the effect of paired users on the operational altitude of the UAV-BS considering pairing between users with the best and worst channel conditions. An exhaustive methodology is devised to determine the feasible altitude range of the UAV-BS for which each user's rate constraint is satisfied within the prescribed transmission power limits. The analyses are further extended by assessing the dependency of the feasible altitude range on a subset of user-pairs and subsequently, a low complexity method to determine the constrained altitude bounds is proposed. The formulated non-convex Non-Linear Fractional Programming (NLFP) problem is solved by employing an alternating optimization technique where at first an energy efficiency maximization problem is solved as a function of altitude by fixing the power allocation to a feasible value. Next, the power allocation is optimized to maximize the objective of energy efficiency by fixing the altitude of the UAV-BS obtained in the previous step. A nested Dinkelbach's structure is opted to solve the NLFP problem and guarantee convergence within an error tolerance limit. The energy efficiency, power allocation, and sum-rates of the proposed NOMA based UAV communication system are evaluated at close to optimum altitude. Explicitly, a lowest possible flying altitude of the UAV-BS is suggested when operating in low Signal to Noise Ratio (γ) regimes to save vital flying energy of the UAV-BS. On the other hand, the NOMA UAV-BS could attain a higher altitude when operating at higher SNR to balance between system throughput and total energy consumption for maximized energy efficiency. Subsequently, the results are compared with the baseline OMA scheme to fortify the better performance of the proposed methodology. Analytical and numerical analyses are demonstrated for the proposed scheme, where results are detailed for various target regions, user-pairing schemes, and deployment environments. Taken together, the proposed scheme achieves improved total energy efficiency in bits/joule. The findings of the Chapter 6 are published as [65].

1.6 Thesis organization

The thesis is organized into following chapters:

Chapter 1 presents a brief introduction to NOMA based UAV communication system followed by the problem statements, associated research objectives, and scope of the thesis.

The classification of UAVs and literature overview of the associated A2G channel model are highlighted in Chapter 2. Henceforth, the chapter discusses some of the most challenging issues related to aerial communication systems in light of the most recent research developments. The chapter also introduces NOMA communication systems, while critical design parameters of power allocation and user-pairing are also analyzed. Next, a brief overview is presented on the state of the art development in the aerial NOMA communication realm. Subsequently, the thesis presents an overview of some of the baseline schemes utilized in the thesis for comparative analyses. Finally, the chapter concludes by discussing the optimization technique utilized in the thesis for various problems.

In Chapter 3, the first section elaborates the overall system modeling by detailing the spatial distribution, A2G channel, and energy consumption model of the aerial communication system. The next section portrays the transmission scheme of the aerial NOMA used in this thesis for performance analysis of the proposed schemes. Finally, the chapter introduces the formulated optimization problems and list the main constraints considered for the formulated problems in the thesis.

A two user model of an aerial NOMA communication system is examined in Chapter 4 of the dissertation. The proposed dynamic power allocation schemes jointly optimized with altitude of the NOMA based UAV-BS are evaluated for the objectives of achievable sum-rate and coverage maximization. The results are presented for both optimized and fixed altitude schemes, where superior performance of NOMA in comparison to OMA scheme is established.

The Chapter 5 extends the NOMA UAV-BS design to a multi-user scenario of a NOMA UAV-BS deployment. The problem of transmission power minimization is formulated as a highly non-convex joint function of user-pairing, power allocation and altitude of the NOMA based UAV-BS. The chapter highlights the high dependence between each design parameter and an iterative CSO based user-pairing strategy is illustrated.

The Chapter 6 explores the notion of total energy efficiency for a multi-user scenario of a NOMA UAV-BS, where a novel bit per energy consumption maximization problem is investigated. The chapter presents a detailed analyses on the feasible altitude range of the NOMA UAV-BS given a best-worst user-pairing scheme. Subsequently, the highly non-convex optimization problem is solved employing a nested Dinkelbach's framework. The result are presented at the end to manifest the improved energy efficiency of the proposed scheme.

Chapter 7 concludes the dissertation. Finally, a discussion on open research issues related to aerial communication systems is furnished.

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LIST OF PUBLICATIONS

Journal with Impact Factor

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Indexed conference proceedings

1. M. F. Sohail and C. Y. Leow, "Maximized fairness for NOMA based drone communication system," 2017 IEEE 13th Malaysia International Conference on Communications (MICC), Johor Bahru, 2017, pp. 119-123.