ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

ENERGY AWARE ENDURANCE FRAMEWORK FOR MISSION CRITICAL AERIAL NETWORKS

Ph.D. THESIS

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Department of Computer Engineering

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Thesis Advisor: Assoc. Prof. Dr. Berk CANBERK

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

GÜDÜMLÜ HAVASAL AĞLAR İÇİN ENERJİ FARKINDA ENDÜRANS MODELİ

DOKTORA TEZİ

Yusuf ÖZÇEVİK
(504152517)

Bilgisayar Mühendisliği Anabilim Dalı

Bilgisayar Mühendisliği Programı

Tez Danışmanı: Assoc. Prof. Dr. Berk CANBERK

ARALIK 2019

Yusuf ÖZÇEVİK, a Ph.D. student of ITU Graduate School of Science Engineering and Technology 504152517 successfully defended the thesis entitled "ENERGY AWARE ENDURANCE FRAMEWORK FOR MISSION CRITICAL AERIAL NETWORKS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Assoc. Prof. Dr. Berk CANBERK** Istanbul Technical University	....
Jury Members :	**Prof. Dr. Sema Fatma OKTUĞ** Istanbul Technical University	....
	Prof. Dr. Özgür Barış AKAN Koç University	....
	Assoc. Prof. Dr. Feza BUZLUCA Istanbul Technical University	....
	Assoc. Prof. Dr. Muhammed Ali AYDIN Istanbul University	....

Date of Submission : 27 November 2019
Date of Defense : 13 December 2019

To my spouse and family,

FOREWORD

First of all, I owe a debt of gratitude to my advisor, Assoc. Prof. Dr. Berk CANBERK. I would like to send my special thanks to him not only for being my advisor, but also a significant person for my career during the period over a decade. He always encouraged and inspired me to keep going on my academic career and always had a pretty understanding about my demands when I had some busy periods with other jobs. It is a great pleasure and an honor to be one of the PhD graduates in his research group named Broadband Communication Research Group, BCRG. It was a significant experience for my career to be a member of this group during my BSc, MSc, and PhD period in Computer Engineering Department of Istanbul Technical University. I believe wholeheartedly that we will catch more academic success in BCRG, together.

Secondly, I would like to thank my thesis committee Prof. Dr. Sema OKTUĞ and Prof. Dr. Özgür Barış AKAN. Their precious suggestions and valuable comments for each period of my thesis guided me to improve the quality and intelligibility of my thesis. I would like to thank them for being always available and for their kindly attitude against all my questions. It was an honor to have the opportunity of discussing my researches together. I have obtained a great vision for my future career from what I have learned from them.

Thirdly, I want to give another thank to all BCRG member, and especially the former PhD graduates Dr. Gökhan SEÇİNTİ and Dr. Müge ÖZÇEVİK. Moreover, I am also grateful to all my former colleagues working in Computing Department of Istanbul Technical University, and Computer Engineering Department of Istanbul Technical University. My colleagues were always kind to me and my directors always had a great understanding to allocate time for my PhD study.

Fourthly, I would also like to acknowledge that BAP Unit of Istanbul Technical University supports my thesis with a project identified by the number: 41757.

Lastly and foremost, I would like to thank my lovely family, especially to my wife Müge ÖZÇEVİK, her parents, my sister and my parents. I always felt their unending support in difficult times and I owed all of my achievements to them. In definite, I could not have achieved my current level of success without their support. Thanks for all.

December 2019

Yusuf ÖZÇEVİK
Computer Engineer, M.Sc.

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ABBREVIATIONS

3D : Three Dimensional
3GPP : The 3rd Generation Partnership Project
A2A : Air to Air
A2G : Air to Ground
ABS : Aerial Base Station
ACO : Ant Colony Optimization
APDP : Aerial Pick-up and Delivery Problem
CAGR : Compound Annual Growth Rate
CAS : Cost Assignment Strategy
DP : Dynamic Programming
FANET : Flying Ad Hoc Network
GA : Genetic Algorithms
GPU : Graphical Processing Unit
HALE : High Altitude - Long Endurance
HTTP3 : Hypertext Transfer Protocol Version 3
ILP : Integer Linear Programming
IoT : Internet of Things
MAVLink : Micro Air Vehicle Link
LALE : Low Altitude - Long Endurance
LASE : Low Altitude - Short Endurance
LiPo : Lithium Polymer
LSN : Linear Sensor Network
LTE : Long Term Evolution
NRT : Non-real Time
MALE : Medium Altitude - Long Endurance
MANET : Mobile Ad Hoc Network
PDP : Pick-up and Delivery Problem
SDN : Software Defined Networking
SITL : Software in the Loop
SN : Sensor Node
TSP : Traveling Salesman Problem
QoE : Quality of Experience
QoS : Quality of Service
QUIC : Quick UDP Internet Connections
U2I : UAV to Infrastructure
U2U : UAV to UAV
UAV : Unmanned Aerial Vehicle
UDN : Ultra Dense Network
UDP : User Datagram Protocol
VANET : Vehicular Ad Hoc Network
WSN : Wireless Sensor Network
VNI : Visual Networking Index

SYMBOLS

δ	**:** Normalized energy consumption
γ	**:** Number of terrestrial replenishments, Replenishment Factor
γ_i	**:** Number of replenishments for i^{th} ABS
η	**:** Average Endurance per Drone
ψ	**:** Number of end-system initiated handovers, Handover Factor
A	**:** Attributes of an ABS
c_{ij}	**:** Cost of the path between V_i and V_j
$cost(s,d)$	**:** Function to compute path traverse cost between two vertices
d_i	**:** Destination vertex parameter for *cost* function
d_{ij}	**:** Binary decision variable indicating V_i-V_j edge is traversed or not
E	**:** Edges in the graph
f	**:** Fitness value in Temporal Flight Planner
G	**:** The topology graph
h_t	**:** The Handover Factor threshold
i,j	**:** Indexes to represent i^{th} or j^{th} entity
l_t	**:** Binary load variable approving at most one ABS at each vertex
N	**:** The number of ABSs in the network
p	**:** A population investigated in Temporal Flight Planner
p_0	**:** The initial population for Temporal Flight Planner
P_{con}	**:** Total power consumption with a conventional approach
P_i	**:** Power consumption of i^{th} entity
P_{pro}	**:** Total power consumption with the proposed approach
r	**:** Relaxation value used in Spatial Flight Planner
s_c	**:** The solution candidate set generated by Temporal Flight Planner
s_d	**:** The discarded solution set for Temporal Flight Planner
s_i	**:** Source vertex parameter for *cost* function
s_u	**:** Set of end-users in each ABS cluster
t	**:** A certain moment in network operational duration
t_e	**:** Estimated operational time for the aerial network
t_r	**:** Remaining operational time used in simulation
x,x'	**:** x value for the location of an ABS in coordinate system
V	**:** Vertices in the graph
V^c	**:** The predefined ABS locations in the topology
y,y'	**:** y value for the location of an ABS in coordinate system
z,z'	**:** z value for the location of an ABS in coordinate system
$\mathbb{Z}i$	**:** Positive integer set

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**ENERGY AWARE ENDURANCE FRAMEWORK
FOR MISSION CRITICAL AERIAL NETWORKS**

SUMMARY

The number of networked mobile devices has increased excessively all around the world and the data traffic requests generated by such devices has begun to overwhelm conventional network infrastructures, recently. At the same time, the proliferation of Unmanned Aerial Vehicles (UAV) in different application areas has also increased. Eventually, these two concepts have been interacting with each other in these days and UAVs becomes one of the most popular tools interacting with computer networking to compose aerial networks. The deployment of such networks provides a flexible and efficient management of traffic requests with a mission specific temporary intention, especially for short duration scenarios. Beside the opportunities provided in aerial networks, there are some major challenges should be carefully recognized to provide the existence of the network in a reasonable and proper way. Energy awareness is one of the major challenges in aerial networks to provide a longer endurance with minimum maintenance cost. There is a considerable amount of interest in the literature to provide energy efficiency for an aerial network. However, the compulsory energy demand to maintain the existence on the air is neglected in most of them. Thus, in the thesis, the major energy consumer of an aerial network is determined as the flying capability and an energy aware endurance framework is presented by taking the flight path planning into account.

The energy awareness for a flight planning in an aerial network can be understand in a proper way by considering the fact that there is a relation between energy consumption and flight characteristic of a UAV. The physical forces exposed by a UAV determine the amount of energy consumption during a path traversal. For this purpose, an energy consumption related topology graph is presented in the thesis by accounting a digraph model that has a UAV in each vertex and also has energy consumption cost on each edge. The gravity force is taken into account for graph modeling because of being the determinant one that cause a compulsory energy consumption and three different digraph model are presented for the validation of the proposed approach. Moreover, an Aerial Pick-up and Delivery Problem (APDP) is presented with Integer Linear Problem (ILP) to provide an optimization problem and to recommend a solution set with an algorithmic approach. Considering the graph model provided, a Spatial Flight Planner is implemented using Bellman-Ford algorithm with Dynamic Programming (DP) approach and a flight planning is provided with minimum energy consumption cost when new flight routes is required in the topology at a certain time t. A further improvement is presented in the proposed model with another flight planning algorithm named Temporal Flight Planner that considers the entire operational time of the aerial network and seeks out not only the minimum energy consumption at time t, but also the global search space. The Genetic Algorithms (GA) fashion is utilized to implement Temporal Flight Planner in order to prune some of the solution candidates in the

enlarged search space and respond in a reasonable amount of time. Subsequent to the implementation, a complexity analysis for time and memory requirements of the algorithms is also conducted and it is presented that the outcomes are restricted within an appropriate boundary considering the deployment purposes of studied scenarios.

A certain case study is presented to evaluate the proposed framework and compare it with a conventional replenishment approach that does not take any information about the topology into account. To this end, three different scale of simulation scenarios and a set of simulation tools are introduced for the evaluation. Moreover, the assumptions about the network architecture is presented clearly and the type of UAVs to be deployed are determined as rotary wings i.e. drones. Eventually, the energy awareness for the end-system perspective is evaluated with respect to a normalized energy consumption value during the operational time (δ), the number of total replenishments between the ground and air named as the replenishment factor (γ), and an average endurance per drone (η). According to the evaluation outcomes, up to 20% less δ value is obtained that corresponds to a remarkable amount of energy saving with the deployment of the proposed framework to compared with a conventional one. Similarly, γ value is decreased with a ratio up to 15% and η value is increased with 18% indicating less number of terrestrial replenishments and more average endurance per drone, respectively. Moreover, considering the stochastic improvement characteristic of evolutionary algorithms, an investigation for GA implementation is conducted to determine the optimality closeness of the provided solution to the global optimum. As a consequence, it can be inferred from the evaluation that the proposed framework is able to provide an energy aware topology maintenance compared with a conventional replenishment approach and the implementation of the proposed framework using evolutionary algorithms does not damage the optimality of provided solutions; rather, it helps to respond in more reasonable duration.

The effect of the proposed framework from an end-user perspective is also investigated because it is reported during the simulations that the proposed solution includes some replacement between the drones on the air. Hence, this situation corresponds a more number of end-system initiated handovers for a terrestrial end-user in average. To this end, the number of end-system initiated handovers i.e. the handover factor (ψ) is investigated for both of the proposed model and a conventional one. A difference up to 14% is reported between these two approaches where the proposed model causes more handovers. Accordingly, the effect of number of end-system initiated handovers is examined with respect to some end-user Quality of Experience (QoE) parameters including average access link latency and packet loss ratio. A heterogeneous end-user traffic generated by real time and non-real time applications is considered in the evaluation. According to the evaluation results, it is presented that the proposed framework causes 10% more average access link latency and 19% more packet loss ratio. As a conclusion, it is deduced from the evaluation that the proposed framework provides causes a disruption on end-user perspective whereas it provides a significant amount of energy saving from the end-system perspective. The trade off between them is also verified in the literature and a Handover Factor Optimizer algorithm is appended to the proposed framework in order to bound the deterioration inside admissible level through a predefined handover factor value. The analyzes for the additional algorithm is also presented.

A final investigation is conducted for the effect of the proposed framework on the end-user parameters under different traffic request including only real time traffic requests and non-real time traffic requests. Hence, the deterioration level for different traffic requests is identified and feasibility of the proposed framework is questioned. According to the evaluation results, it is seen that there are more access link latency and packet loss ratio under the case with non-real time traffic requests. Nonetheless, the application field for the proposed system and scenarios studied in the thesis are real time in general because of recent application protocols used by terrestrial end-users such as Hypertext Transfer Protocol Version 3 (HTTP3) and Quick User-Datagram-Protocol (UDP) Internet Connections (QUIC). As a consequence, it can be claimed that the performance degradation of an end-user for both traffic types are in acceptable level considering the energy savings in the end-system.

GÜDÜMLÜ HAVASAL AĞLAR İÇİN ENERJİ FARKINDA ENDÜRANS MODELİ

ÖZET

Cisco teknik raporuna göre (Visual Networking Index, VNI), internete bağlı hareketli cihaz sayısı dünya genelinde hızla artmaktadır. Rapora göre, 2017 yılında 8.6 milyar olarak tespit edilen cihaz sayısının 2022 yılı itibarıyla 12.3 milyara ulaşması beklenmektedir. Cihaz sayısında öngörülen artış dikkate alındığında, bu cihazlar tarafından üretilen mobil veri trafiğinin de artması kaçınılmazdır. Aynı rapora göre, dünya genelinde aylık mobil veri trafiği 2017 yılında 12 Exabyte iken, 2022 yılında 77 Exabyte olması öngörülmektedir. Söz konusu artışın mevcut karasal ağ alt yapıları ile yönetilmesi son derece zordur. Bu sebeple, yenilikçi ağ alt yapılarına duyulan gereksinim günden güne ortaya çıkmaktadır. İnternete bağlı cihaz sayısı ve bu cihazların ürettiği mobil veri trafiğinde yaşanan artışa paralel olarak, günümüzde gelişen teknolojilerden biri de havasal ağlardır. Uluslararası İnsansız Araç Sistemleri Derneği (Association for Unmanned Vehicle Systems International) raporuna göre, Amerika Birleşik Devletleri için İnsansız Hava Aracı (İHA) endüstrisinden doğan doğrudan ekonomik etki 2015 yılında 1.2 milyar amerikan doları iken, 2025 yılında 5.1 milyar amerikan doları olması beklenmektedir. Aynı raporda, İHA'ların uygulama alanlarından bir tanesi de haberleşme sistemleri olarak belirtilmektedir. Belirtilen gelişmeler doğrultusunda, İHA kullanılarak oluşturulan havasal ağ topolojileri son yıllarda yayın olarak kullanılmaktadır. Havasal ağlar tek başlarına bir servis alt yapısı oluşturmak üzere kullanıldığı gibi gibi karasal ağ ekipmanlarına yardımcı olmak üzere de kullanılır. Her iki kullanım amacının ortak özelliklerinden birisi havasal ağların kısa zamanlı ve göreve özel olmasıdır. Ağın havadaki fiziksel varlığını sürdürebilmek için bir güç kaynağına ihtiyaç duyulması, bu durumun en önemli sebebi olarak gösterilebilir. Bu bağlamda, enerji farkındalığı, havasal ağlarda asgari bakım maliyeti ile daha uzun bir dayanıklılık sağlamak için üzerinde durulması gereken en önemli konulardan biri olarak ele alınmaktadır. Literatürdeki çalışmalarda, havasal ağlar için enerji farkındalığı sağlamak üzere bir çok çalışma yapılmış olsa da, bu çalışmaların sadece bir kısmı ağın havadaki varlığını sürdürmesi için gerek duyduğu zorunlu enerjiyi dikkate alır. Havasal ağlarda, hesaplama ve haberleşme için harcanan ernerji miktarının, ağı havada tutmak için gereken enerji miktarına göre çok daha az olduğu bilinmektedir. Dahası, bir İHA'nın uçarken harcadığı enerji miktarı; uçuş yönü, uçuş hızı gibi bir çok parametreye ve maruz kaldığı fiziksel kuvvetlere göre farklılık gösterir. Bu sebeple, bu tezde, bir İHA'nın uçuş karakteristiği ile enerji tüketimi ilişkisi göz önüne alınarak, havasal ağın sürekliliğini sağlamak için gerek duyulan İHA değişimleri sırasında, enerji farkında bir uçuş planlaması sunulur.

Havasal ağlarda, bir İHA'nın enerji tüketimini etkileyen en önemli faktör, İHA'nın maruz kaldığı fiziksel kuvvetlerdir ve uygun bir enerji farkındalığı sağlamak için dikkate alınması gerekir. İHA'ya etki eden bileşenler arasında, yer çekimi kuvveti, en belirleyici kuvvettir ve bir İHA'nın hareketi esnasında harcadığı enerji ile doğrudan

ilişkilendirilebilir. Bu sebeple, tezde, enerji tüketimiyle ilişkili bir topoloji grafı modellenmektedir. Bu grafta, İHA konumları düğümlerle, bir yolu katetmek için gereken enerji tüketim maliyetleri ise kenarlarla ifade edilmektedir. Önerilen yaklaşımın doğrulanması için üç farklı yönlü ve tamamlanmış graf modeli sunulur ve her bir graph modelinde yer çekimine karşı yapılan hareketler farklı şekilde maliyetlendirilir. Topoloji grafı oluşturulduktan sonra, bir optimizasyon problemi sağlamak ve belirlenen algoritmik bir yaklaşımla bir çözüm kümesi önermek için Tamsayılı Doğrusal Programlama (Integer Linear Programming, ILP) ile birlikte bir Havasal Toplama ve Dağıtma Problemi (Aerial Pickup and Delivery Problem, APDP) tanıtılır. Sunulan topoloji modeli ve optimizasyon problemi göz önüne alındığında, İHA değişimine gerek duyulan bir t anında, en az enerji tüketimine sahip uçuş planlamasını sağlamak üzere bir Mekansal Uçuş Planlayıcısı (Spatial Flight Planner) önerilir. Uçuş planlayıcısının gerçeklenmesi için Dinamik Programlama (Dynamic Programing, DP) yaklaşımıyla Bellman-Ford algoritması kullanılarak topoloji grafı üzerindeki en az maliyetli uçuş planı araştırılır. Ayrıca, önerilen sistem, havasal ağın tüm operasyonel zamanını göz önünde bulunduran ve sadece t zamanındaki minimum enerji tüketimini değil, aynı zamanda küresel arama alanını tarayan Zamansal Uçuş Planlayıcısı (Temporal Flight Planner) adlı bir uçuş planlama algoritması ile ilave bir geliştirme daha ortaya koyar. Genişleyen arama alanını makul bir sürede taramak üzere Genetik Algoritmalar (Genetic Algorithms, GA) yaklaşımı kullanılır. Böylece, olası çözüm kümesinin bir kısmı elenerek optimuma yakın bir alt çözüm kümesi taranır ve sistemden daha kısa sürede yanıt alınır. Önerilen sistemin gerçeklenmesinden sonra, algoritmaların zaman ve bellek karmaşıklıklarını ölçmek üzere bir dizi analiz yürütülmekedir. Tezde incelenen havasal ağ için belirlenen uygulama alanı ve çalışılan senaryolar dikkate alındığında, sonuçların uygun sınır dahilinde olduğu belirtilebilir.

Önerilen sistemin değerlendirilmesi ve topoloji hakkında enerji farkındalığı gözetmeyen geleneksel bir yaklaşım ile karşılaştırılması için kapsamlı bir simülasyon ortamı sunulmaktadır. Bu sebeple, üç farklı senaryo ölçeği göz önüne alınarak farklı sayıda İHA, karasal son kullanıcı ve kapsama alanı belirlenir. Dahası, simülasyon ortamının oluşturulması ve çıktıların elde edilmesi için gereken bir dizi simülasyon aracı tanıtılır. Ayrıca, simülasyon boyunca kullanılacak ağ mimarisine ilişkin tüm varsayımlar açıkca sunulur. Tezde tanıtılan sistemin değerlendirmesi için, çeşitli boyut ve kanat tipine sahip İHA'lardan en yaygın olarak kullanılan, döner kanatlı dronlar kullanılmaktadır. Simülasyon ortamında test edilen havasal ağın bir sosyal etkinlik için bir araya toplanan kullanıcılara hizmet sağladığı düşünülmektedir. Önerilen sistem ve geleneksel yaklaşım için her bir senaryo ölçeği dört saat çalıştırılarak simülasyon ortamından veriler toplanır ve tezde tanıtılan üç performans kriteri üzerinden bir karşılaştırma sağlanır. Bu performans kriterlerinden δ, simülasyon boyunca harcanan toplam enerji miktarının normalize edilmesiyle elde edilir ve 0-100 arası değerler almaktadır. Değerlendirme sonucuna göre, önerilen sistem, δ parametresi dikkate alındığında %20'ye varan enerji tasarrufu sağlamaktadır. Performans kriterlerinden ikincisi, γ parametresi, havasal ağın varlığı boyunca, hava-kara arasında, ihtiyaç duyulan toplam dron değiştirme sayısını göstermektedir. Bir başka deyişle, hizmet süresi boyunca enerji kaynağını tüketen ve yerdeki yedek dronlardan biri ile değiştirilmesi gereken toplam dron sayısıdır. Elde edilen bulgulara göre, önerilen sistem kullanıldığında, %15'e kadar daha az sayıda dron enerji kaynağını tüketerek değişime ihtiyaç duymaktadır. Performans kriterlerinden üçüncüsü ise, η, bir dronun ortalama havada kalma süresini işaret etmektedir. Önerilen sistem ile bu değer %18 oranında artırılmaktadır. Değerlendirme sonuçlarından elde edilen bulgulara göre, önerilen sistemin, geleneksel bir yönteme göre daha başarılı bir enerji farkındalığı yarattığı vurgulanabilir. Dahası, arama alanının zaman ekseninde genişletilmesi sonucu elde edilen bulguların, belirli bir t anı için elde edilen bulgulara göre daha da iyi olduğu gösterilmektedir. Öte yandan, geniş arama alanında tarama yaparak makul bir sürede çözüm bulmak için kullanılan evrimsel algoritmalar, (Evolutionary Algorithms), rassal yapıları gereği her zaman en iyi sonucu bulmayı garanti etmemektedir. Bu sebeple, GA yönteminin kullanılması ile elde edilen sonuçların evrensel optimum sonuca ne kadar yakın olduğu, sistemin başarımının kanıtlanması açısından, incelenmektedir. Buna göre, Zamansal Uçuş Planlayıcısı'nın DP ve GA yaklaşımları ile gerçeklenmesi sonucu elde edilen bulgular birbirleriyle karşılaştırılır. GA gerçeklemesi ile elde edilen bulguların, DP gerçeklemesi ile elde edilen bulgulara göre %5'e kadar daha kötü enerji farkındalığına sebep olduğu; ancak, GA gerçeklemesi ile sistemin 30 kata kadar daha kısa sürede yanıt vermesinin sağlandığı gösterilmektedir. Bu sebeple, sistemin uygun bir şekilde hizmet verebilmesi için GA yaklaşımının kullanımı onaylanmaktadır. Sonuç olarak, önerilen sistem kullanıldığında, çalışmada ele alınan geleneksel yaklaşımdan daha uygun bir enerji farkındalığı sağlandığı ve önerilen sistemin evrimsel algoritmalar kullanılarak gerçeklenmesinin, daha makul sürede yanıt vermeye yardımcı olurken, sağlanan çözümlerin üstünlüğüne zarar vermediği savunulabilir.

Simülasyonlar sırasında önerilen sistem tarafından bulunan çözümlerde, uçuş planlamasının havadaki dronlar arasında yer değiştirmeler içerdiği rapor edilmektedir. Bu sebeple, karasal son kullanıcıların servis taleplerini kesintisiz olarak karşılamak üzere, dronlar üzerine konuşlandırılmış Havasal Baz İstasyonları (HBİ) arasında kullanıcı devri yapılması gerekmektedir. Elde edilen bulgulara göre, önerilen sistem, geleneksel bir yönteme kıyasla %14'e kadar daha fazla kullanıcı devri sayısına (ψ) sebep olmaktadır. Literatürdeki çalışmalara göre, kullanıcı devri sayısının artması durumunda son kullanıcı performansına dair bazı parametrelerde düşüş yaşandığı görülmektedir. Bu nedenle, önerilen sistemin sebep olduğu kullanıcı devri sayısının, son kullanıcı performansına etkisini araştırmak üzere, simülasyon ortamı genişletilerek ortalama kullanıcı düzlemi gecikmesi parametresi (average access link latency) ve paket kayıp oranı parametresi (packet loss ratio) incelenmektedir. İncelemede, gerçek zamanlı ve gerçek zamanlı olmayan uygulamaların ürettiği heterojen bir son kullanıcı trafiği göz önünde bulundurulur. Değerlendirme sonuçlarına göre, önerilen sistemin %10'a kadar daha fazla ortalama kullanıcı düzlemi gecikmesine ve %19'a kadar daha fazla paket kaybı oranına neden olduğu belirlenir. Sonuç olarak, önerilen sistemin son kullanıcı perspektifinde bir bozulmaya neden olduğu, ancak enerji farkındalığı perspektifinden ise önemli miktarda bir enerji tasarrufu sağladığı sonucuna varılmaktadır. Dahası, literatürde yer alan teknik raporlar incelendiğinde, son kullanıcı performansında meydana gelen kötüleşmenin kabul edilebilir bir seviyede olduğu ortaya konmaktadır. Ayrıca, önerilen sistemin son kullanıcı performansı üzerindeki olumsuz etkisini sınırlandırmak adına, bir Kullanıcı Devri Faktörü İyileştiricisi (Handover Factor Optimizer) algoritması sisteme eklenir. Böylece, son kullanıcı performansında meydana gelebilecek bozulma, önceden belirlenen bir kullanıcı faktörü değeri ile sınırlandırılır. Önerilen eklenti üzerinde gerçekleştirilen zaman karmaşıklığı ve bellek karmaşıklığı analizleri de tezde sunulmaktadır.

Son olarak, önerilen sistemin farklı trafik istekleri olan son kullanıcılar üzerindeki etkisini daha ayrıntılı incelemek üzere, sadece gerçek zamanlı ve sadece gerçek zamanlı olmayan trafik istekleri üreten simülasyon ortamları ayrı ayrı incelenmektedir. Böylece, önerilen sistem nedeniyle kullanıcı performansında meydana gelen düşüş farklı trafik isteklerine göre detaylıca ele alınmaktadır ve önerilen sistemin farklı kullanım senaryoları için uygulanabilirliği araştırılmaktadır. Değerlendirme sonuçlarına göre, gerçek zamanlı olmayan trafik istekleri ile ele alınan senaryoda, daha fazla kullanıcı düzlemi gecikmesi ve paket kaybı oranı olduğu görülmektedir. Bu nedenle, önerilen sistemin, gerçek zamanlı olmayan trafik isteği bulunan son kullanıcılar için dikkatli bir şekilde görevlendirilmesi gerektiği vurgulanır. Bununla birlikte, önerilen sistemin uygulama alanı ve tezde incelenen senaryolar dikkate alındığında, genel olarak Hiper-Metin Transfer Protokolü (Hypertext Transfer Protocol Version 3, HTTP3) ve Hızlı Kullanıcı-Datagram-Protokolü İnternet Bağlantıları (Quick User-Datagram-Protocol (UDP) Internet Connections, QUIC) gibi yeni nesil gerçek zamanlı protokoller kullanan son kullanıcı uygulamarı karşımıza çıkmaktadır. Sonuç olarak, bir son kullanıcı tarafından üretilebilecek her iki trafik tipi için, önerilen sistem nedeniyle meydana gelen performans düşüşünün, sistemdeki enerji tasarrufu göz önüne alındığında, kabul edilebilir düzeyde olduğu iddia edilir.

1. INTRODUCTION

In the last decade, number of networked mobile devices has increased tremendously all around the world. According to the Cisco Visual Networking Index (VNI) report [1], the Compound Annual Growth Rate (CAGR) for number of mobile devices is computed as 7% in the time period between 2017-2022. It is stated in the report that their number exceeded 8 billion in 2017, and is expected to reach 12 billion by 2022 as illustrated with Figure 1.1. Moreover, the percentage of each mobile device types is also detailed in the original report. As a result of this growth in number of mobile devices, worldwide mobile data traffic has also increased and is predicted to continue increasing in the following years. According to the same report, global mobile data traffic exceeded 12 exabytes per month in 2017 and is expected to exceed 77 exabytes per month in 2022 with a CAGR of 46%. The change trend in global data traffic is demonstrated in Figure 1.2.

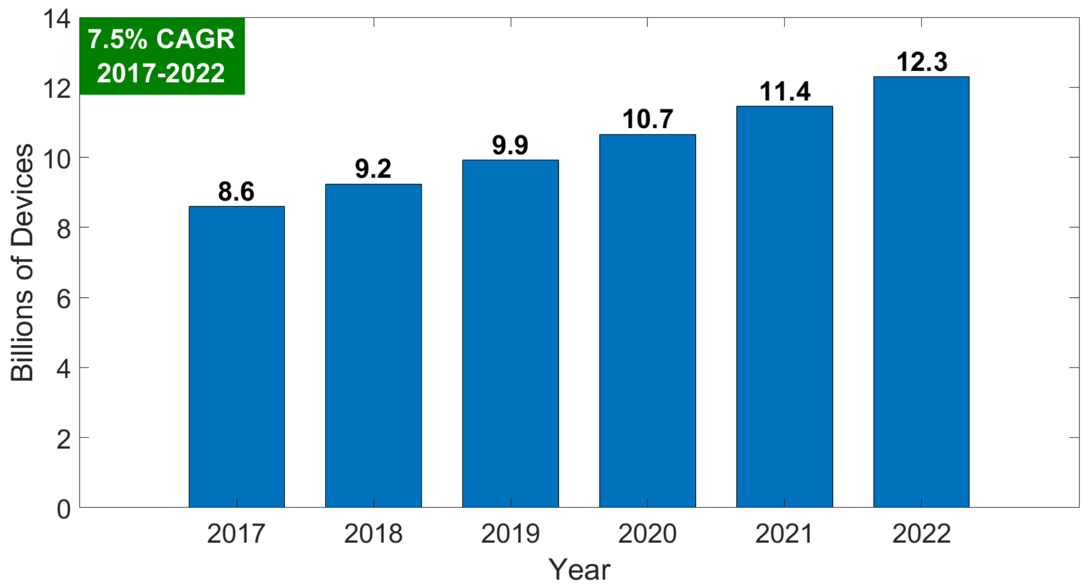


Figure 1.1 : Global mobile devices and connections.

Considering the increase trend in connected mobile devices and data traffic originated from them, traditional network infrastructures become inefficient to provide service especially under dense areas of big crowds. Moreover, stationary network infrastructures become infeasible to serve considering their high mobility characteristics. Today, some mobile network infrastructures are studied to correspond mission specific data demand generated by networked mobile devices. Unmanned Aerial Vehicles (UAVs), is one of them to provide highly mobile and resilient aerial network topologies.

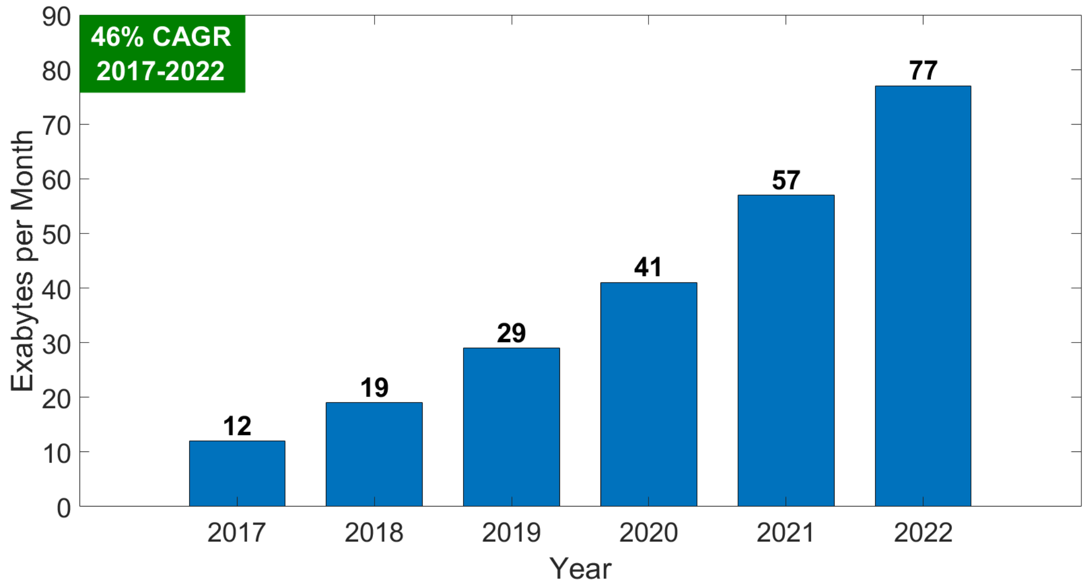


Figure 1.2 : Global mobile data traffic.

Understanding of UAVs, their features, challenges and usage areas is essential to provide a remarkable aerial network infrastructure. In the literature, initially, UAV systems are studied for academic and military purposes, however, in today's world, there are lots of commercial usage of them such as trading, marketing, transportation and communication. Furthermore, the attention on UAV systems is increasing day by day. According to [2], direct economic impact from the UAV industry is forecasted for United States as show in Figure 1.3. It is stated in the report that, direct economic impact from the UAV industry in US is about $3.6 Billions in 2018 and is expected to reach $5 Billions by 2025. owing to increasing number of application fields of UAVs.

Communication technologies is one of the novel areas that aerial systems have been deployed to construct aerial networks as i) stand-alone network infrastructure, ii) assistant network infrastructure for terrestrial components. In most of the cases a network equipment is embedded on a UAV board to provide an Aerial Base Station (ABS). There are different type, scale and purpose of aerial networks, recently. A rotary-wing or fixed wing UAV can be used to produce an ABS. These ABSs can be deployed in the air by using a single or a number of UAVs i.e UAV swarms. The system

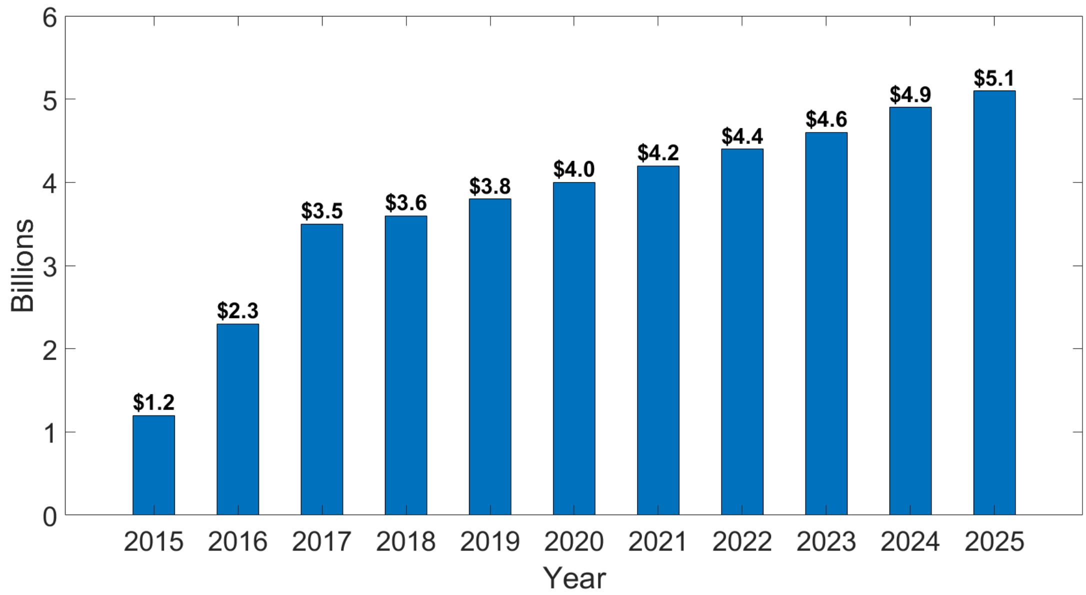


Figure 1.3 : Direct economic impact from the UAV industry in United States.

can be deployed as Low Altitude - Short Endurance (LASE), Low Altitude - Long Endurance (LALE), Medium Altitude - Long Endurance (MALE), or High Altitude - Long Endurance (HALE) according to application objective. Considering the type, scale and objectives of such systems, an air-to-ground (A2G) or air-to-air (A2A) communications schemes can be established to control the system with centralized controller or autonomously. As a common feature for all different deployment of aerial networks, it can be asserted that the are generally used for mission specific purposes during a short term in order to provide a resilient communication infrastructure. A permanent service from aerial networks is not eligible due to the fact that their power source requirement is constrained by their flying ability.

1.1 Purpose and Scope of the Thesis

In this thesis, energy awareness of aerial networks are studied to overcome power source limitations that affects the endurance of the network. Endurance of an aerial network refers to the duration of physical presence of network components in the infrastructure. Energy awareness is a crucial issue for aerial networks to provide high endurance and has received a great attention recently. The main goal of energy awareness in aerial networks is to use the exhaustible power source more effectively. The optimization objective is providing more endurance with the same amount power supply under some energy consumption constraints. The frame of the study is depicted considering the main research directions as following and a concrete prerequisites of the study is also given in Section 3.1.

Energy awareness of aerial networks can be handled from different perspectives. Energy awareness schemes in conventional terrestrial networks are also compelling for aerial networks. Communicational and computational energy requirements can be considered to provide an energy aware design of aerial networks. There are some studies to reduce communicational and computational power consumption of aerial networks in the literature that intends to provide energy efficient network schemes. However, the fundamental energy consumer of such networks are not communicational or computational, it is the compulsory power required by rotors while flying as stated in [3], [4], and [5]. Thus, in the thesis, the energy consumption characteristic of UAVs are focused to provide an energy aware aerial network scheme so as to remain the network operational for a longer time. For this purpose, the species for UAVs studied in the thesis are restricted as only rotary-wing ones because of the fact that they are commonly accessible for personal use and appropriate for SALE environments in which communication domain applications exist.

Flight characteristic of UAVs is affected by lots of aspects such as, additional weight on board, flight angles of rotors, environmental circumstances, etc. In the literature, solutions for energy aware flight of UAVs mainly consider the physical structure of a UAV and require some architectural intervention to provide energy efficiency. However, such approaches are not flexible when the physical environment of aerial networks is taken into account. Hence, in this thesis, a centralized algorithmic software solution is studied which is independent of the UAVs' physical structure to decide an optimal flight planning for a UAV when moving from a 3D coordinate to another one. Moreover, as aforementioned, one of the most common characteristic of aerial networks is that they are deployed for a short term and an estimated operational time can be provided before the deployment. The social event scenarios such as concert, soccer game, etc. are studied in the thesis in which a high traffic demand from different traffic types occurs during the pre-estimated operational time. Furthermore, these scenarios usually have an operational time more than a UAV endurance. Thus, some replenishment processes are required for ABSs with a drained battery to maintain the network online. The compulsory power requirement by the rotors peak whenever a replenishment is on the way because of a movement from current position. According to investigations in [3], [4], [5], and [6] it can be asserted that energy consumption characteristic of a UAV diverse with respect to different kind and volume of forces exposed by the UAV on the fly during a forward flight or hovering duration. Thus, power consumption by the rotors is directly proportional to these forces in order to maintain flying. The proposed algorithmic model is consulted for the cases when a movement in the topology is required.

1.2 Contribution of the Thesis

In this thesis, an energy aware endurance framework is proposed to save energy with a proper flight planning for a replenishment process considering the relation between flight characteristic and energy consumption profile of a UAV. For this purpose, the gravity force is mainly taken into account because of being the determinant force among all of the others. Subsequently, a graph model is provided for the topology using three different cost assignment strategies that represents UAVs in the nodes and energy consumption costs on the edges. By applying three different cost assignment strategies, the penalty against the gravity force is tried to be verified. Once the topology graph is obtained, a spatial flight planner algorithm is designed that responds a flight planning with minimum energy consumption for a replenishment at a specific moment t. Moreover, a temporal flight planner algorithm is also developed to extend the search space in time domain during the estimated operational time. In this way, it is aimed to seek a more proper solution for minimum energy consumption within the entire topology maintenance duration. The performance of the proposed flight planner framework is investigated by comparing it with a simple replenishment approach that does not take any information about the topology into account. Besides, the response time of the proposed model is also investigated with complexity analysis and experimentally obtained values. Evolutionary algorithms are consulted to provide reasonable response time from the service calls. Furthermore, the effect of the proposed system model is also investigated from an end-user perspective and is bounded with a handover factor optimizer algorithm. Lastly, the evaluation of the proposed framework on different traffic types including real time and non-real time traffic arising from several kind of end user applications is also performed and presented. The details for the contribution of the thesis is given in Section 3, Section 4 and it is evaluated in Section 5.1.

Considering the earlier stated challenges of aerial networks and the scope of the thesis, the contributions to address an energy aware endurance framework for mission critical aerial networks can be identified as following:

- An abstract digraph model, $G(V,E)$, with three different cost assignment approaches for the aerial topology that consists of energy consumption related costs on the edges, E, and location of ABSs as vertices, V, examined in Section 4.2.1;
- A particular Pickup and Delivery Problem (PDP) definition for flight planning during a replenishment process named as an Aerial Pickup and Delivery Problem (APDP) and a problem formulation with Integer Linear Programming (ILP) presented in Section 3.2;
- An algorithmic approach using evolutionary algorithms for energy aware flight planning as explained in Section 4.2.2, Section 4.2.3 and Section 4.2.4; and analyzed in Section 4.3 to investigate the response time and algorithmic complexity of the proposed flight planner algorithm;
- A test environment to compare the proposed model with a simple replenishment strategy under different traffic types from an end-system perspective considering a normalized energy consumption (δ) parameter, a replenishment factor that count total number of replenishments (γ) parameter, an average endurance per drone (η) parameter; and from an end-user perspective considering an end-system initialized handover factor (ψ) parameter, average access link latency, and packet loss ratio as highlighted in Section 5.2.

2. LITERATURE REVIEW

The literature investigation is performed from different perspective considering the research directions highlighted in the thesis. First of all, the characteristics, challenges, opportunities and application domains of aerial systems including communication applications are surveyed and presented in Section 2.1. Subsequently, energy efficiency approaches for both aerial networks and other aerial systems are examined and summarized in Section 2.2.1 and Section 2.2.2, respectively. Afterward, in Section 2.3, the performance and implementation domains of evolutionary algorithms are investigated in the literature cause they are considered for the proposed flight planner development. Lastly, service expectations of end-users using a variety of applications are examined in Section 2.4 so as to seek the performance of the proposed framework from an end-user perspective.

2.1 Aerial Networks

There are lots of survey papers in the literature that provide a comprehensive study on aerial systems considering different aspects and characteristics. Some of them are investigated and summarized within a communication perspective in order to identify the applications, main challenges and open issues about the aerial networks. For this purpose, [7], [8], [9], [10], [11], [12], and [13] covering UAV-aided aerial networks are presented as following. In [7], UAV-aided wireless communication is investigated on different use cases by presenting basic networking architecture and main channel characteristics. Moreover, challenges and new opportunities for future directions are also introduced in the study. In [8], Mobile Ad Hoc Networks (MANETs) and Vehicular Ad Hoc Networks (VANETs) are stated and compared with aerial networks according to their distinct and common characteristics. The authors mainly focus on some specific issues for aerial networks considering particular features such as mobility of nodes, fluid topology, discontinuous links, power and bandwidth constraints. Routing, handover and energy efficiency in aerial networks are main issues introduced in the survey. Moreover, Software Defined Networking (SDN) is stated by the authors to be facilitated in aerial network schemes in order to provide flexible deployment, service management, reduced cost, increased security and availability in networks. In [9], the functions, services and requirements of UAV-based aerial communication systems are presented. More specifically, some sort of services are examined in the survey in order to provide robust, efficient, and energy-aware communication in aerial networks. Moreover, widely used network infrastructures such as UAV-to-UAV (U2U) and UAV-to-Infrastructure (U2I), communication frameworks, data traffic demands, a variety of communication protocols and recent technologies for UAV communication links are also identified by the authors. A case study is also provided such that UAVs are deployed for efficient data collection from different types of Wireless Sensor Networks (WSNs) for different topology types including linear sensor networks (LSNs), geometric and clustered WSNs. In [10], the authors introduce characteristics, properties and requirements of aerial networks for civil applications during the period 2000–2015 from a communications and networking perspective. They evaluate quality-of service requirements, networking metrics for considered missions, traffic requirements and provide a broad categorization of aerial network applications. The authors also survey the appropriateness of current communication technologies to provide reliable aerial networking. Moreover, common requirements in communication such as connectivity, adaptability, safety, privacy, security, and scalability are also discussed. Experimental results from many projects in the literature are also reported. [11] asserts that UAVs can be deployed to provide aerial network infrastructure to enhance coverage, capacity, reliability, and energy efficiency of wireless networks. The authors conduct a comprehensive tutorial on potential benefits and applications of UAVs in wireless aerial networks. Three-dimensional (3D) deployment, performance analysis, air-to-ground channel modeling, and energy efficiency issues of aerial networks are explored in the study. Well-known open problems and future research aspects of aerial networks are also introduced. Moreover, various analytical frameworks and mathematical tools such as optimization theory, machine learning, stochastic geometry, transport theory and game theory are stated to deal with the mentioned open research issues. In [12], an extensive survey on UAV systems, their use cases and UAV related issues are represented. Regulations and standardization efforts, and public safety interests are addressed. The authors also propose an aerial network infrastructure for delivery of UAV-based Internet of Things (IoT) services. They present relevant major challenges and requirements. [13] investigates Flying Ad-Hoc Networks (FANETs) considering the challenges compared to conventional ad hoc networks. Moreover, traditional routing protocols for FANETs are classified into six basic categories. Finally, studied categories are critically analyzed and compared according to various performance metrics.

Besides the general purpose surveys for aerial systems, there are also more specific studies on aerial network in the literature considering network features such as reliability, availability, coverage, etc. [14] proposes a framework to analyze and optimize A2G links in aerial networks considering the height, path loss and multi path fading. The authors propose an analytical model for the optimal UAV height minimizing the outage probability of a link. In [15], the authors propose a stochastic geometry to provide an aerial network model consisting of UAVs for urban environments. In the model, the authors consider network parameters such as the density and the height from the ground. They present an expression for the coverage probability as a function of these parameters. In [16], the authors consider a scenario consisting of a single cellular cell network, cellular users and UAVs deployed for aerial infrastructure. In this scenario, UAVs upload their collected data to the base station on the ground. They consider U2U and U2I communication schemes and derive a trajectory and allocation control problem to maximize the uplink sum-rate. [17] proposes to deploy UAV aided aerial networks for battlefield communication. The authors introduce a routing model named as Landmark Ad Hoc Routing for such networks consisting a hierarchical structure with backbone nodes, high quality backbone links and UAVs. In [18], the authors provide an aerial network to relay messages between two distant ground nodes for some delay-tolerant applications. They aim to maximize throughput with proposed Load-Carry-and-Deliver Paradigm assisted with UAVs. [19] deploys UAVs with a wireless ad-hoc network perspective to provide an aerial network infrastructure. The authors propose a dynamic spectrum management scheme for a multi-rate, multi-channel aerial network using link adaptation. They also consider the impact of channel state prediction quality for the throughput of the network. [20] deploys UAVs as aerial sensor networks to present disaster management applications for disaster scenarios. The sensors in the aerial network provide an aerial imaging system and deliver high quality sensor data such as images or videos. These data are transmitted to the ground, brought together, analyzed in real-time, and finally delivered to the relevant user. Moreover, the authors also study on the optimal placement of sensors considering the challenges. They define the coverage problem as ILP and also show their evaluation results. [21] presents the development of flight control design and simulation process that can be used for aerial vehicles in local area networks. The authors aim to provide reduced risk during flight tests especially in complex and dense scenarios thanks to proposed simulation tool. They validate their simulation model and assert that an efficient simulation tool is offered in the work for specific use cases.

2.2 Energy Efficiency

In this section, energy efficiency approaches in the literature for aerial networks and for other aerial systems are reviewed in Section 2.2.1 and Section 2.2.2, respectively.

2.2.1 Energy efficiency on aerial networks

There are studies on energy awareness in the literature for various use cases to provide energy efficient aerial networks. Some of them are briefly summarized in this section. In [22], the authors try to optimize deployment of multi UAVs as aerial base stations to collect data from IoT devices on the ground. In this study, total transmit power of the IoT devices is minimized by clustering them and providing one UAV for each cluster to serve them. Moreover, an optimal UAV mobility scheme is proposed to provide reliable communication for IoT devices under minimum energy consumption. The authors utilize optimal transport theory to come up with optimum paths that will be used by UAVs to serve terrestrial devices. [6] considers communication throughput and energy consumption of UAVs in the aerial topology to provide an energy efficient aerial network. The authors firstly provide a model on propulsion energy consumption of UAVs according to flying speed, direction and acceleration. Then, they present a UAV trajectory scheme where flight radius and speed are optimized in order to minimize the energy consumption. In [23] the authors assert UAVs can be deployed as data collectors for sensor nodes (SNs) in WSNs to enhance the network operational duration. For this purpose, they propose a general fading channel model for SN-UAV links. Moreover, they also introduce an optimized wake-up schedule for SNs considering UAV's trajectory to save energy. They introduce a mixed-integer non-convex optimization problem and apply an efficient iterative algorithm as successive convex optimization technique, to find a sub-optimal solution. [24] claim that collaborative networks are getting more popular recently and one of them is formed between WSNs and UAVs i.e. aerial networks. The authors provide a novel data dissemination approach by applying fire fly optimization algorithm to provide energy efficient relaying. They show that the proposed network scheme provides steady connectivity, better sensor network operational duration, and enhanced coverage. [25] also studies on UAV-aided wireless relay networking. The authors propose an optimal design for beamforming and UAV path planning for this aerial and mobile network infrastructures. In their scenarios, they deploy a UAV with single antenna as relay between a mobile access point and a fixed base station each equipped with multiple antennas. In the end, they derive a closed-form outage probability expression to investigate the performance of the proposed relay network infrastructure. In [26], the authors present an optimal trade-off between the communication and the computational energy for aerial UAV networks. Particularly, they introduce a mixed-integer optimization problem for a multi-hop and hierarchical clustering based, self-organizing UAV network. They also consider data aggregation to route information in an energy-efficient way. [27] proposes an optimal flying path scheme for UAV-aided IoT sensor networks. They use a location aware information map with multiple layers and introduce different utility functions based on the sensor density, energy consumption, duration on fly and risk level. They apply GA to maximize the weighted sum of utility functions. Finally, they approve that the optimum solution can be achieved by setting the weights meanwhile responding the required constraints. [28] introduces an optimization algorithm to reduce the amount of energy required for movement coordination of multiple vehicles in a UAV swarm. The approach aims to use the most appropriate wireless communication channels between UAVs considering channel features such as path loss and power received. [29] considers cognitive context aware capabilities of a hybrid aerial-terrestrial infrastructure for emergency scenarios to provide energy aware communication. The authors analyze the challenges and superiority of such networks schemes relaying strategies presented in the study.

2.2.2 Energy efficiency on other aerial systems

Endurance limitations exist for all aerial systems deploying UAVs. Thereby, beside energy aware studies in aerial networks, energy efficiency strategies proposed on other aerial systems are also investigated for literature survey. Some of them alter physical structure of a UAV to provide energy efficiency and to maintain endurance for a larger period of time. [30] offers to equip a UAV with vibration and solar sensors to harvest energy from movements and sunlight. The authors aim to generate piezoelectric energy for a UAV on the flight. [31] introduces a new triangular shaped quadrotor configuration. The authors deploy a large rotor in the center of UAV platform for lifting and three small rotors for UAV movement control purpose. They apply momentum theory for energy consumption of the new configuration and assert that their model provide less energy consumption according to their evaluation.

Algorithmic approaches considering energy model of a UAV also exist in the literature for energy awareness in UAV systems and they are mainly inspired for the thesis. They usually aim to accomplish a set of objectives with minimum energy consumption. [32] presents multi-UAV flight planning as an optimization problem to obtain the maximum presence as well as satisfying some constraints during the mission. The authors compound Genetic Algorithms (GA) and Ant Colony Optimization (ACO) to provide a hybrid approach for path planning of multi-UAVs. They also show that proposed model can solve the test scenarios effectively in a reasonable amount of duration. [33] introduces an autonomous path planning scheme for mission specific UAV systems controlled by multi controllers. The authors deploy GA in parallel manner with multiple Graphical Processing Units (GPUs). They assert that the applied approach is efficient and can be used for real time scenarios to calculate flight routes even in large areas with lots of constraints. [34] presents a situation aware UAV mission route planning to enhance the probability of success in the mission. The authors propose a problem solver considering weightings for fuel and threat costs. [35] investigates on vehicle routing problems in UAV systems with drone delivery scenarios. The authors provide an energy consumption scheme for multi-rotor drones taking the payload and battery weight into account. They express the problem with mixed integer linear programming (MILP) and apply simulated annealing heuristic to provide sub-optimal solutions. [36] proposes an energy aware UAV path planning scheme in scenarios of sensing with photogrammetry by considering the coverage area and spatial resolution. Moreover, the proposed model also examines energy consumption relation with payload weight and maximum speed of a UAV. [4] investigates rotor and battery dynamics for a quad-rotor drone and presents an energy model. The authors provide a problem statement for energy optimization during a mission to satisfy a set of constraints. [37] defines six basic components in a UAV power consumption point of view. Then, the authors consider energy requirements of each component to provide an overall energy efficient scheme in a UAV design. In [38], the authors focus on UAV path planning process of an aerial system to provide an energy efficiency perspective. In the study, Euclidean paths are associated with energy costs and Dijkstra's Algorithm is applied to find an energy efficient path for the system. [39] tries to overcome endurance limitation of existing UAV systems with quad-rotor drones according to energy consumption. The authors aim to utilize power consumption model of a rotor to provide minimum energy paths considering an initial and a final location of a UAV. In the proposed model, the authors present a solution for angular accelerations of the four propellers. [40] provides an estimation model for endurance of a UAV with multiple rotors. Lithium Polymer (LiPo) batteries are embedded as power sources and both of battery variability as well as the effects of electric propulsion system are considered for the proposed estimation model. The momentum theory is also taken into account for computations in the study. [41] aims to provide an automated power management scheme for UAV swarms. In this context, the authors present an autonomous recharging scheme named Ground Recharge Stations for battery powered quad-rotor UAVs. [42] provides an autonomous battery maintenance scheme for small size UAV systems. A concurrent charge and change procedure is introduced to alleviate the challenges of existing charge-only approaches. In this model, a drained battery of a UAV is changed with a replenished one as well as recharging several others. Finally, they assert that the model is able to enhance endurance of evaluated UAV scenario.

According to the investigation for energy awareness on aerial systems, it is inferred from the literature that applying algorithmic solutions is more appropriate due to the physical environment of aerial networks.

2.3 Evolutionary Algorithms on Complex Problems

Evolutionary algorithms are mainly considered for UAV system flight planning schemes because of their discrete optimization perspective. They are applied for various problem domains in information systems to provide an efficient search for the solution. Some examples are presented in [43], [44] and [45]. In [43], the authors deploy ACO to alleviate memory and time requirements of dynamic programming used for distributed database queries. Thus, they claim that they introduce a polynomial time approximation algorithm with the proposed model. [44] studies on bio-informatics and computational biology, specifically on challenging multiple sequence alignment problem. The authors propose a GA with ACO to provide an efficient search scheme on problem domain. They assert that their work has superior run time and memory performance comparing to existing ones. In robotics domain, [45] aims to take advantage of both GA and ACO for path planning problem of mobile robots. The authors propose a hybrid approach named smartPATH for efficient and fast path selection. Moreover, they also aim to avoid terminating on local optimum solution by applying these heuristics.

There are also some studies in the literature that apply GA for aerial systems in order to effectively provide a solution against some objectives. [27] studies an optimal flying scheme in UAV assisted sensor networks and they implement GA approach to solve their multi-objective utility function against provided constraints. [32] deploys GA with ACO approach to provide a collaborative solution against their combinational optimization problem for multi-UAV flight planning with maximum surveillance. [33] also introduces an effective path planning scheme for mission specific aerial systems with GA implementation in a parallel architecture using multiple GPUs. Moreover, as well as in aerial systems, GA algorithm is also studied for different application domains to provide effective solution. [44] applies GA to solve a common multiple sequence alignment problem in bio-informatics and computational biology. The authors assert that this implementation has superior run time and memory performance comparing to existing ones. In robotics domain, [45] aims to take advantage of both GA and ACO for path planning problem of mobile robots. [46] offers GA to solve a very common discrete optimization problem, the Traveling Salesman Problem (TSP), efficiently with the cooperation of DP. [47] also uses the same pair to solve green vehicle routing and scheduling problem that tries to minimizes CO_2 emission.

In the thesis, the benefits of collaborative heuristics are utilized to provide a proper end-system with a reasonable response time. It is decided to deploy DP and GA on the flight planner framework considering their advantages, use cases and implementation details during the literature investigation. In this manner, our framework employs both of DP and GA in collaboratively.

2.4 The Handover Effect on Different Service Expectations of End-users

The thesis focuses on the energy efficiency of the end-system. At the same time, the effect of the proposed framework is also investigated from an end-user perspective because it offers to change the location of a number of drones besides the replenished one and this results in more number of end-user handovers compared to a simple replenishment approach. Hence, the relation between the number of end-system initiated handovers and end-user service expectations is also investigated with a certain literature survey.

According to [48], handover characteristic of a network directly affects the QoE of an end-user and the authors try to maximize the offered service in a cellular network with handover occurrences. Moreover, [49] claims that number of handovers in a cellular network is a major performance indicator. Hence, the authors propose a handover number estimation approach to get information about the network considering their occurrences. Similarly, [50] points out the same issue and presents a new scheme to determine the number of handovers during a session by applying probability and statistics methods. [51] presents a survey on handover mechanisms for Long Term Evolution (LTE) networks and also asserts that the ping-pong rate, which increases the number of handovers, has a direct impact on the performance. Considering the studies in the literature, the effect of the proposed system on the number of handovers is examined considering packet loss ratio and average access link latency in the network edge. The drawback of the proposed framework is bounded in an acceptable level in order to provide a better satisfaction for an end-user.

A diversity of applications on mobile end-user platforms have been arised, recently. As a result, different traffic demands are generated by the end users that cause a heterogeneity in mobile data traffic. In such networks, service expectations and performance indicators for each end-user may differ. In [52], a quality class indicator provided by The 3rd Generation Partnership Project (3GPP) is summarized in a table to show the packet delay and the packet loss ratio for different applications. Moreover, performance requirements and different QoE demands are also stated for a variety of services. Similarly, [53] presents a user behavior model against different application traffic profiles that consider the network performance using web traffic and media streaming. [54] conducts a thesis study to show the difference in traffic types even in different periods of the same day. In [55], the authors assert that different end-user applications require real time or non-real time constraints in MANETs. They evaluate the performance of some routing protocols against different traffic types generated by end-user applications. [56] investigates the relation between number of terrestrial handovers and average latency for a real time application traffic request. The authors analyze and compare different handover techniques to minimize the latency. [57] investigates the latency, loss rate and blocking probability versus user speed during a terrestrial handover for real time and non-real time services. As a result, in this study, the performance of the proposed framework from an end-user perspective is also evaluated considering only real time traffic demands and only non-real time traffic demands. The end-system initiated handover number is bounded according to acceptable service expectations of end-users presented in the literature.

3. NETWORK ARCHITECTURE

Various aerial network schemes have arise in parallel with the enhanced usage of UAV systems. Some of them have critical, mission specific purposes whereas some of them are for only commercial usage. Aerial network deployments for military and disaster scenarios require different services than commercial ones. They clearly have harder real-time and strict resiliency constraints. Commercial deployments usually serve for a concert location, a football stadium and etc. Their fail may not be too much critical. Independent from the scenario, for all of the deployments of aerial networks, the endurance is highly depend on the power consumption during the flight. This makes the network presence limited on the air, thereby most of aerial networks aim to provide short-term service. In the thesis, we consider deployment scenarios for social events such as a concert festival with huge crowds, soccer game in a stadium, etc. An example scenario of our network environment is given with Figure 3.1. There are terrestrial users, ABSs and a centralized controller in the figure. The controller uses Micro Air Vehicle Link (MAVLink) protocol, a common lightweight messaging protocol to manage UAVs , to orchestrates the ABSs and the ABSs provide communication service to the end-users using WiFi protocol.

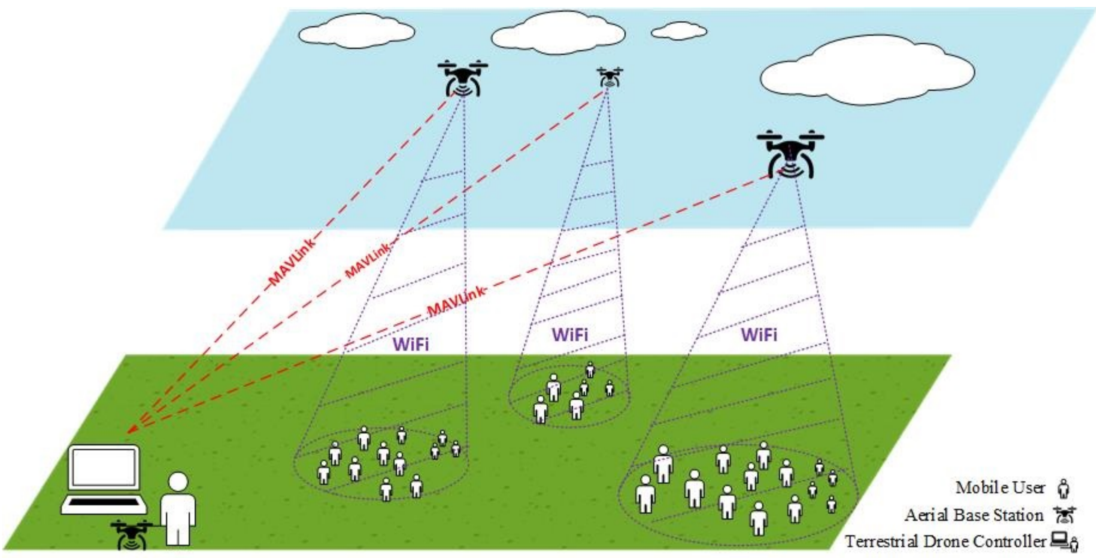


Figure 3.1 : The network architecture.

3.1 Prerequisites

In the given network architecture, a proper location for each ABSs is given to the proposed system model. Thus, there is no consideration about the topology construction process for the aerial network architecture used in the thesis. On the other hand, if some of the ABSs are needed to be replenished during the estimated operational time, then the proposed scheme is consulted to obtain an energy aware flight planning. There some studies in the literature that seek a proper topology construction considering some objectives such as number of ABSs to be used, height and coverage of each ABSs, number of end-user clusters, etc. [58] provides a survey on location optimization for base station embedded UAVs in an aerial network. The authors assert that the geographical coordinates, altitude and coverage are major parameters to provide service for a terrestrial area. [59] studies on optimum placement for UAVs in a more specific network topology to provide an aerial relay network. The authors emphasize that reliability of such networks should be considered carefully with optimum altitudes and coordinates. In [60], the authors consider to deploy base station embedded UAVs in Ultra Dense Networks (UDN) in order to provide better Quality of Service (QoS). For this purpose, they take into account the terrestrial end-user clusters to cover them with minimum number of UAVs. Similarly, [61] offers gathering geographical data from terrestrial users and provide a relief strategy with the help of ABS deployment in 5G networks. As a result, it can be asserted that a common characteristic of the studies in the literature is covering a cluster of terrestrial users with an optimum number of UAVs. More specifically, each drone should serve a number of users because of the acquisition cost. Hence, the terrestrial end-user clusters served by an ABS are thought as balanced in the study. The worst case run time complexity and memory space complexity of the proposed framework are calculated considering this assumption. The rest of the assumptions and features about the network architecture throughout the thesis are listed as following:

- The aerial network has at least two base station embedded drones, having a quadrotor platform with the ability of forward flight and hovering, in the topology.

The swarm on the air is controlled by a centralized ground controller i.e. there is not an autonomous system.

- The 3D coordinate of each drone in the aerial network is predetermined by another work such as in [60] and [61] where terrestrial users are clustered in a balanced way to be served by an ABS. Thus, we do not consider to find suitable drone locations. This study only focuses on finding a suitable flight planning to maintain the topology with energy awareness.
- There may be different number and kind of end-users served from each ABS attached on drone platforms. Therefore, each base station is under different amount of computational and communicational burden. Hence, after the first construction of the aerial topology, the endurance for each ABS may differ and need of replenishments arise at different times.
- The mobility pattern for the end-users is considered as a linear mobility model [62] with an initial speed of 0 km/h. In other words, it is assumed that the end-users are not mobile.
- At any given time t, a more suitable coordinate set for drones on the air can be found by a third party framework. In such conditions our framework can be triggered to determine the most suitable flight planning throughout the topology.
- There is a mission specific, short-term deployment for the aerial network with hard real time and strict resiliency constraints. Replenishments should be performed as fast as possible. Hence, UAVs on the fly can show aggressive maneuver and flight skills that cause more power consumption during a replenishment.
- The operational time of the aerial network is predictable and should be longer enough to drain some ABSs so as to require some replenishments.
- For the network environment, we neglect the environmental effects such as wind or rain. We assume that the weather condition is as suitable as for any UAV system to fly.
- The altitude of the aerial topology is considered as up to 300 meters which provides a proper flight and is referenced in many of the studies in the literature.

3.2 Problem Definition

Before introducing the formal problem definition, Figure 3.2 illustrates a scenario to emphasize motional energy awareness of an aerial network. Assume that Figure 3.2(a) shows an aerial network topology with four nodes i.e. three ABSs numbered as 1 (blue), 2 (orange), and 3 (red); and one terrestrial controller on the ground. There are also some redundant ABSs near the ground controller given as 4 (green). The location of the redundant ones are the same as the location of the ground controller, accordingly they are not shown as separate nodes. There should be a replenishment between a redundant one and a flying ABS whenever its battery is about to drain. In such a topology, assume that node 3 is about to run out of its battery and should be replenished by the ground controller. Figure 3.2(b) shows the landing route of node 3 with the dashed red line and departure route of node 4 with dashed green line. In this case, the energy consumption of the system can be identified according to $P_{con} = P_3 + P_4$. However, there may be other replenishment strategies for the nodes considering the energy consumption of the entire topology. In Figure 3.2(c), node 3 follows the same route while landing, on the other hand node 4 does not. Node 2 is moved to former position of node 3, and node 4 is moved to old coordinates of node 2, simultaneously. Applying such a strategy gives an energy consumption according to $P_{pro} = P_3 + P_4^{'} + P_2$ and this value may be less than $P_{con} = P_3 + P_4$ computed for the scenario in Figure 3.2(b). Considering the energy consumption profile and flight characteristic of an ABS, a flight planning for the aerial topology can be obtained as in Figure 3.2(c) where node 3 is not directly replaced by node 4.

In the literature, pickup and deliver problem is offered to solve similar problems for terrestrial scenarios with data delivery objectives. [63] proposes a hybrid approach compounding linear and integer programming. The authors also considers collision constraint during path planning process. In [64], the authors try to minimize delivery time and distance traveled by proposing a new scheme named Collection and Delivery Problem with Transfers. Thus, in the thesis, a more formal definition of the illustrated problem is presented as an APDP with some alteration to the general PDP defined in [65]. Moreover, ILP approach can be employed to provide a formulation as stated in [66] and [67]. As a consequence, an analogy for our problem domain is provided below and the problem is formulated with Eq. 3.1-3.4.

- The predefined drone locations can be seen as the consumers (V^c) in the original PDP that needs the products i.e. the ABSs;
- Each edge between (V_i, V_j); $i \neq j$; $i, j = 1, \ldots, N+1$ has a cost $c_{ij} \in \mathbb{Z}i$. The costs on the graph edges are assigned as stated in Section 4.2.1 considering the energy consumption characteristic of a corresponding traversal;
- The capacity of each drone can be considered as 1, i.e. each drone carries an ABS, as well as required volume of each consumer can also be considered as 1, i.e there is need for one ABS at each predefined drone location.

According to the mentioned characteristic, a simplified version of PDP with less constraints can be given as APDP with the following ILP definition:

$$\text{minimize} \qquad \delta = \sum_{V_i, V_j \in V} c_{ij} \cdot d_{ij} \tag{3.1}$$

$$\text{subject to} \qquad \sum_{V_i \in V} d_{ij} = \sum_{V_i \in V} d_{ji} = 1, \; V_j \in V^c \tag{3.2}$$

$$l_t \in \{0, 1\}, \; t = 1, \ldots, N \tag{3.3}$$

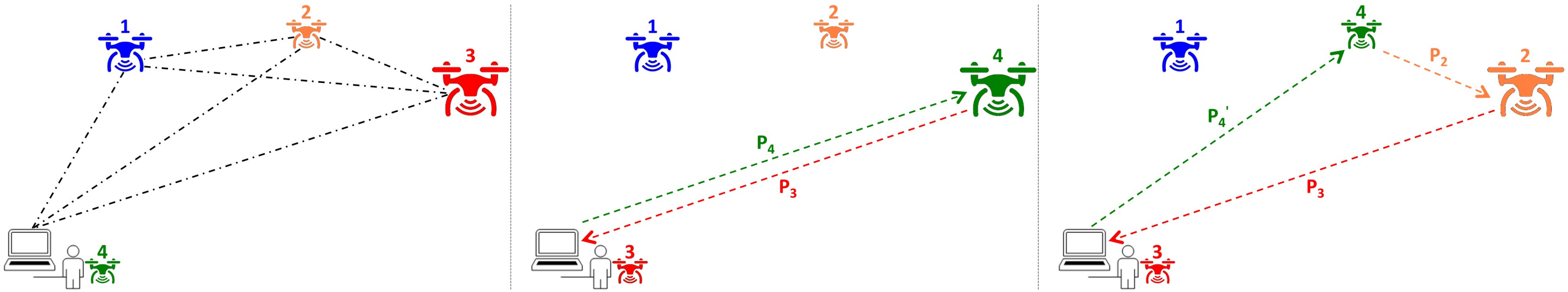
$$d_{ij} \in \{0, 1\} \tag{3.4}$$

where Eq. 3.1, the objective function, minimizes δ whenever an ABS replenishment is required; Eq. 3.2 provides that there is one ABS at each predefined location; Eq. 3.3 guarantees that each ABS has a load 0, i.e. in the predefined position; or has a load 1, i.e. traveling in the topology to get to the destination; and Eq. 3.4 represents a decision variable to illustrate the path between (V_i, V_j) is traversed or not.

The average endurance for a drone (η), i.e. the flight duration of a single ABS in an aerial topology can be calculated according to the following formula:

$$\eta = Battery\ Capacity\ (Ah) \times \frac{Discharge\ (\%)}{Average\ Amp\ Draw\ (A)} \times 60 \tag{3.5}$$

where $Battery\,Capacity$, $Discharge$, $Average\,Amp\,Draw$ are material specific variables and 60 is a constant to obtain the value in minutes. *Average Amp Draw* varies according to the power required by an ABS and directly affects the endurance. In the thesis, we model the topology with a digraph $G = (V,E)$ with $N+1$ vertices, where N is the number of ABSs in aerial network and 1 is the centralized terrestrial controller, and $(N)(N+1)$ edges, as a property of digraph. A complete directed graph, digraph, is the most appropriate candidate to model the aerial topology because of the fact that energy consumption of a UAV varies for different directions of a traversal. Hence, a cost value is assigned for each directed edge to present the required amount of energy for traversing that edge. Moreover, three different cost assignment approaches are investigated to provide a cross validation on the proposed scheme. The details of the approaches are given in Section 4.2.1. After constructing the topology digraph using one of the graph modeling approaches, we propose an algorithm that decides the most suitable flight planning to provide an endurance augmentation. Moreover, total number of replenishments for the operation is also considered according to η parameter. Assume that η_i is the endurance value of i^{th} ABS, then there should be γ_i replenishment for this ABS calculated as $r_i = t_e/\eta_i$. The total number of replenishments in the topology i.e. the replenishment factor, can be calculated as $\gamma = \sum_1^N \gamma_i$, where N is the number of ABSs. A comparison for the effect of different strategies on the δ, γ, and η parameters is given in Section 5.2.1.



(a) Graph representation of topology.
(b) A simple drone replenishment strategy.
(c) An energy aware replenishment strategy.

Figure 3.2 : An aerial network topology with three ABSs and a terrestrial drone controller.

4. PROPOSED SYSTEM MODEL

The proposed system architecture studied in the thesis is given with Figure 4.1. There are two major parts named End User Application Wrapper that includes underlying implementation details and the Flight Planner Framework that presents the proposed state of the art. In the figure, a flow of a single service call is also indicated by labeling them with numbers in red ribbons. Whenever the call is reached to the system, it is processed by End User Application Wrapper, then is delegated to the Flight Planner Framework and finally responded by End User Application Wrapper, again. In this section, the implementation details for each part of the system model is presented as following.

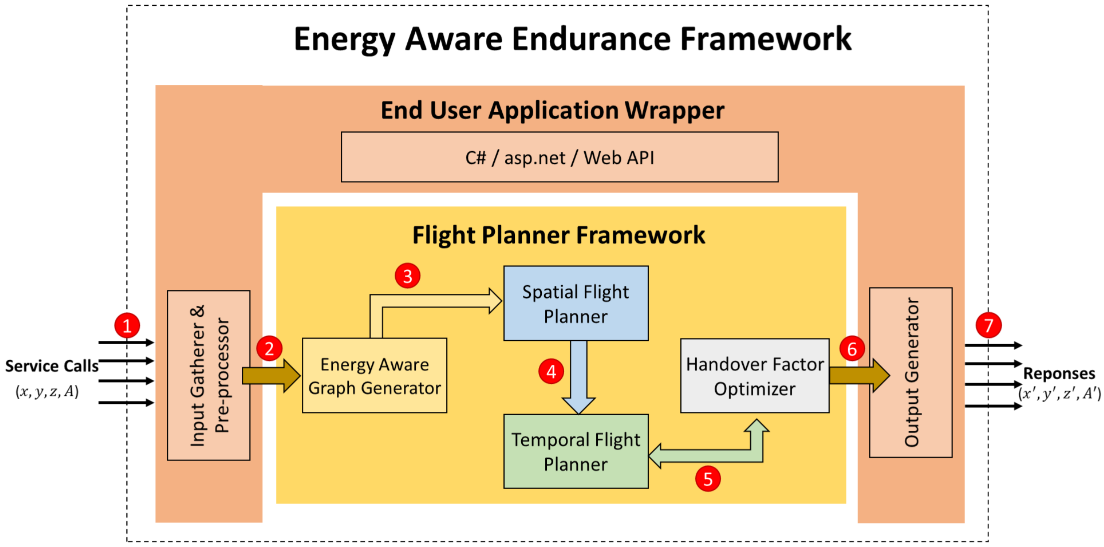


Figure 4.1 : The proposed system architecture.

4.1 End-user Application Wrapper

End User Application Wrapper part of the proposed system model includes the implementation details of the underlying Flight Planner Framework. C# programming language with asp.net framework is used during the implementation. This part is developed considering three major components as service calls, implementation and responses.

4.1.1 Service calls

The service call for the proposed system model takes four arguments as (x, y, z, A) where x, y, z triple defines the coordinate system values of an ABS and A defines the attributes of the ABS. These attributes include a complex object of each property defined in MAVLink protocol such as remaining battery percentage, flight duration, total amount of consumed energy, number of connected end-users, etc. The data required for the Flight Planner Framework is extracted from the object and delegated to the Flight Planner Framework. The preferred format for inputs is determined as JSON for the system but different data serialization formats can also be implemented support different kind of requests.

4.1.2 Implementation details

A Web API service is provided in the system to communicate with controllers from remote application servers or ABS software. In this way, it becomes easy and flexible to embed the proposed framework for each topology controlling system. Different end system softwares can give some input sequences in requested format to our application server, and get an output sequence indicating the most suitable flight planning decision for the desired topology. Moreover, a variety of input formats and output formats can be generated on demand in the future thanks to the restful web service architecture. There is an input gatherer and pre-processor part, and an output generator part to enable client-specific input and output formats. Thus, we will not restrict the customers of the system to a use certain format.

4.1.3 Responses

The responses of the system to each ABSs in the aerial topology are in the same format with service call as (x', y', z', A'). Here, x', y', z' triple represents the new coordinate values of a corresponding ABS after a replenishment decision and A' indicates the new attributes assigned to the ABS. This response, in summary, includes the new geographical location of an ABS, number of handovers to be performed, etc. Only JSON format is supported for the implementation, but as a future work, this can be improved for other formats.

4.2 Flight Planner Framework

The Flight Planner Framework given in the proposed system architecture (Figure 4.1) is highlighted in Figure 4.2. It has four major components as a Digraph Generator, Spatial Flight Planner, Temporal Flight Planner and Handover Factor Optimizer. Moreover, a secondary Optimality Checker for the Spatial Flight Planner is also provided to investigate a negative cycle. The details of each components are given in this section.

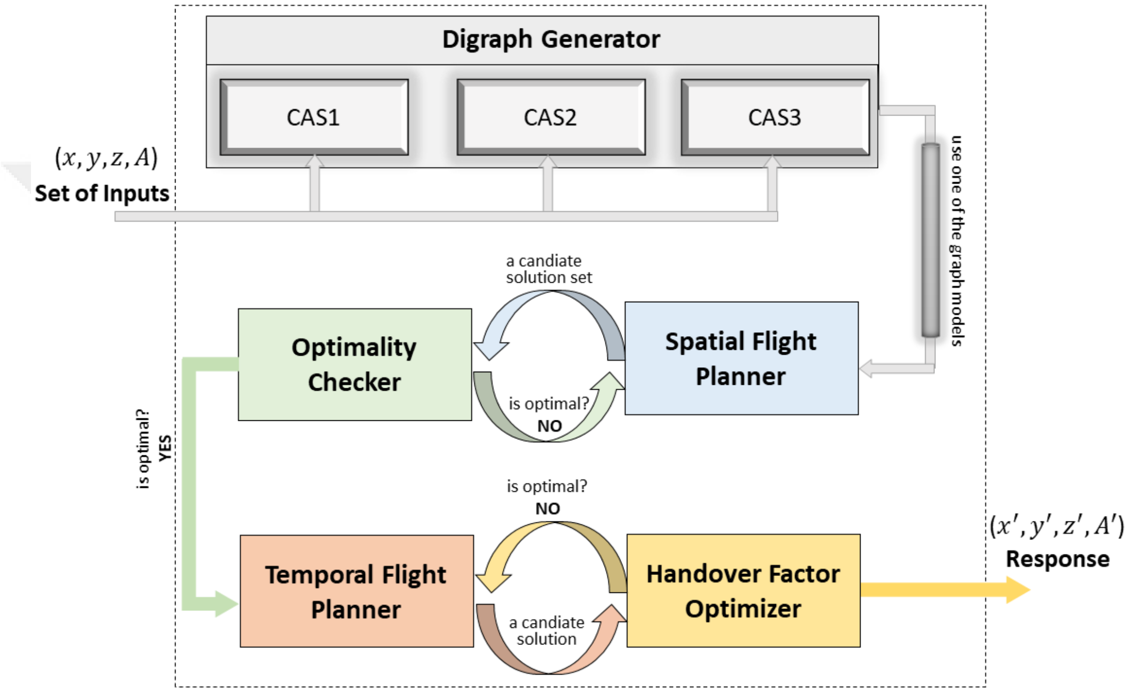


Figure 4.2 : The flight planner framework.

4.2.1 Digraph generator

In the thesis, a digraph model for an aerial topology is proposed considering that the edges have energy consumption related costs through the traversal of a path by a UAV. The Digraph Generator of the proposed framework constructs a topology digraph considering the energy consumption model of a UAV. The energy consumption model studied in the thesis is similar as in [68] in which the authors assert that hovering consumes more power than forward flying with an optimal velocity; however, a forward flight with high velocity consumes much more energy than hovering. In this thesis, as stated in the assumptions of Section 3.1, high-speed replenishments are considered where a drone speed exceeds 60 km/h. Hence, the same energy consumption model in [68] holds for the proposed framework and studied scenarios.

Unfortunately, there is no single formula to represent the energy consumption amount through a flight route. Energy consumption of a rotor is affected by many factors such as propeller angles, environmental conditions (wind, rain, etc), speed, on-board weight, and etc. For all of the mentioned factors, an opposite or parallel force is experienced by the drone. Therefore, we try to provide an abstract energy consumption related costs by taking into account the gravity force, the determinant one among all of the others. For this reason, we present three different cost assignment strategies to provide an appropriate graph model that will be used by flight planner algorithms to find out the minimum energy consumption during a replenishment. For these strategies, different characteristics of a UAV traversal is taken into account as stated in Section 4.2.1.1, Section 4.2.1.2, and Section 4.2.1.3. In the end, we evaluate their effects by comparing them with a simple replenishment approach that directly replenishes two ABSs without considering any information about the topology.

4.2.1.1 Cost assignment strategy 1 (CAS1)

This approach assigns a cost for a path traversal considering the job against/parallel to the gravity force. It punishes the moves containing vertical components opposite to the gravity force and encourages the ones in the same direction with it. Hence, it assigns a cost of 1 or -1 for going up and going down, respectively. Moreover, it is neutral to hovering and assigns 0 for preserving the same altitude. In brief, this approach only considers the vertical component of a move and assign a cost to the edge as -1, 0 or 1. This situation provides some alternative solutions to a simple replenishment strategy. On the other hand, the length and horizontal components of the traversal are not considered. Therefore, this strategy has less information about energy consumption on a corresponding path; however, is practical to eliminate some probable solution candidates consisting of movements opposite to the gravity force that require lots of power.

4.2.1.2 Cost assignment strategy 2 (CAS2)

The lack of traversal length in CAS1 is fulfilled within this strategy, named CAS2. This approach considers the Euclidean Distance between two ABSs given with $cost(s,d) = \sqrt{\sum_{i=1}^{3}(d_i - s_i)^2}$ as a coefficient to the values obtained in CAS1 and multiplies the corresponding values with each other. For a post processing, the cost values are normalized according to the one that have the greatest absolute cost in order to provide a range between $[-1,1]$. In brief, this strategy generates relative cost values for each edge in the graph considering their magnitudes and this provides more information about the graph compared with a simple replenishment approach and CAS1.

4.2.1.3 Cost assignment strategy 3 (CAS3)

This approach takes into account the Manhattan Distance instead of the Euclidean Distance as in CAS2 considering the fact that energy consumption cost varies according to different directions contained in a move. Thus, it provides $cost(s,d) = (\sum_{i=1}^{2} |(d_i - s_i)|) + (d_3 - s_3)$ as a cost assignment formula considering the vertical and horizontal components of a path traversal in separate. After calculating the cost values for each edge, a normalization process is again applied to get relative cost of edges between $[-1,1]$. In brief, it gives more information about the topology graph compared to a simple replenishment approach and CAS1; and provides different information compared to CAS2.

4.2.2 Spatial flight planner

The proposed Spatial Flight Planner algorithm aims to provide a flight plan with minimum cost on the generated digraph at a given time t. As the digraph may have negative costs on its edges, Bellman-Ford algorithm allowing negative costs are used. Moreover, the algorithm is implemented with DP approach in order to get a back trace and check for the optimality of the solution candidate.

Algorithm 1: The Spatial Flight Planning Algorithm

Data: A digraph $G = (V,E)$, a source vertex i.e. the centralized terrestrial drone controller $s \in V$, relaxation value (r)

Result: A solution candidate with shortest path from s to $v \in V$

```
iterate cost of all edges with r value ;
initialize l_t[i] = 0, for all i < N ;
initialize d[v][0] = ∞ for v ≠ s ;
initialize d[s][i] = 0, for all i < N ;
for i ← 1 to N − 1 do
    for each v ≠ s do
        d[v][i] = min(cost(v,x) + d[x][i − 1]) where (v,x) ∈ E
    end
end
backtracke d matrix and fill l_t array with 1 accordingly ;
∀ v output d[v][n − 1], l_t array
```

Algorithm 1 takes three inputs as the topology graph, position of source vertex and a relaxation value. In the algorithm, the landing path of a drained drone is not considered, because it has the same affect for all solution candidates and does not affect the decision to be taken. To replenish the landing one with a new drone, the source vertex of the algorithm is chosen as the terrestrial ground controller. The algorithm initialize some variables to be used in lines 1-3. The relaxation value $r = 0$ by default, unless it is changed by the optimality check in Algorithm 2. After initialization steps, DP approach is applied to find a solution candidate recursively.

Algorithm 1 provides a shortest path candidate from source to destination and there are N drones in the topology. In our model, each drone traverses at most one path to maintain the topology whenever a replenishment occurs. Therefore, if a shortest path is found consisting only one edge, it means there is a direct replenishment between the drained drone and the new one. Otherwise, it is supposed that the new drone traverses across the first edge in the shortest path, the drone at that reached vertex traverses the second edge, and so on. After deciding on a solution candidate, the result is examined by Algorithm 2 and some iterations may occur between two algorithms if needed.

4.2.2.1 The optimality checker

The Optimality Checker Algorithm for provided solution candidate is given in Algorithm 2. The algorithm is responsible for determining whether there is a negative cycle or not by examining the back trace of the solution candidate. If there is no negative cycle, the solution candidate becomes a solution and delegated to the Temporal Flight Planner as the initial population. If the algorithm detects a negative cycle, than it computes a relaxation value r, i.e. the magnitude of the lowest negative cost, and assign it to Algorithm 1 to repeat the solution search process again.

Algorithm 2: The Optimality Checker Algorithm

Data: Trace of the shortest path from s to d

Result: Optimality decision, relaxation value (r)

1 **foreach** $v \in$ *back trace* **do**
2   check for how many times v is examined ;
3   **if** *more than N-1 examination* **then**
4   decide a negative cycle and stop ;
5         $r \leftarrow$ the absolute value of the edge with the lowest cost;
6   return r to $Algorithm$ 1;
7   **end**
8 **end**
9 return a positive optimality decision ;

Algorithm 2 iterates over all nodes in the back trace with the for-loop given between 1-7. During this process, if the algorithm examines any node more than n-1 times, then it must be considering paths containing more than n-1 edges, i.e. paths with cycles. The only way for that situation is containing a negative cycle on the walk. Therefore, the algorithm stops, calculates an r value and the solution search procedure returns to Algorithm 1. If Algorithm 2 iterates over all nodes and does not halt, then in line 8, it decides that the provided solution candidate is optimal at time t.

4.2.3 Temporal flight planner

The proposed Temporal Flight Planner extends the optimum search space in the time domain by applying GA with an initial population provided by the Spatial Flight Planner. In this way, it is aimed to investigate the effects of a decision given for a certain moment t considering the future opportunities in the whole search space. Otherwise, a decision taken for time t may deteriorate a possible minimum energy consumption opportunity at $t+t^+$ where t^+ represents another amount of time. This situation is called as getting stuck on the local optimum solution and should be avoided to provide a global optimum solution during the operational time. For this purpose, an algorithm is implemented and its pseudo-code is given in Algorithm 3.

Algorithm 3: The Temporal Flight Planning Algorithm

Data: A digraph $G = (V, E)$, discarded soltuion candidate set s_d, an initial population p_0, estimated operational time t_e

Result: A solution candidate set s_c with minimum energy consumption

1 initialize $t_r = t_e$ for the remaining time ;
2 compute fitness value f for p_0 ;
3 **while** $t_r > 0$ **do**
4   **while** *not converged to a specific fitness value* **do**
5   select parents from p_0 ;
6   crossover genes and generate a new population ;
7   mutate on the new population ;
8   update f ;
9   **end**
10   insert new candidate into s_c ;
11   recompute t_r ;
12 **end**
13 output s_c ;

Algorithm 3 takes four arguments as the topology graph, discarded solution candidates (initially an empty set), an initial population and the estimated operational time for the network. Then, some variables are initialized in lines 1-2 i.e. a remaining time for the estimated operational duration and fitness value for the initial population, respectively. In the outer while loop between lines 3-12, the time elapsed for the operational duration is checked whereas in the inner while loop between lines 4-9, GA is applied. As long as the fitness value of the recent population is not converged, the inner while loop selects new parents, crossovers genes, mutates on the new population and recalculates the fitness value. After the inner while loop completes, in line 10, the solution with converged fitness value is stored as a solution candidate. In line 11, the remaining time is updated and the time domain is extended if there is still some time remaining before the termination of the network deployment. Finally, in line 13, the solution candidate set is returned to the Handover Factor Optimizer, Algorithm 4.

4.2.4 Handover factor optimizer

The proposed Handover Factor Optimizer is aimed to check the solution candidate set whether it provides a handover factor below a threshold, or not. Thus, the end-user QoE is improved against end-system initiated handovers. For this purpose, an algorithm is developed as given with Algorithm 4.

Algorithm 4: The Handover Factor Optimizer Algorithm

```
   Data: A digraph G = (V,E), a solution candidate set s_c, set of end-users in
         each ABS cluster s_u, handover factor treshold h_t
   Result: Optimality decision, discarded solution candidate set s_d
1  initialize handover count h = 0 ;
2  foreach c ∈ s_c do
3  |   foreach u ∈ s_u do
4  |   |   update h
5  |   end
6  end
7  if h > h_t then
8  |   decide a negative optimality decision ;
9  |   randomly chose a population p from s_c ;
10 |   return to Algorithm 3 with s_d = s_c and p ;
11 end
12 output a positive optimality decision ;
```

Algorithm 4 takes four arguments as the topology graph, a solution candidate set, set of end-users in each terrestrial cluster and a handover factor threshold. In line 1, a parameter is initialized to keep the number of current handover counts. The nested for loops between line 2-6, the handover count parameter is increased according to the number of end-system initiated handovers. Then, in line 7, a comparison between the total number of end-system initiated handovers and the threshold for that value is compared. If the threshold is exceeded, then a negative optimality decision is taken, a new initial population and discarded set of solution candidates are decided and returned to Algorithm 3 as the arguments. Otherwise, a positive optimality decision is made and the algorithm terminates.

4.3 Analysis on the Proposed System Model

A running time complexity analysis is conducted considering the algorithm implementations for the proposed framework. Moreover, a space complexity analysis is also stated to illustrate the memory burden of the implementation. Hence, the analyzes for each of the aforementioned algorithms are presented as following.

Algorithm 1 takes time proportional to the out degree of $|v|$. So, the inner for loop between line 5-7 takes time proportional to the sum of the out degrees of all the nodes, which is $O(|V|)$. Considering all of the edges in the digraph, the total time can be calculated as $O(|E| \cdot |V|)$. By applying the relation between $|V|$ and $|E|$, $|E| = |V| \cdot$

$(|V|+1)$, the worst time complexity of Algorithm 1 can be represented as $O(|V|^3)$. Moreover, constructing the back trace of the proposed shortest path takes $O(|E|+|V|)$ time complexity with DP approach. However, it is just a low-order term and can be neglected in the overall running time, $O(|V|^3)$. Besides the time complexity of Algorithm 1, it requires $|V|$ amount of space for back tracing, so the space complexity of Algorithm 1 can be decided as $O(|V|)$.

The running time of Algorithm 2 is self-explanatory and can be presented as $O(|V|)$ according to the for-loop between lines 1-7. The algorithm does not require any additional space for running, so space complexity of it can be seen as $O(1)$. Both of the time and space complexities of Algorithm 2 are low-order terms compared to the ones of Algorithm 1. Therefore it can be stated that, Algorithm 1 decides the run time and space complexity of the proposed Spatial Flight Planer as $O(|V|^3)$ and $O(|V|)$, respectively.

Algorithm 3 implements GA inside a time iterator while loop. Hence, the outer loop between 3-12 does not depend on the input number, whereas the runtime complexity of the inner loop between 4-9 is directly related with GA implementation. A usual implementation of GA has $O(g \cdot (p \cdot i + p \cdot i + p))$ (which corresponds to $O(g \cdot p \cdot i)$) computational time complexity where g is the number of generations, p is the population size and i is the size of individuals. If the number of vertices in the topology is considered, in the worst case g, p and i can be set to V. Thus, the worst case computational time complexity of Algorithm 3 can be represented as $O(|V|^3)$. Similarly, the space complexity of Algorithm 3 can be asserted as $O(|V|)$ because of the storage required to keep generations, populations and individuals which are directly related with v.

The running time of Algorithm 4 can be presented as $O(V \cdot M)$ because of the nested for loops where V is the number of vertices and M is the number of terrestrial users. On the other hand, the space complexity of Algorithm 4 can be asserted as $O(1)$ because of the storage need only for some parameters during the execution.

As a conclusion, considering all of the proposed algorithms, the run time complexity of the whole framework presented in Figure 4.2 can be considered as the biggest value among $O(|V|^3)$ and $O(V \cdot M)$. A third order polynomial time complexity can be seen as problematic for large number of inputs; however, for aerial network topologies there are at most dozen of nodes in the topology, so it can asserted that the run time complexity of the proposed framework does not diverge in practice. Moreover, it can be asserted that the average running time of the system is substantially lower in practice. The space complexity of the proposed framework is proportional to the number of vertices and can be presented as $O(|V|)$. Thus, it can be asserted that the proposed framework is practical according to the time and space complexity considering the number of ABSs and number of terrestrial users in presented scenarios. As a consequence, it can be claimed that the proposed framework is able to respond in a reasonable amount of time and is feasible for aerial networks according to the run time and space complexity analyzes.

5. EVALUATION OF THE STUDY

The evaluation of the proposed system model is performed under three different scenarios using a set of simulation tools and compared with a simple replenishment strategy. The simulation methodology with the tools used and the performance evaluation under presented scenarios are introduced in this section. At the end, the outcomes are presented with respect to the evaluation metrics from the end-system perspective as well as an end-user perspective.

5.1 Simulation Methodology

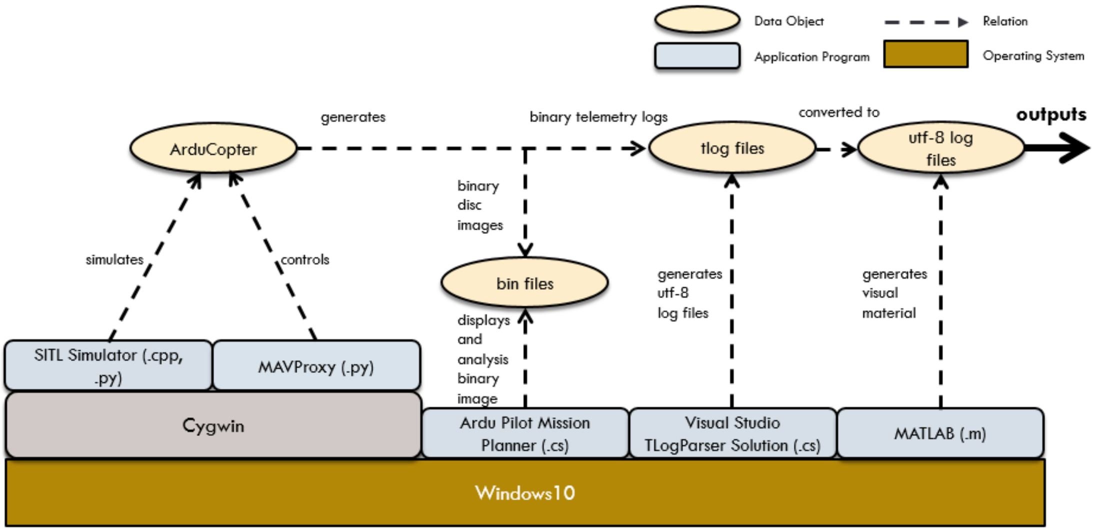


Figure 5.1 : Simulation methodology.

In the thesis, a simulation and a post processing environment are prepared according to Figure 5.1. In the figure, the operating system used is illustrated with a rectangle, software programs are given with rounded corner rectangles, data objects generated from the simulation are presented with ellipses and the relation between different objects are introduced with arrows. Windows 10 operating system is chosen as underlying environment for application programs. Cygwin software is set up to emulate UNIX commands for MAVProxy drone controller and Software in the Loop (SITL) simulator software. The SITL simulator creates an ArduCopter instance to emulate a quad rotor UAV on Google Map API. This

UAV is controlled from MAVProxy command line with required commands during the simulation. After simulating the scenarios, logs files are dumped from the controller in two different formats as binary disc images and binary telemetry log files. *Ardu Pilot Mission Planner* software is used to analyze and display flight data from a graphical user interface. Moreover, a data cleaning operation is conducted to remove unnecessary information in the log files through a *C#* project solution named *TLogParser*. Then, some graphical representation of the clean data is obtained through a *MATLAB* project. Eventually, the outputs of the simulation are represented with a variety of visual material. The implementation languages for additional patches are also given within brackets in the figure. For instance, some $C++$ and *pyhton* scripts are provided for SITL simulator whereas *C#* functions are prepared in Visual Studio for post processing.

5.2 Performance Evaluation

Evaluation scenarios for the proposed framework with three different cost assignment approaches and also for a simple replenishment strategy is given in Figure 5.2. In this figure, a stadium is considered for a social event with three distinct coverage areas under different communication overhead. In S=(3,3000), 3 ABSs indicated with green color provide an aerial topology for the case with 3000 users within the green coverage area. In S=(6,6000), a moderate overhead with 6000 users placed in blue coverage area is taken into account and 6 ABSs, indicated as blue, are deployed to create an aerial topology. Finally, in S=(12,12000), a dozen of red ABSs construct the topology to serve 12000 users within red coverage area. For all of three scenarios, an endurance of four hours is chosen as the operational time for the aerial network. The summary of the simulation parameters is given with Table 5.1. Performance evaluation of different strategies are compared for the given test environment from the end-system perspective according to normalized energy consumption (δ) parameter, number of replenishments i.e. the replenishment factor (γ) parameter and average endurance per drone (η) parameter. Moreover, the effect of the proposed framework on the QoE of an end-user is also investigated considering the number of end-system initiated handovers i.e. the handover factor (ψ) parameter. It is clear that the proposed framework causes a number of additional handovers during the operational time because of some inner replenishments through a flight planning. As a results, the average access link latency and packet loss ratio parameters are affected and this may deteriorate QoE of an end-user. The trade-off between the energy saving in the end-system and performance deterioration of an end-user is also examined throughout the evaluation.

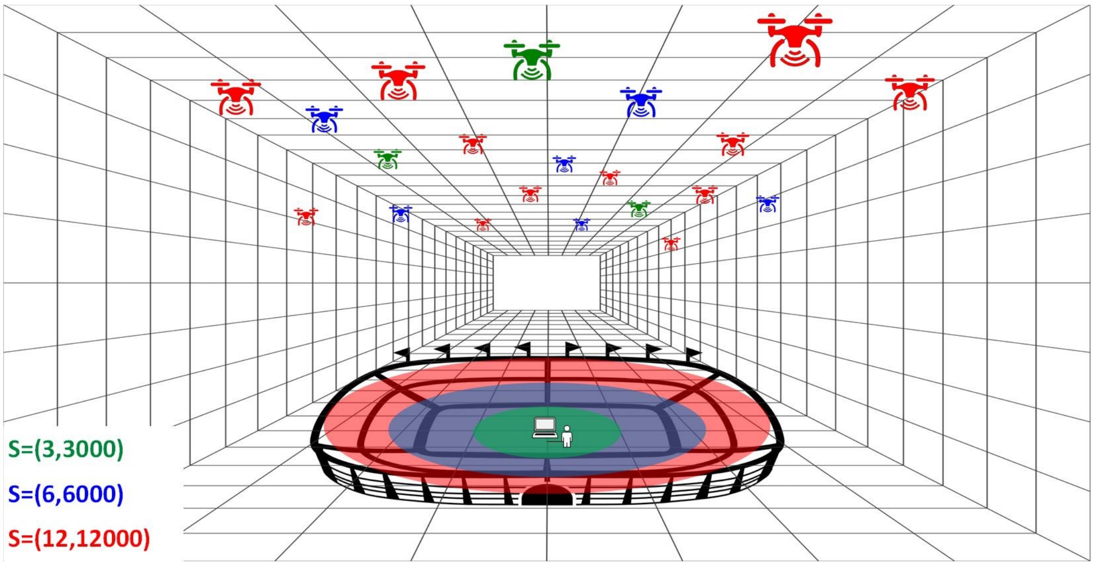
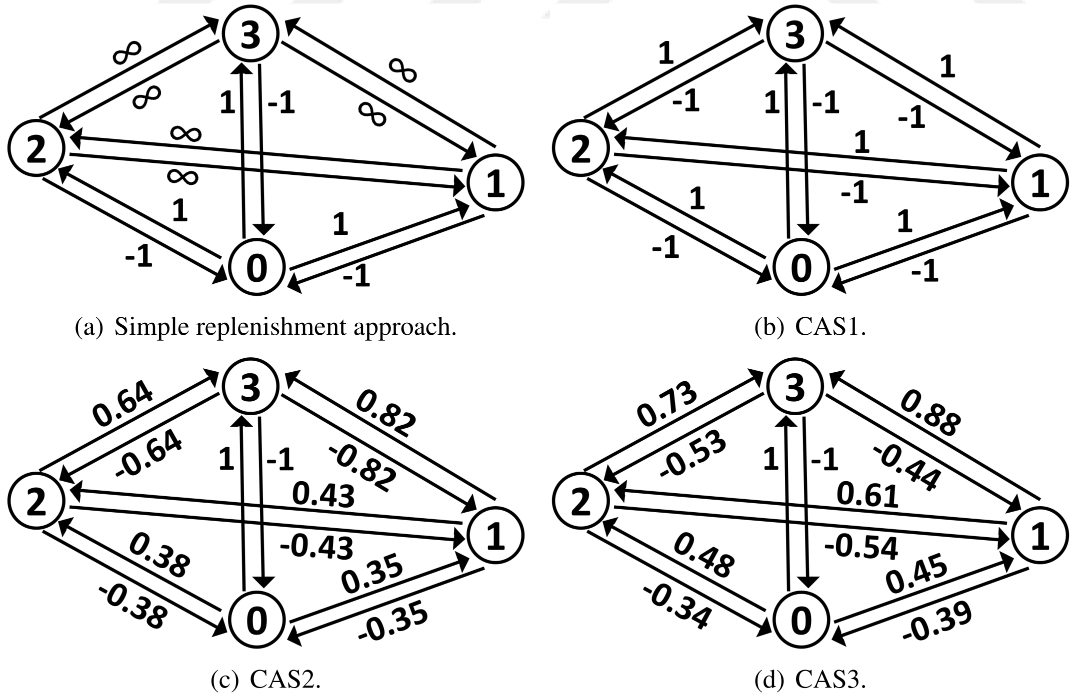


Figure 5.2 : Scenarios considering different scale of coverage areas and overhead.

	S=(3,3000)	S=(6,6000)	S=(12,12000)
Number of Users	3000	6000	12000
Number of ABSs	3	6	12
Coverage Area (m^2)	5000	10000	15000
Duration (min)	240	240	240

Table 5.1 : Simulation parameters for different scenarios.

An example topology model provided by the proposed framework is given in Figure 5.3. The figure illustrates four digraphs generated with respect to different approaches for one of the scenarios within S=(3,3000) in order to provide a better understanding of Digraph Generator in our proposed framework. Figure 5.3(a), Figure 5.3(b), Figure 5.3(c) and Figure 5.3(d) represent traversal costs generated by simple replenishment approach, CAS1, CAS2, and CAS3, respectively. In the figures, node 1, node 2 and node 3 represent ABSs whereas node 0 represents the terrestrial drone controller. In Figure 5.3(a), the costs are assigned so that only a direct replenishment is permitted because of infinity values as energy consumption cost for some traversals. In Figure 5.3(b), only 1 and -1 are assigned as traversal costs considering the vertical direction of the move. In Figure 5.3(c), traversal costs are computed according to CAS2 and normalized to get values between [-1, 1]. Similarly, in Figure 5.3(d), CAS3 is applied and a normalization is performed to assign costs. Note that, for all of the graphs, 0 costs that indicate hovering in the same node location are not shown for the sake of simplicity. In such an environment, consider that the ABS represented with node 2 is about to drain its battery after some time of its launch. According to the digraphs generated and costs included, the proposed framework generates different outputs for simple replenishment approach and the others. Considering the digraph of simple replenishment approach, a direct replacement between node 0 and node 2 is decided by the algorithm. On the other hand, at a specific time t, considering their digraphs and costs assigned for all of three other approaches, the proposed framework decides to place node 3 in the position of node 2, launch node 0 to the former position of node 3, and bring down node 2 using the same traversal as in simple replenishment approach. For an aerial topology with more drones as in S=(6,6000) and S=(12,12000), there will be different flight planning for each of the approaches considering the entire operational time and this leads different amount of overall energy consumption during the deployment.



(a) Simple replenishment approach. (b) CAS1.

(c) CAS2. (d) CAS3.

Figure 5.3 : Digraphs generated by different approaches for S=(3,3000).

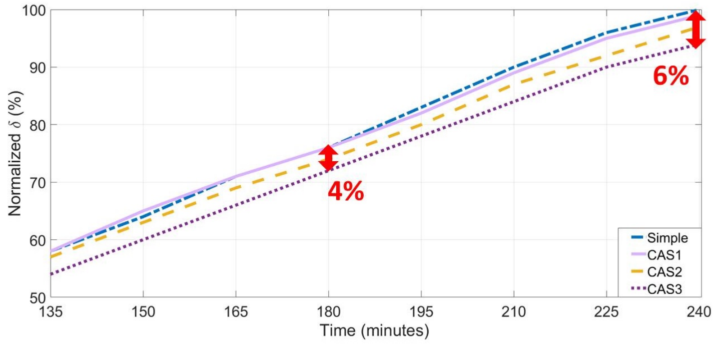
The rest of this section provides evaluation outcomes from the end-system perspective in Section 5.2.1 and also from an end-user perspective in Section 5.2.2 considering the simulation methodology and simulation environment aforementioned. Moreover, different service expectations of end-users are also taken into account and the effect of it on the proposed framework is also investigated in Section 5.2.3, again from both of the end-system perspective and an end-user perspective.

5.2.1 End-system perspective

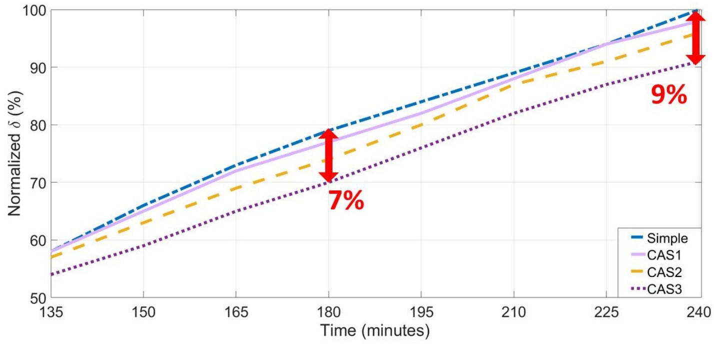
The performance metrics used for the evaluation from the end-system perspective are normalized energy consumption (δ), the replenishment factor (γ) and average endurance per drone (η). The performance of the proposed Spatial Flight Planner and Temporal Flight Planner algorithms on the proposed topology modeling approaches are investigated separately in Section 5.2.1.1 and Section 5.2.1.2. Moreover, they are also compared with a simple replenishment approach that directly changes ABSs in need without considering any information about the topology. Furthermore, the practical response time for the proposed framework implemantation using evolutionary algorithms is also validated and the closeness of GA implementation of Temporal Flight Planner to the global optimum solution for each of the evaluation criteria is also presented in Section 5.2.1.3.

5.2.1.1 Spatial flight planner

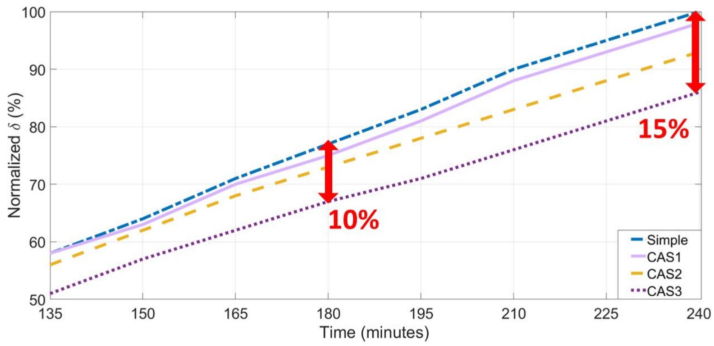
Figure 5.4 shows the normalized δ parameter throughout the simulation in three different scenarios. The energy consumption values obtained from simulation logs for each different approaches are normalized according to the biggest amount and values between 0 and 100 is obtained to provide a clearer illustration. Figure 5.4(a) represents the power consumption for S=(3,3000) considering aforementioned approaches. According to the results, the simple replenishment approach consumes most power as it reaches to 100%. On the other hand, CAS1, CAS2 and CAS3 consume 1%,3 %, and 6% less power than the simple one, respectively. The lowest improvement is achieved in S=(3,3000) which deploys only three ABSs to construct the aerial topology. For S=(6,6000) given with Figure 5.4(b), the improvements enlarge to 2% , 4%, and 9%. Figure 5.4(c) represents a remarkable improvement achieved in S=(12,12000) as 15% by applying CAS3. According to the evaluation results, the gap between the outcomes from the proposed approaches and from a simple replenishment strategy increases as the number of replenishments increase because of rising i) simulation time ii) network size. In Figure 5.4, the magnitude of red arrows



(a) S=(3,3000).



(b) S=(6,6000).



(c) S=(12,12000).

Figure 5.4 : Normalized energy consumption outcomes, δ, for different approaches, in studied scenarios.

located at each hour in x-axes illustrate this relation. The benefit of providing a flight planning on an appropriate topology model is clearly seen from the figure. Moreover, a major insight can be obtained from the study that applying CAS3 gives lowest δ values for all scenarios, because it provides more appropriate penalties for the moves against gravity force, and this leads to having more information about the relation between flight characteristic and energy consumption profile of an ABS. On the other hand, the simple replenishment approach always change a drained ABS with a new one without considering a flight planning strategy. Hence, it is expected to have a greater energy consumption outcome among the proposed approaches, because, the proposed framework decides the same flight planning with the simple replenishment approach, even in the worst case.

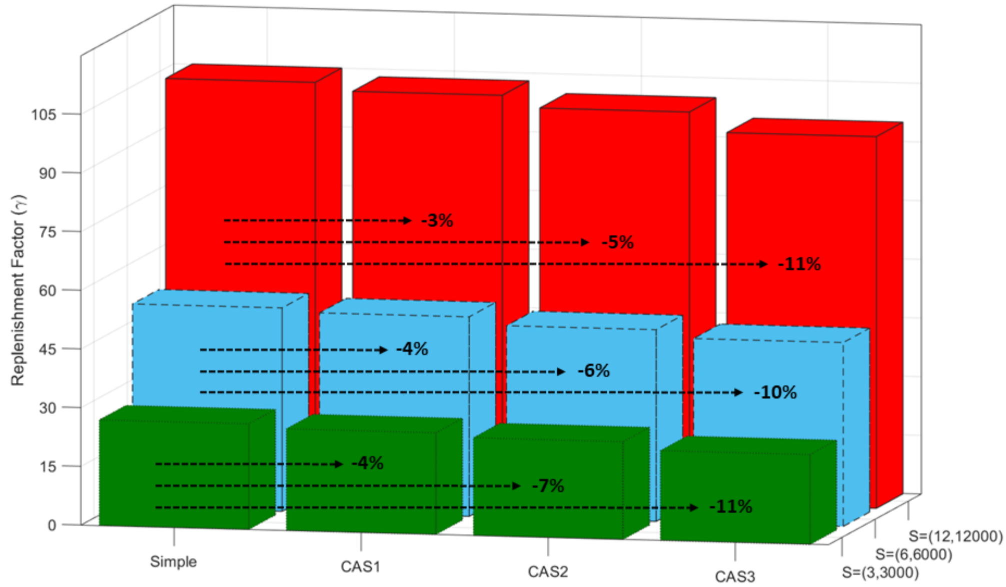


Figure 5.5 : The Replenishment Factor, γ, for different approaches, in studied scenarios.

Figure 5.5 presents the γ parameter obtained for four different strategies in three different scenarios. As seen in the figure, using CAS3 for the topology gives better results than the others in all scenarios since its graph generation strategy gives a better understanding in energy consumption profile of an ABS during a path traversal. A decrease of 11% is obtained by applying CAS3 for S=(12,12000) which is the largest improvement among the evaluation. Applying CAS1 does not make much sense compared to a simple replenishment strategy and gives similar outputs. The results obtained from the CAS2 are clearly better than CAS1 and simple replenishment approaches; however, worser than the CAS3, again. The difference in the same approach for different scenarios is arised from varying number of ABSs, inherently. Thus, the replenishment factor values obtained from S=(12,12000) are greater than the ones obtained in S=(6,6000) considering a corresponding approach and the same relation also exists between S=(6,6000) and S=(3,3000).

Figure 5.6 compares η values computed from simulation logs considering different approaches and test scenarios. According to the outcomes, the proposed approaches provide higher η values in all scenarios compared to a simple replenishment approach which uses no information about flight planning. Again, CAS3 gives the highest η values for all scenarios as a result of producing meaningful punishments against the

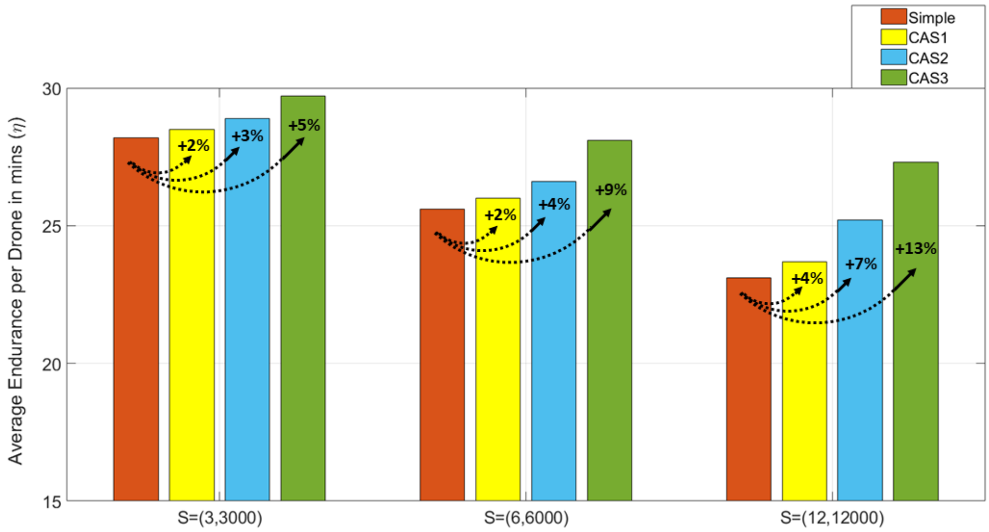


Figure 5.6 : Average endurance per drone, η, for different approaches, in studied scenarios.

moves opposite the gravity force. In S=(3,3000), the advantage of proposed approaches are not obvious, but even better than the simple one. The reason for this can be asserted that there is a small number of ABSs in the topology to utilize the proposed scheme. The best variation from the average flight endurance is obtained from S=(12,12000). There is a dozen of ABSs in the topology and modeling the graph using CAS3 provides 13% more flight endurance per ABS. The values in the graph are decreasing from S=(3,3000) to S=(12,12000). This can be explained with the size of geographical area covered which is depicted as in Figure 5.2. As the coverage area increases, some of the ABSs traverse longer paths and this leads to more power consumption during the flight that results a decrease in η value.

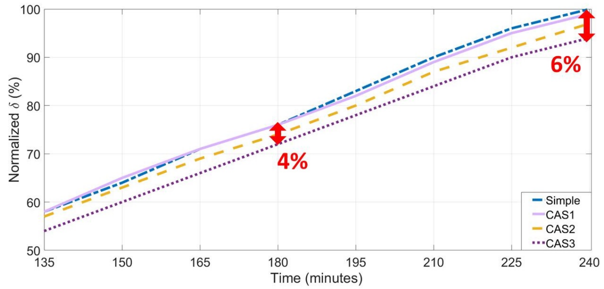
		Simple	CAS1	CAS2	CAS3	Max. Gain
S=(3,3000)	δ	100	99	97	94	**6%**
	γ	27	26	25	24	**11%**
	η	28.2	28.5	28.9	29.7	**6%**
S=(6,6000)	δ	100	98	96	91	**9%**
	γ	52	50	49	47	**10%**
	η	25.6	26.0	26.6	27.9	**9%**
S=(12,12000)	δ	100	98	93	85	**15%**
	γ	105	102	100	95	**11%**
	η	23.4	24.2	25.1	26.5	**13%**

Table 5.2 : Evaluation results for the single deployment of Spatial Flight Planner according to different scenarios and strategies.

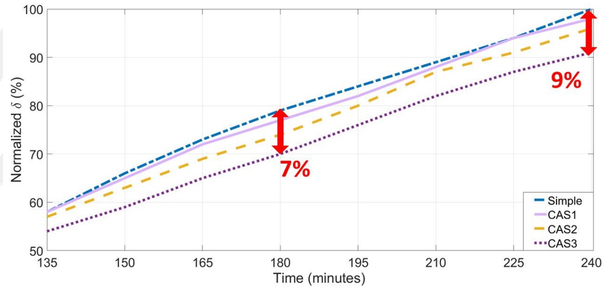
Beside graphical illustration of the performance evaluation, a summary of the evaluation results extracted from the simulation logs is given with Table 5.2. The table contains numeric values for three scenarios according to different approaches. Moreover, a gain obtained between the worst and the best approaches is also illustrated in the right most column. It is clearly seen from the table that, an appropriate energy consumption model for flight planning that represents convenient cost assignments provides a better performance outcome according to δ, γ, and η parameters.

5.2.1.2 Temporal flight planner

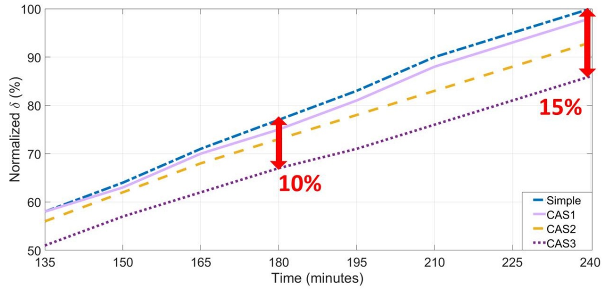
The performance evaluation of the proposed framework is extended considering the Temporal Flight Planner and a comparison is presented with respect to the performance metrics obtained from the deployment of only Spatial Flight Planner. The simulation scenarios presented so far are repeated for Temporal Flight Planner and the change in δ parameter is obtained as indicated with Figure 5.7. There are six sub-figures organized within three columns and two rows. The first row of Figure 5.7 includes the results from the deployment of only Spatial Flight Planning. On the other hand, the second row presents the outcomes from a cooperative deployment of both flight planning algorithms. Moreover, the first, the second and the thirds columns of Figure 5.7 illustrates the evaluation obtained from S=(3,3000), S=(6,6000), and S=(12,12000), respectively. According to the evaluation results, the cooperative deployment gives rise to a reduced energy consumption for each of the scenarios considering each of the proposed graph modeling schemes. The proposed CAS3 for graph modeling again takes the lead for all three scenarios because of the having more information about energy consumption characteristic of a UAV through a corresponding traversal. Compared with a simple replenishment approach, its energy consumption is decreased with a ratio of 20% when both flight planning algorithms are deployed. When Figure 5.7(b) and Figure 5.7(e) are compared, additional 5% energy gain is obtained between the single and cooperative deployments. Similar decrease in energy consumption can be witnessed between Figure 5.7(c) and Figure 5.7(f); and also between Figure 5.7(a) and Figure 5.7(d) considering the same graph modeling scheme. As a consequence, it can be asserted that Temporal Flight Planning further decreases the normalized energy consumption, δ, according to our simulation results for three different scale of scenarios and four different graph modeling approaches.



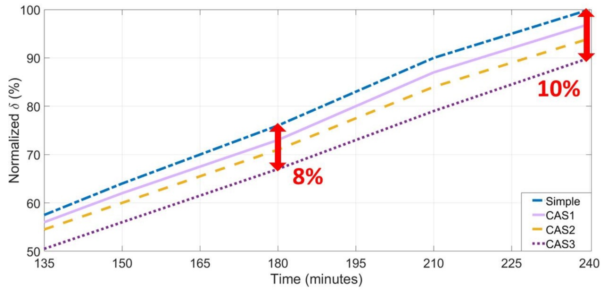
(a) Single deployment of Spatial Flight Planner on S=(3,3000).



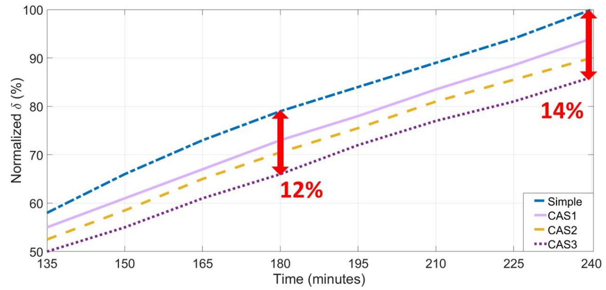
(b) Single deployment of Spatial Flight Planning on S=(6,6000).



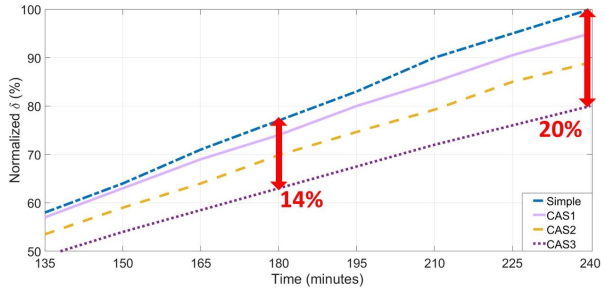
(c) Single deployment of Spatial Flight Planning on S=(12,12000).



(d) Cooperative deployment with Temporal Flight Planning on S=(3,3000.)

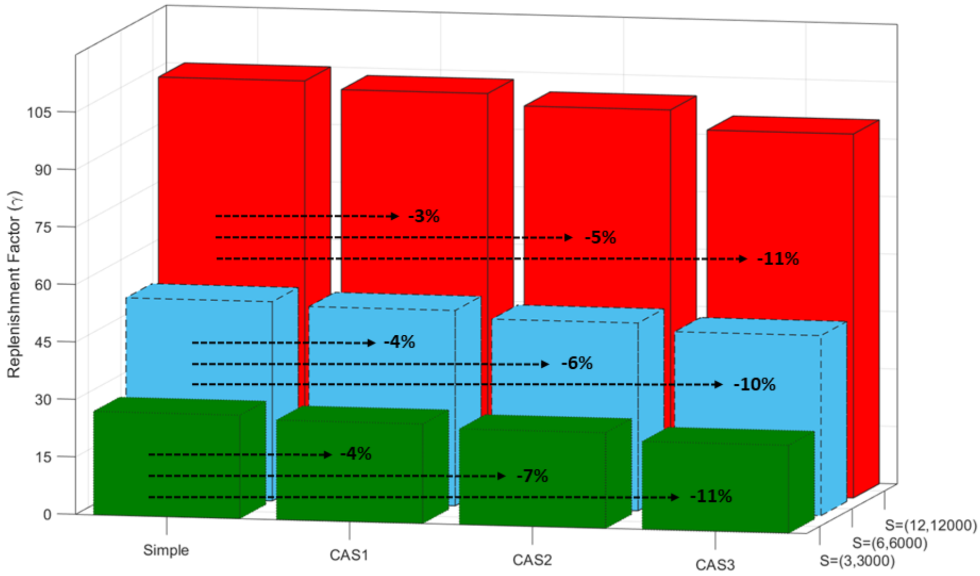


(e) Cooperative deployment with Temporal Flight Planning on S=(6,6000).

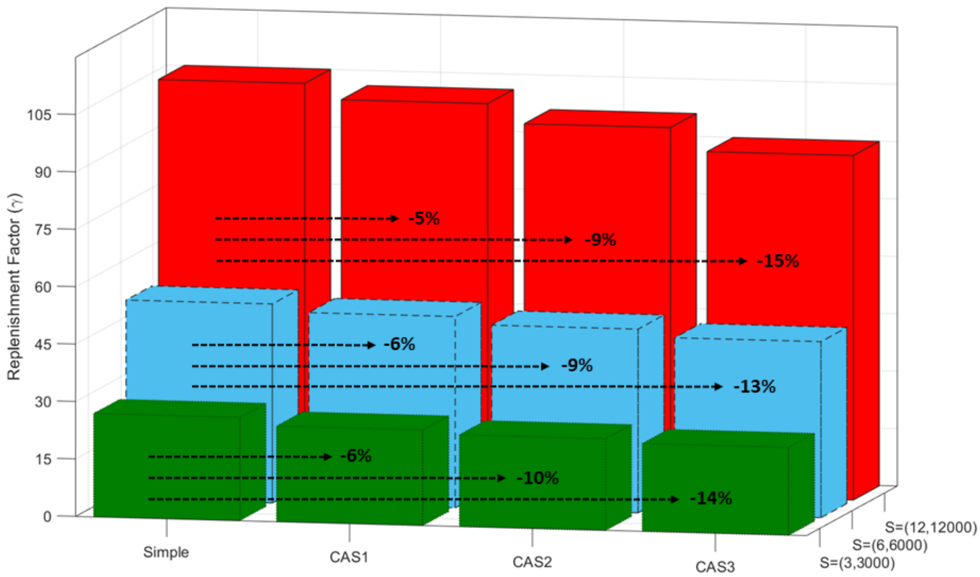


(f) Cooperative deployment with Temporal Flight Planning on S=(12,12000).

Figure 5.7 : Normalized energy consumption outcomes, δ, for different graph modeling schemes, in studied scenarios, considering a single deployment of Spatial Flight Planner and cooperative deployment with Temporal Flight Planner.



(a) The Earlier Version of the Proposed Framework with Spatial Flight Planner

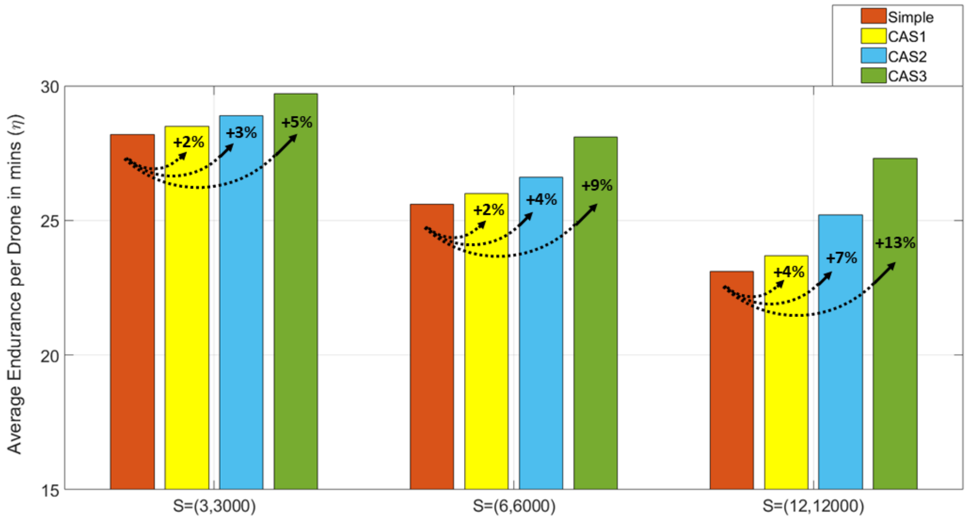


(b) The Revised Proposed Framework with Temporal Flight Planner

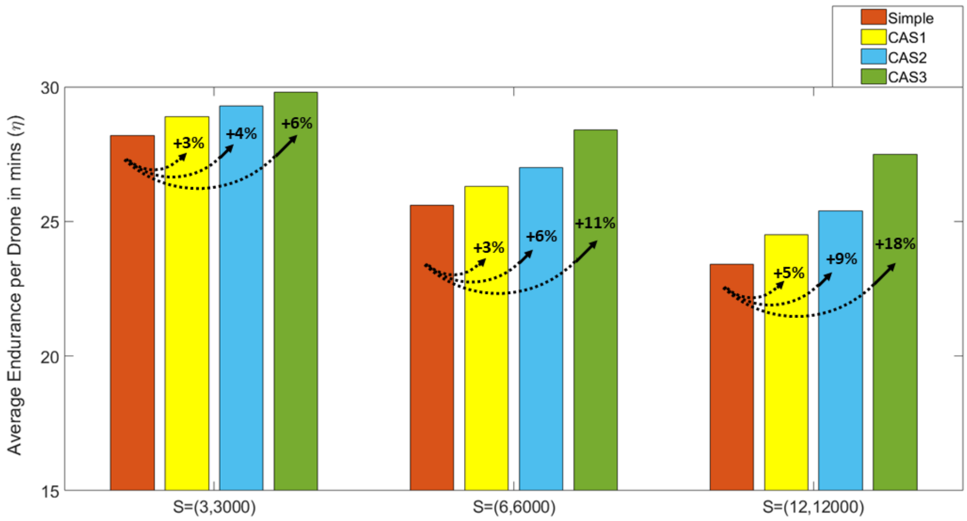
Figure 5.8 : The Replenishment Factor, γ, for Different Graph Modeling Schemes, in Studied Scenarios, Considering the Single Deployment of Spatial Flight Planner and Cooperative Deployment with Temporal Flight Planner

The effect of the Temporal Flight Planner deployment on the replenishment factor parameter, γ, is also investigated considering the studied scenarios and graph modeling approaches. The evaluation outcomes and the comparison of two different deployment schemes according to γ are given with Figure 5.8. When S=(12,12000), scenarios given in Figure 5.8(a) and Figure 5.8(b) are compared, it is seen that CAS3 gives rise to a decrease of 11% and 15%, respectively. Hence, it can be asserted that a further decrease on γ parameter is obtained with the deployment of Temporal Flight Planner.

Similar reductions on γ parameter can be seen from Figure 5.8(a) and Figure 5.8(b) considering the same graph modeling approach on a certain scenario. To sum up, the improvement with Temporal Flight Planner outperforms the single deployment of Spatial Flight Planner considering the γ parameter.



(a) The earlier version of the proposed framework with Spatial Flight Planner.



(b) The revised proposed framework with Temporal Flight Planner.

Figure 5.9 : Average endurance per drone, η, for different graph modeling schemes, in studied scenarios, considering a single deployment of Spatial Flight Planner and cooperative ceployment with Temporal Flight Planner.

The average endurance per drone parameter, η, is also investigated to evaluate the effect of Temporal Flight Planner and the outcomes are presented in Figure 5.9. When S=(12,12000) in Figure 5.9(a) and in Figure 5.9(b) are compared, it is seen that CAS3 provides 13% and 18% more η value than the simple replenishment approach. There is an increase of 5% thanks to Temporal Flight Planner for this specific case. Similarly, it is also seen from the figure that Temporal Flight Planner further improves the average endurance also for S=(3,3000) and S=(6,6000) under a certain graph modeling scheme. Thus, it can be asserted that η parameter is increased with the help of Temporal Flight Planner throughout our simulations compared to solo deployment of Spatial Flight Planner.

		Simple	CAS1	CAS2	CAS3	Max. Gain
S=(3,3000)	δ	100	99 $\rightarrow$ **97**	97 $\rightarrow$ **94**	94 $\rightarrow$ **90**	6% $\rightarrow$ **10%**
	γ	27	26 $\rightarrow$ **25**	25 $\rightarrow$ **24**	24 $\rightarrow$ **23**	11% $\rightarrow$ **14%**
	η	28.2	28.5 $\rightarrow$ **28.9**	28.9 $\rightarrow$ **29.2**	29.7 $\rightarrow$ **29.8**	5% $\rightarrow$ **6%**
S=(6,6000)	δ	100	98 $\rightarrow$ **94**	96 $\rightarrow$ **90**	91 $\rightarrow$ **86**	9% $\rightarrow$ **14%**
	γ	52	50 $\rightarrow$ **50**	49 $\rightarrow$ **48**	47 $\rightarrow$ **46**	10% $\rightarrow$ **13%**
	η	25.6	26.0 $\rightarrow$ **26.3**	26.6 $\rightarrow$ **27.0**	27.9 $\rightarrow$ **28.4**	9% $\rightarrow$ **11%**
S=(12,12000)	δ	100	98 $\rightarrow$ **94**	93 $\rightarrow$ **89**	85 $\rightarrow$ **80**	15% $\rightarrow$ **20%**
	γ	105	102 $\rightarrow$ **101**	100 $\rightarrow$ **96**	95 $\rightarrow$ **90**	11% $\rightarrow$ **15%**
	η	23.4	24.2 $\rightarrow$ **24.5**	25.1 $\rightarrow$ **25.4**	26.5 $\rightarrow$ **27.5**	13% $\rightarrow$ **18%**

Table 5.3 : Evaluation results for cooperative deployment with Temporal Flight Planner according to different scenarios and strategies.

The evaluation summary of the simulation results is also given in Table 5.3. The proposed graph modeling schemes including CAS1, CAS2 and CAS3 approaches are presented under three different scale of scenarios and compared with a simple replenishment approach. Moreover, the outcomes obtained from single deployment of Spatial Flight Planner are also represented in the table as the left side of the arrows in each row. On the other hand, the results obtained with Temporal Flight Planner extension are given on the right side of the arrows. Thus, the improvement can clearly be seen. According to Table 5.3, the results obtained after the deployment of Temporal Flight Planner are better than the previous ones. The gain obtained on δ parameter reaches to 20% with CAS3. Similarly, γ parameter degradation reaches to 25% and η parameter rises up to a ratio of 18% both under S=(12,12000) scenario with CAS3. Furthermore, the best results giving the maximum gains are again obtained with CAS3 having more information about the topology under a dense scenario S=(12,12000) as in the previous study. This can be explained by the scale of the scenario and with the fact that having more information about energy consumption paths in the topology with CAS3. As a consequence, it can finally be asserted that the proposed Temporal Flight Planner further improves the study considering the energy awareness from the end-system perspective.

5.2.1.3 Optimality check for GA implementation of temporal flight planner

The running time complexity of an implementation plays an important role to get a response in a reasonable amount of time especially for the problems with extensive search space. There are some studies to overcome this challenge in the literature. As indicated in [69], traditional approaches give place to evolutionary mechanisms to solve complex real world problems and one of the approved approach is GA. The authors conduct one of the initial studies on GA to solve such a complex problem, robot path planning, by GA implementation. A recent and enhanced version of the similar problem is also studied in [70]. The authors assert that GA implementation provides less execution time compared with alternative traditional algorithms, especially in more complex problems. Similarly, [71] inquires the capabilities and characteristic of GA approach to solve path planning problems for large environments in again robotic domain. Moreover, [72] reviews not only GA, but also other evolutionary heuristics to solve path planning problem more efficiently in complex problem domains. Thus, considering an effective implementation, GA approach is utilized in the thesis to implement Temporal Flight Planner having a huge search area. However, such meta-heuristic approaches including GA do not guarantee to terminate with an exact optimum solution because of the stochastic characteristic of development phases as stated in [73] and [74]. Thus, a further investigation is required to evaluate the proposed implementation in a more proper way. [75] gives an evaluation between GA, Simulated Annealing (SA) and ACO on Traveling Salesman Problem (TSP) and highlights that GA provides a superior results and is the closest one to the optimum solution generated by traditional solvers. Moreover, the authors also indicate that all proper implementation of such heuristics give the same or very closer solutions to the optimum solution. A similar optimality investigation for GA is studied for an Intrusion Detection System (IDS) in [76]. The authors assert that GA implementation for this application specific domain provides very close solution to some costly machine learning methods. [77] introduces a novel multi-objective GA for mobile robot path planning and the authors assert that both conventional GA and multi-objective GA produce appropriate solutions for efficient path planning. To conclude, an optimality investigation for GA implementation of the proposed Temporal Flight Planner is conducted due to the fact that optimization heuristics may not always give the global optimum. The GA implementation for Temporal Flight Planner is compared with a DP implementation, a costly one in terms of running time and memory consumption. A sparse scenario from the study is selected and it is aimed to evaluate how close the solutions offered by the proposed implementation to the global optimum value. The evaluation results are presented in the rest of this section.

Before introducing the evaluation details, it can be asserted that CAS3 graph modeling strategy is superior than CAS1 and CAS2 according to the evaluation results so far. Hence, for the sake of simplicity, it is considered to compare a simple replenishment strategy with the proposed strategy only on a CAS3 digraph model in the rest of the study. The evaluation environment for optimality check is prepared for S=(3,3000) scenario and simulated for four hours. A DP implementation of the Temporal Flight Planner is used to find the global optimum for every request and the usual running flow given in Figure 4.1 is followed. According to the DP implementation, average response time for a flow is calculated as 48 seconds and an average of 0.9 MB memory is used to respond with a flight plan. The memory usage can be seen as proper considering the improvement in today's hardware, but it can be stated that the response time that corresponds to 2.7% of overall endurance of an ABS is not feasible for aerial networks. On the other hand, the GA implementation is able to respond within an average of 1.6 seconds that corresponds to only 0.1% of the endurance and with an average of 0.1 MB memory usage. It can be asserted that the difference arises from pruning some of the search space in GA implementation thanks to a proper initial population provided by the Spatial Flight Planner. The implementation of Temporal Flight Planner with DP and GA clearly show that GA provides much more feasible response time for a sparse scenario. Thus, the scale of the scenario for evaluation is not extended to S=(6,6000) and S=(12,12000) because of the fact that the gap between the response time of GA and DP will further increase to do so. For denser scenarios, it is clear that the respond time percentage will further increase because of i) respond time increase with respect to the running time complexity of DP implementation stated in Section 4.3, ii) average endurance decrease as explained in Section 5.2.1.1. To conclude, the optimality check for GA with respect to the parameters from end-system perspective is performed under the aforementioned circumstances and presented as follows.

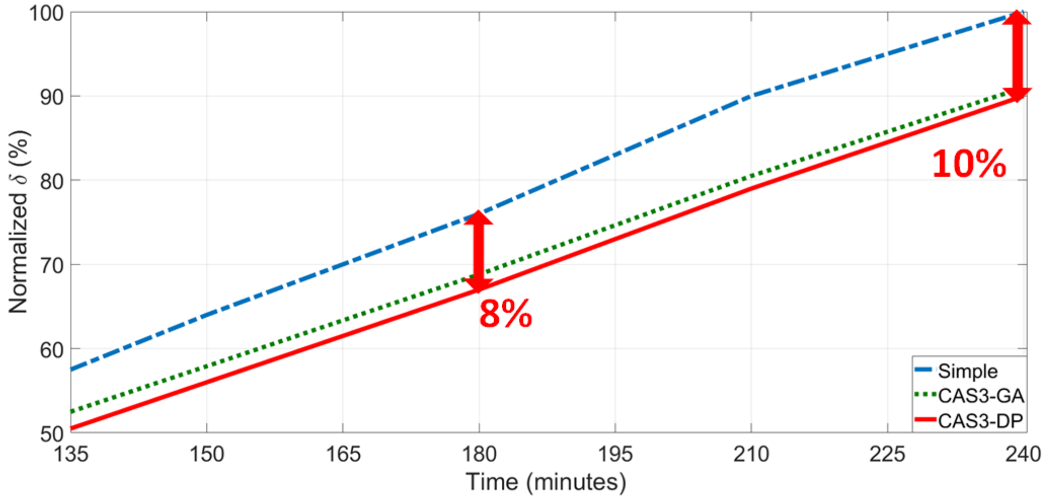


Figure 5.10 : Normalized energy consumption outcomes, δ, for different approaches, in S=(3,3000).

The evaluation for δ parameter with respect to a simple replenishment strategy (Simple); GA implementation (CAS3-GA) and DP implementation (CAS3-DP) of Temporal Flight Planner is given in Figure 5.10. According to evaluation results, it can be asserted that the solution provided by GA implementation is close enough to the global optimum obtained by DP implementation due to an average closeness ratio of 98,2% as indicated with red straight line and green dotted line in the figure. It is calculated considering each of the closeness values obtained whenever a replenishment occurs during the simulation. Moreover, the total energy saving value at the end of the simulation obtained by GA implementation has a closeness ratio of 98,8% which is also very close to the global optimum. According to evaluation results, it can be asserted that the loss in energy consumption is worth to the gain in response time owing to the proposed GA implementation.

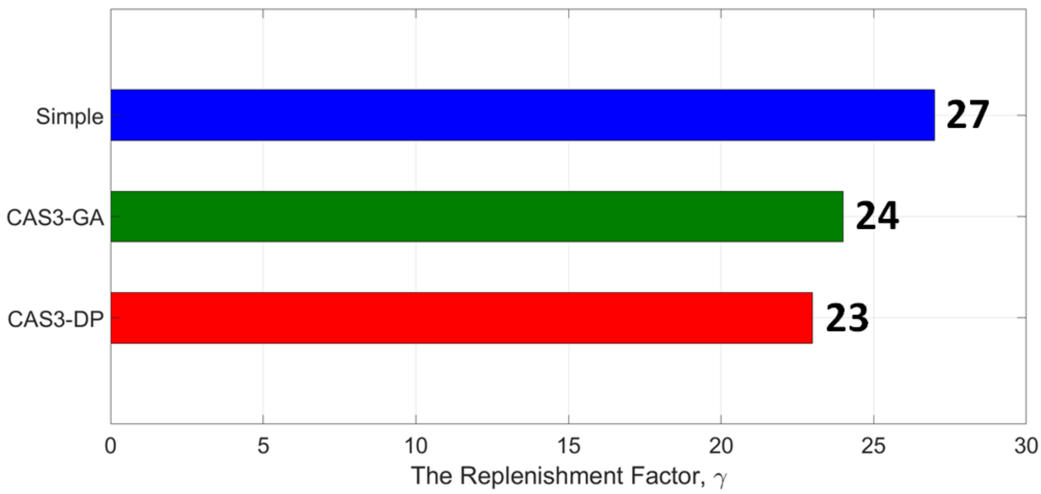


Figure 5.11 : The Replenishment Factor, γ, for different approaches, in S=(3,3000).

The results for γ parameter is also evaluated to investigate the closeness of GA implementation and is given with Figure 5.11. It can be asserted that the values obtained is acceptable considering the run time and memory consumption gain in GA implementation. An average closeness value is calculated as 95,2% considering each replenishment requests during the operational time. The average is computed following the same approach as in the calculation for δ parameter. Furthermore, the difference between DP implementation and GA implementation at the end of the mission is 4,3% that means a closeness of 95,7%. In more detail, for GA implementation, only one more replenishment takes place than in DP.

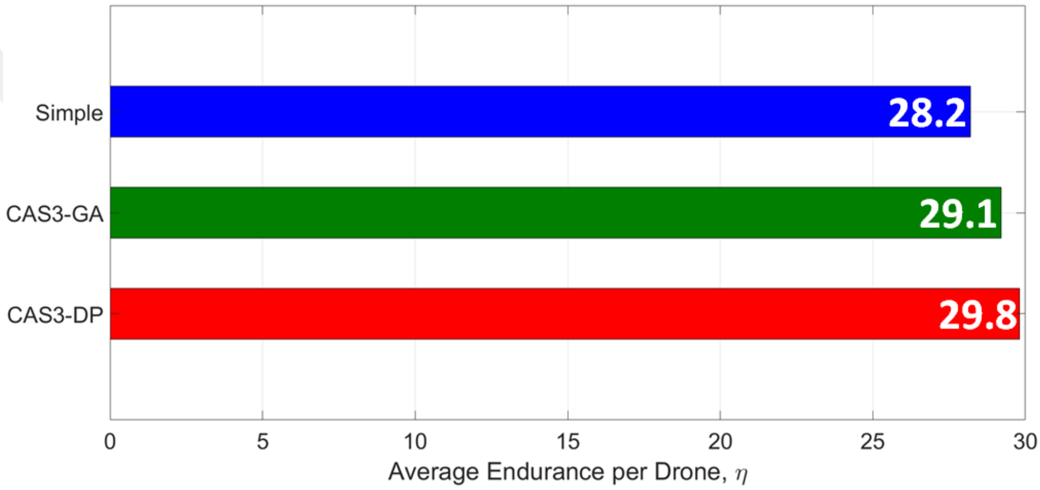


Figure 5.12 : Average endurance per drone, η, for different approaches, in S=(3,3000).

The evaluation is also conducted on η parameter for closeness investigation of GA and the results are represented in Figure 5.12. The η parameter closeness of GA implementation is obtained as 97.6% which corresponds to a dozen of less seconds for average endurance of an ABS. The deterioration of the values obtained with GA implementation for η parameter can be observed as admissible as in δ and γ parameters.

To conclude the optimality closeness investigation of GA implementation, it can be asserted that the end-system performance parameters get worse with a negligible level to compared with DP implementation which always terminates with the global optimum. On the other hand, the benefit of GA implementation is remarkably better than DP in terms of memory usage and response time to a client. Hence, it can be inferred from the closeness investigation that it is practical to use GA for Temporal Flight Planner of the proposed framework.

5.2.2 End-user perspective

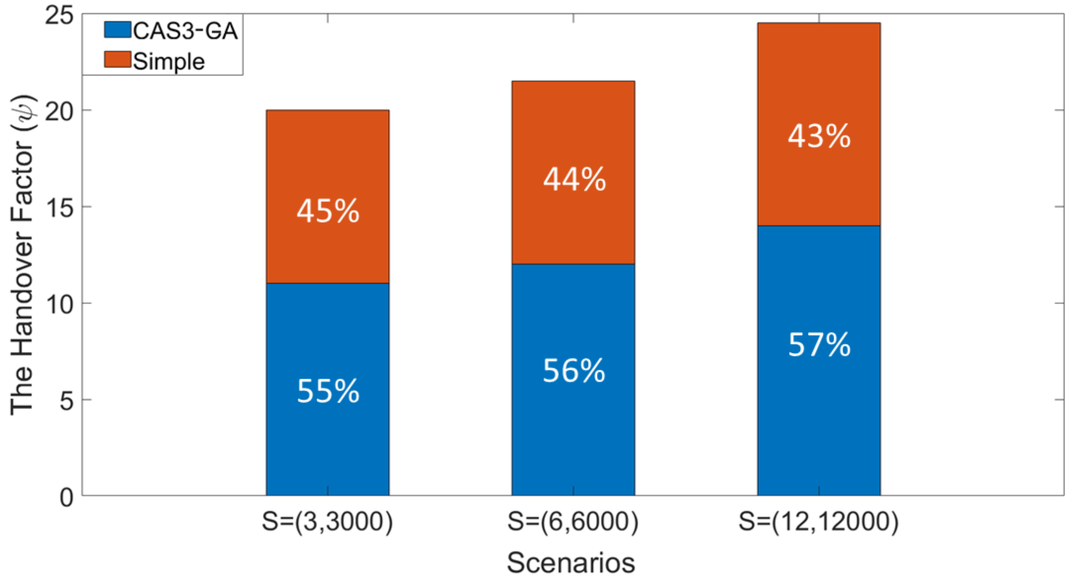


Figure 5.13 : Average number of end-system initiated handovers experienced per user: the Handover Factor, ψ.

The handover factor (ψ) parameter that represents the number of average end-system initiated handovers for an end-user is considered to evaluate the proposed framework from an end-user perspective. There are some inner replacement of ABSs in the topology in order to prevent energy consumption when the proposed framework deployed. Thus, it is expected that there are more number of handovers with the proposed approach compared to a simple replenishment strategy. According to Figure 5.13, it is seen that simple replenishment strategy results in less number of handovers under different scale of scenarios for 4 hours simulation time. In S=(3,3000), there are approximately average of 9 handovers per user whereas the ψ value equals to 11 with CAS3. Similarly, the ψ ratio in S=(S,6000) and S=(12,12000) with more user density, is increased up to 57% as a result of the proposed framework deployment. According to [78], there will be a latency for the handover process and this will affect the QoE for an end-user. A further investigation can be found in [79] which gives the details for latency in each phase of handover process. Accordingly, a performance investigation for average latency and packet loss parameters is considered in the thesis. An average latency for the access link is taken into account, as indicated in [80], instead of an entire end-to-end delay since the deployment of the proposed framework affects only the latency in the network edge. To sum up, a new simulation environment is prepared using MATLAB Simulink extension given in Figure 5.14 to evaluate the proposed flight planner framework from an end-user perspective. In this way, it is aimed to present the effect of the proposed framework on average access link latency in the network edge and packet loss ratio.

Traffic Source Properties	
Traffic Type	50% Real Time Traffic 50% Non-real Time Traffic
Arrival Pattern	Constant for Real Time Traffic Exponential for Non-real Time Traffic
Packet Size	1500 Bytes for Real Time Traffic 500 Bytes for Non-real Time Traffic
ABS Properties	
Queue Size	10K Packets
Handover Delay	15 msec
End-user Properties	
Flow Duration	240 mins
Mobility Model	Linear Mobility Model with 0 km/h Speed

Table 5.4 : Parameters configuration for simulation scenarios to investigate end-user performance.

The simulation environment given in Figure 5.14 is prepared for the scenario S=(3,3000) and has three major components as the traffic sources, 3 ABSs and 3000 end-users. It is assumed in the simulation that each end-user has a flow duration of 30 minutes during the four hour simulation scenario. 50% of the time i.e. 15 minutes is hold for real time data traffic and the remaining part for non-real time data traffic. Hence, it is assumed that one of two traffic sources given within the blue rectangle in Figure 5.14 has constant packet arrival pattern to generate non-real time traffic and the other one has exponential arrival pattern for real time traffic. Similarly, the packet sizes are chosen as 1500 bytes and 500 bytes for real time traffic source and non-real time traffic source, respectively. The queue size for each of three ABSs is chosen as 10K packets and the handover latency for an end-user is considered as 15 msec as stated in [81]. The mobility pattern for terrestrial end-users is chosen as linear mobility model with no initial speed, i.e. the position of the terrestrial end-users are fixed. The summary of all of the parameters configuration can be seen in Table 5.4.

The simulation is also repeated for the other two scenarios given with S=(6,6000) and S=(12,12000) by replacing three ABSs indicated within the red rectangle in Figure 5.14 with six ABSs and 12 ABSs, respectively.

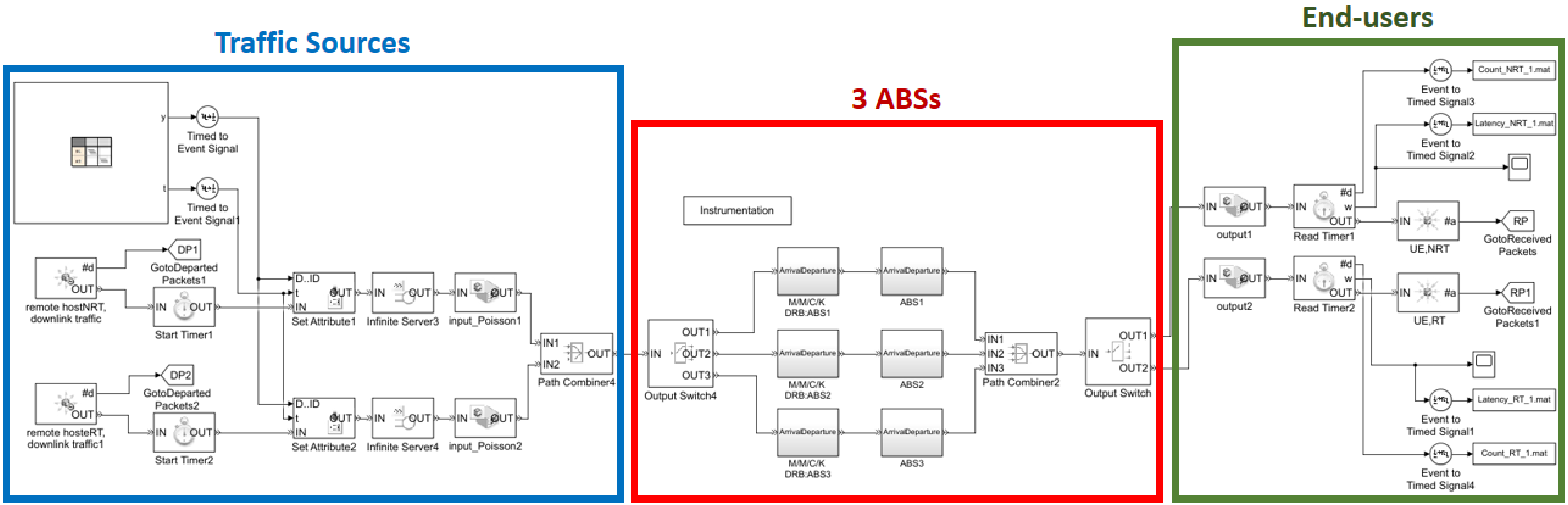
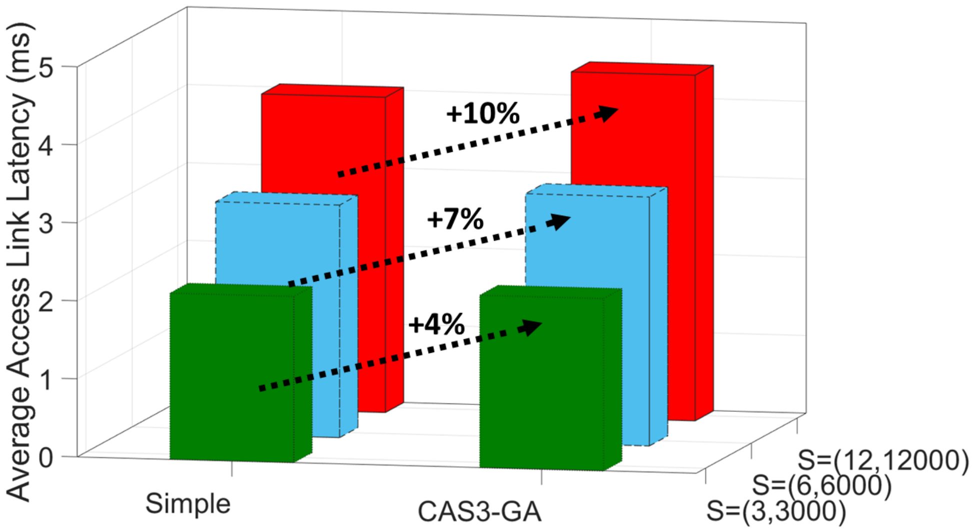
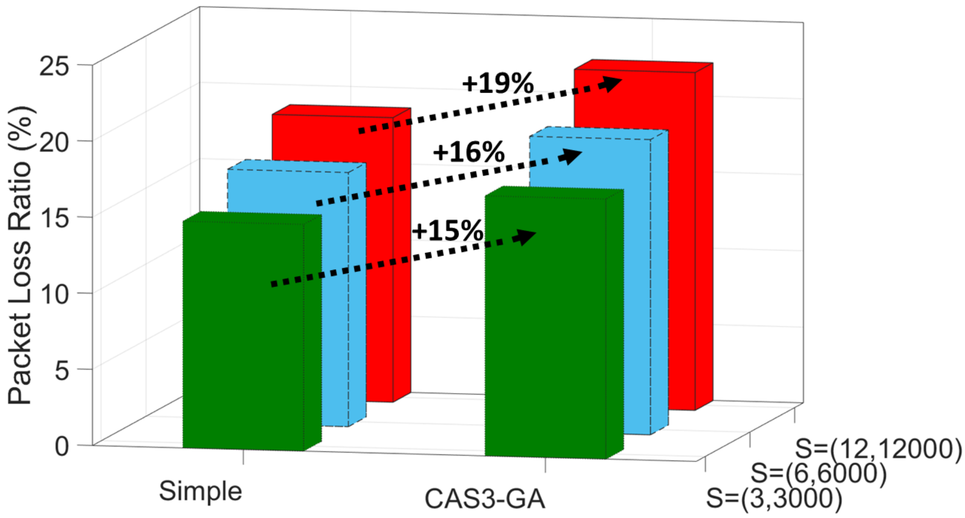


Figure 5.14 : Simulation environment for end-user perspective evaluation.



(a) Average access link latency.



(b) Packet loss ratio.

Figure 5.15 : Average access link latency and packet loss ratio values, under different scenarios, with simple replenishment approach and the proposed approach using CAS3.

The evaluation outcomes from the simulations are given with Table 5.5. The visual representation for the evaluation of these parameters are also presented in Figure 5.15(a) and Figure 5.15(b). It is seen from the table and Figure 5.15(a) that the average access link latency is increased for all of the scenarios when the proposed framework is consulted. The increase reaches to 10% with S=(12,12000) where 20% energy saving is obtained. Similarly, in S=(6,6000) 7% more average access link latency is obtained whereas 14% less energy is consumed. Moreover, in S=(3,3000), there is 4% latency increase versus 10% energy consumption decrease. Considering the values represented in the right most columns of Table 5.5 and Table 5.3, it can be asserted that there is much less latency increase than the energy consumption gain with the proposed framework deployment. There is also another issue in Figure 5.15(a) that the average access link latency increases even in the same replenishment strategy when the scenario get denser. This can be explained by the fact that there will be more number of end-system initiated handovers for denser scenarios. As seen in Figure 5.15(b), the packet loss ratio also increases with the deployment of the proposed framework due to the fact that a larger ψ is obtained compared to a simple replenishment approach. This value reaches up to 19% in our simulation for scenario S=(12,12000) with the specified queue length. The effect of more ψ value can also be seen with the deployment of the same strategy for a denser scenario in Figure 5.15(b). To conclude, there is also a trade off between packet loss ratio and energy consumption gain. It can again be asserted that the proposed framework provides a more valuable decrease in energy consumption than the increase in packet loss ratio.

		Simple	CAS3	Difference
S=(3,3000)	Avg. Latency(ms)	2.13	2.21	**4%**
	Packet Loss Ratio(%)	14.9	17.1	**15%**
S=(6,6000)	Avg. Latency(ms)	2.98	3.19	**7%**
	Packet Loss Ratio(%)	16.7	19.4	**16%**
S=(12,12000)	Avg. Latency(ms)	4.04	4.43	**10%**
	Packet Loss Ratio(%)	18.7	22.2	**19%**

Table 5.5 : Average delay and packet loss values under different scenarios with simple replenishment and CAS3 approaches.

To conclude the investigation, a performance evaluation for the proposed framework is conducted for an end-user perspective. For this purpose, the experiments presented in Section 5.2.1 are repeated for the revised proposed framework with a Temporal Flight Planner extension. Average access link latency and packet loss ratio parameters are considered to evaluate the proposed framework since there is more number of inner replacement for the ABSs in the topology compared to a simple replenishment strategy. Finally, it is seen that there is performance degradation in terms of the aforementioned parameters, but the energy consumption gain for the end-system may be seen as more valuable than the loss in QoE for an end-user when the amounts are compared with each other.

5.2.3 Performance evaluation for different traffic types

The evaluation of the proposed framework on QoE of an end-user is investigated under a heterogeneous traffic for both real time and non-real time requests and presented in the previous section. A further evaluation is provided in this section to identify the vulnerability of end-user QoE with respect to different traffic requests against the proposed framework. For this purpose, a network environment under homogeneous traffic requests is provided for both of the traffic types. Hence, the performance deterioration caused by the proposed framework is examined under only real time traffic requests and under only non-real time traffic requests, separately. The effect of different traffic requests on performance of the proposed framework is evaluated for both the end-system perspective and an end-user perspective. The outcomes of the evaluation from both perspectives are presented in the rest of this section.

5.2.3.1 End-system perspective

The performance evaluation for end-system parameters is surveyed with respect to different sources generating only real time traffic and only non-real time traffic. The simulation scenarios introduced in Section 5.2.1 are repeated and an evaluation is performed with respect to δ, γ, and η parameters. According to the evaluation result, it can be asserted that there is not a noteworthy change on these parameters due to the fact that the computational and communicational power consumption of an ABS can be neglected against the compulsory power required to keep the it on the air. The change on the evaluation parameters are limited within a ratio of only 0.8% for different traffic types studied. Hence, it can be asserted that end-system related performance parameters that evaluate the energy awareness of the system do not influenced by different traffic requests. Therefore, the results and corresponding visual materials are not given again in this section to avoid repeating the ones presented previously.

5.2.3.2 End-user perspective

In this section, the investigation for the effect of proposed system from an end-user perspective is enhanced considering a variety of popular applications and traffic types generated by them. For this purpose, Distributed-Internet Traffic Generator (D-ITG), introduced in [82], is collaboratively used with MATLAB Simulink tool for the evaluation. Three different scale of aforementioned scenarios are simulated under only

		Real Time	Non-real Time
Source Properties	**Arrival Pattern** **Packet Size**	Constant Bit Rate 1500 Bytes	Exponential Bit Rate 500 Bytes
ABS Properties	**Queue Size** **Handover Delay**	10K Packets 15 msec	
End-user Properties	**Flow Duration** **Mobility Model**	240 mins Linear Mobility Model with 0 km/h Speed	

Table 5.6 : Parameters configuration for simulation scenarios to investigate the effect on different traffic types.

real time traffic and only non-real time traffic, separately. The details of evaluation environment and the results for average access link latency and packet loss ratio parameters are presented. The configuration for the simulation parameters are the same as the ones given in Section 5.2.2; however, they are interpreted separately and given in Table 5.6. The simulation is repeated for 12 different cases considering three different scale of scenarios, two different traffic types, two different replenishment strategies and the evaluation is illustrated with Table 5.7, Figure 5.16 and Figure 5.17.

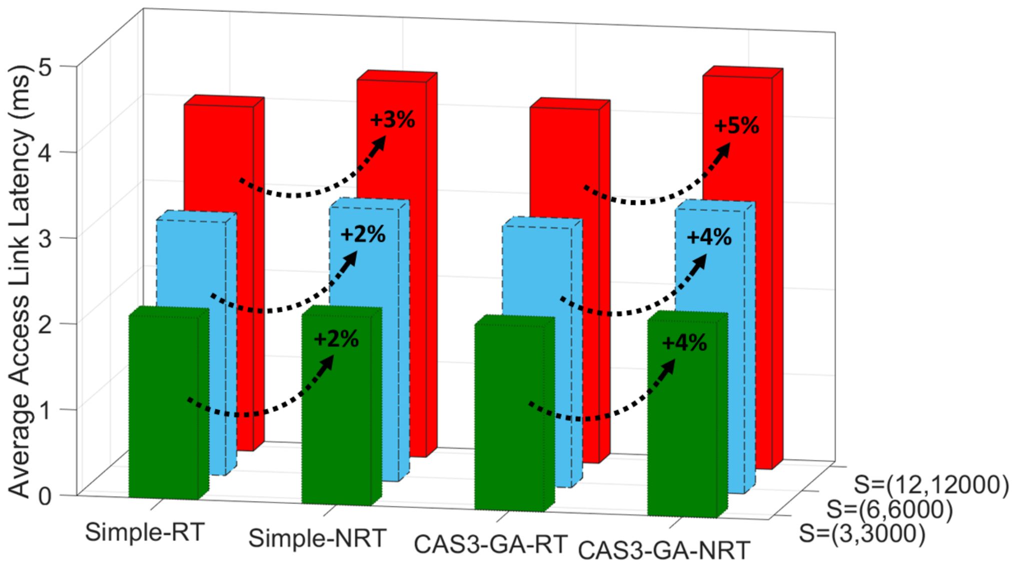


Figure 5.16 : Average access link latency with different flight planning approaches for different traffic types.

Figure 5.16 illustrates average access link latency for a simple replenishment approach and the proposed CAS3-GA approach under different types of traffic request. In the figure, RT corresponds to the scenario with real time traffic requests whereas NRT indicates the one with non-real time requests. As seen in the figure and in Table 5.7, the proposed approach deteriorates average latency compared to a simple replenishment approach for each of the corresponding traffic types. However, the performance lost can be tolerated against the energy saving owing to the proposed framework. It can be asserted that the number of end-system initiated handovers cause an increase in average latency for all scenarios and this value reaches to 4.56 ms for S=(12,12000) with the proposed approach according to Table 5.7. There is also another curious situation shown with arrows in the figure that the performance is further decayed under non-real time traffic for both of the topology maintenance approaches. For example, in S=(12,12000), an increase on average access link latency occurs with a ratio of 3% and %5 for simple approach and for CAS3-GA approach, respectively. The increase in the latency values under non-real time traffic compared to real time traffic is explained in [83] and [84] considering a handover process and the underlying protocols. As a results, it can be asserted that the proposed approach may carelessly deteriorate the average end user latency for dense areas under especially non-real time traffic load. Thus, the use case of the proposed framework should carefully be examined in such deployments.

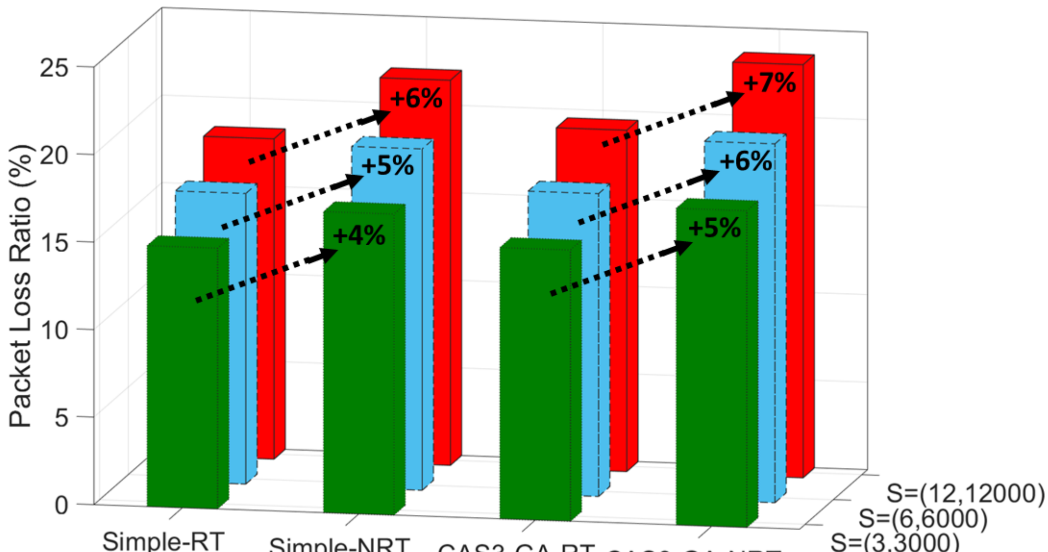


Figure 5.17 : Packet loss ratio with different flight planning approaches for different traffic types.

The evaluation between a simple replenishment approach and the proposed CAS3-GA approach under different traffic types are given in Figure 5.17 in terms of packet loss ratio. In the figure, Simple-RT scenario corresponds to a simple replenishment approach deployment under real time traffic requests whereas CAS3-GA-RT indicates the deployment of GA implementation for the proposed CAS3 approach under real time traffic request. The same evaluation considering different flight planning approaches is also repeated under non-real time traffic requests represented with NRT abbreviation. As seen in the figure, non-real time is more sensitive to the end-system initiated handovers and cause more packet loss ratio for each of the corresponding approaches and scenarios. As an instance, there are 6% and 7% increase in S=(12,12000) considering the simple approach and CAS3-GA approach, respectively. It can be asserted that there is a correlated relation between the average access link latency and the packet loss ratio and the change trend on these parameters is parallel. Considering the last row of Table 5.7, the increase in packet loss ratio reaches to 23.6% under non-real time traffic for S=(12,12000) with the deployment of proposed CAS3 approach. It should be again noted that the proposed scheme should be considered carefully for denser scenarios with non-real time traffic requests.

		Real Time		**Non-real Time**	
		Simple	**CAS3**	**Simple**	**CAS3**
S=(3,3000)	Avg. Lat.(ms)	2.12	2.20	2.16	2.28
	Loss Rat.(%)	14.9	17.2	15.5	18.1
S=(6,6000)	Avg. Lat.(ms)	2.95	3.17	3.02	3.29
	Loss Rat.(%)	16.6	19.5	17.3	20.5
S=(12,12000)	Avg. Lat.(ms)	4.01	4.37	4.12	4.56
	Loss Rat.(%)	18.3	22.0	19.5	23.6

Table 5.7 : Average delay and packet loss values for a simple replenishment and the proposed CAS3-GA approaches under different traffic types in different scenarios.

The evaluation scenarios and results obtained are summarized in Table 5.7. The average end-user latency and the packet loss ratio parameters are presented with respect to different scale of scenarios, different approaches and different traffic types in the table. According to the results, the same information can be gathered from the table compared to the survey in Section 5.2.2. Moreover, the vulnerability of different traffic types is also investigated against end-system initiated handovers in the proposed system model. The deterioration in end-user parameters are getting bigger under non-real time traffic when the proposed framework is applied. However, a mobile end-user traffic pattern commonly follows a real time characteristic with novel protocols used in most of mobile applications such as HTTP3 and QUIC, and the deployment target of the proposed system includes such users. Thus, the change in non-real time traffic can be thought as inconsiderable for the proposed framework. As a consequence, it can be inferred from the investigation that the proposed framework provides a remarkable amount of energy saving considering the compulsory energy usage of a drone; however, it should carefully be used for dense environments with non-real time traffic requests in order not to impair the performance of end-users badly.

6. CONCLUSION

Aerial networks have been proposed as a stand-alone service or an extension for conventional terrestrial network infrastructures and still getting more attention for different application fields. However, such networks have a major drawback because of physical deployment environment i.e. their existence is highly dependent on a consumable power source. To this end, energy awareness of aerial networks is one of the most substantial characteristics that should be carefully attended to maintain the network for a longer endurance. Thus, a comprehensive study is conducted to provide an energy aware endurance framework for some industrial deployment purposes of aerial networks. In the thesis, different energy-dependent components of an aerial network equipment i.e. an ABS are investigated and it is inferred that compulsory energy demand to maintain flying is much more than the ones required by computation and communication. Therefore, the relation between the energy consumption and flight characteristic of a UAV is examined to reduce the energy consumption for flying during the operational time. For this purpose, an algorithmic solution is studied that models an aerial topology and provides lowest energy consumption flight traversals to provide an endurance enhancement.

The proposed system model firstly constructs a digraph model on the aerial topology that has an ABS at each vertex and an energy consumption related cost on each edge considering the direction and magnitude of the path traversal. Subsequently, an APDP is presented with ILP on the generated digraph and a Spatial Flight Planner is proposed to decide a shortest path for ABS replenishment required at a certain time t. Moreover, a Temporal Flight Planner is also offered to enhance the search space for the entire operational time. In this way, a more proper solution at time t can be investigated considering the global solution set. The implementation of the framework is also analyzed and some evolutionary algorithms are utilized to provide a practical end-system which is able to respond in a reasonable time. Hence, Bellman-Ford algorithm with DP implementation is considered for Spatial Flight Planner and GA approach is used for Temporal Flight Planner. The run-time complexity and space complexity of the implementation are also presented and approved.

The evaluation for the proposed system is analyzed with a social event scenario simulated under three different sparsity scale. Moreover, a conventional topology maintenance scheme is also simulated under the same circumstances to have a comparison and a sensible evaluation. The assumptions on the aerial topology are stated in detail for all simulation scenarios and rotary wing UAVS i.e. drones are used. Eventually, the outcomes obtained from the simulation are compared to each other with respect to a set of parameters. According to the evaluation results, the proposed framework provides a better solution set than the conventional one in terms of energy savings up to 20% for the presented dense scenario. The number of terrestrial replenishments is also decreased with a ratio of 15% and average endurance per drone is enhanced 18% compared with the conventional approach. Moreover, the optimality closeness to the global optimum solution for the GA implementation in the proposed framework is also confirmed with some additional evaluations.

A noteworthy improvement on energy awareness for the aerial network scenarios studied in the thesis is obtained considering end-system parameters. Moreover, the effect of the proposed system on end-user perspective is also examined. During the simulation process, it is recorded that the proposed framework generates more intra-handover than the conventional one. Thus, the effect of more end-system initiated handovers for a terrestrial end-user is investigated. For this purpose, access link latency and packet loss parameters are considered under a heterogeneous traffic consists of real time and non-real time traffic requests. Eventually, the change in these parameters are presented when the proposed approach and a conventional approach are applied. According to the evaluation results, it can be stated that there are 10% more access link latency and 19% more packet loss ratio when the case of proposed model deployment. However, it can be asserted from the study that the deterioration in end-user parameters can be tolerated when the amount of energy saving for the end-system is taken into account. Moreover, a Handover Factor Optimizer algorithm is also presented as an extension to the proposed framework to bound the deterioration on end-user parameters considering a predefined handover factor value.

A further investigation is also conducted to present the vulnerability comparison between real time and non-real time traffic requests against the proposed system model. To this end, the access link latency and packet loss ratio parameters are evaluated considering only real time traffic requests and non-real time traffic requests of an end-user, separately. According to the outcomes, it can be stated that the proposed model deteriorates non-real time traffic requests in a worse way to compared with the disruption under real time requests. However, this can be seen as acceptable considering the studied scenarios in which the end-users extensively use applications that generate real time traffic with some novel communication protocols such as HTTP3 and QUIC.

To address one of the future directions of the study, the implementation of the proposed framework can be enhanced in a parallel manner for a further improvement on the response time. In this way, a better user experience for the system customers can be provided. Another future work on the study can be considered as eliminating the prerequisites on the network topology such as being a centralized architecture, end-users with linear mobility model, etc. The proposed model can be arranged to be compatible with autonomous aerial systems by providing a lightweight protocol design, and a variety of mobility models can be studied for the end-users.

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CURRICULUM VITAE

Name Surname: Yusuf ÖZÇEVİK

Place and Date of Birth: İzmir, Turkey, 11 February 1991

E-Mail: ozcevik@itu.edu.tr

EDUCATION:

- **M.Sc.:** 2015, Istanbul Technical University, Faculty of Computer and Informatics, Department of Computer Engineering, Computer Engineering Programme
- **B.Sc.:** 2013, Istanbul Technical University, Faculty of Computer and Informatics, Department of Computer Engineering

PROFESSIONAL EXPERIENCE:

- 2019-present, Prelector/Developer at Ege University, International Computer Graduate School.
- 2018-2019, Research Assistant at Istanbul Technical University, Faculty of Computer and Informatics Engineering.
- 2017-present, Reviewer for journal: IEEE Computer Communications.
- 2014-present, Reviewer for journal: The International Journal of Communication Systems (IJCS).
- 2014-present, Reviewer for several international/national conferences: International Conference on Computing, Networking and Communications (ICNC'18 ISA); IEEE International Conference on Communications (ICC'17 GCSN); 2017 IEEE Wireless Communications and Networking Conference (WCNC); The 41st IEEE Conference on Local Computer Networks (LCN 2016); 21st IEEE International Workshop on Computer Aided Modelling and Design of Communication Links and Networks (IEEE CAMAD 2016); International Conference on Computing, Networking and Communications (ICNC'15 GCNC); Globecom 2014 Workshop - Cloud Computing Systems, Networks, and Applications (GC14 WS - CCSNA); IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom, 2014).
- 2014, Technical Programme Comitee (TPC) Member in The International Workshop on Energy Awareness for Heterogeneous Networks: Recent Hardware and Software-Defined Solutions (EAHN 2014), in conjunction with IEEE DCOSS 2014.

- 2014-2018, Senior Software Developer in Istanbul Technical University, Computing Department.

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