NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
DIVISION OF INFORMATION TRANSMISSION AND MATERIAL TECHNOLOGY

Optimization Algorithms for High Throughput Wireless and Satellite Networks

Doctoral Thesis

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Σχολη Ηλεκτρολογων Μηχανικων
Και Μηχανικων Υπολογιστων
Τομεας Συστηματων Μεταδοσης Πληροφοριας
Και Τεχνολογιας Υλικων

Αλγόριθμοι Βελτιστοποίησης Ασυρμάτων και Δορυφορικών Δικτύων Υψηλής Ρυθμοαπόδοσης

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ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ
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«Από πείσμα και τρέλα θα ζω σε τούτη τη χώρα

ώσπου να 'βρω νερό, γιατί ανήκω εδώ.»

(Στίχοι από «Τα Καράβια μου καίω»)

— Νίκος Πορτοκάλογλου

Περίληψη

Η τεράστια αύξηση των απαιτήσεων των χρηστών ασύρματων δικτύων για πολύ υψηλές ταχύτητες δεδομένων ευρυζωνικών υπηρεσιών αποτελεί κοινό τόπο. Επιπλέον, υπάρχει η ανάγκη να ενισχυθεί η απόδοση των δικτύων υποστήριξης όσον αφορά την διατήρηση της χωρητικότητάς τους σε περιπτώσεις πιθανής συμφόρησης ή παύσης λειτουργίας της ζεύξης επικοινωνίας. Λαμβάνοντας επίσης υπόψη ότι ένας από τους κύριους στόχους στα ασύρματα δίκτυα πέμπτης γενιάς (5G) είναι η ικανοποίηση των υψηλών ταχυτήτων των χρηστών, τα δορυφορικά δίκτυα αποτελούν αναπόσπαστο μέρος αυτού του δικτύου. Συγκεκριμένα, τα δορυφορικά συστήματα υψηλής ρυθμοαπόδοσης (High Throughput Satellites, HTS) αποτελούν αξιόπιστη λύση συνδεσιμότητας και επικοινωνίας. Μπορούν να παρέχουν είτε κατευθείαν τηλεπικοινωνιακές υπηρεσίες σε αγροτικές και απομονωμένες περιοχές όπου τα επίγεια δίκτυα ενδεχομένως να έχουν περιορισμένη συνδεσιμότητα ή την υποστήριξη επίγειων υποδομών σε δίκτυα 5G, ως «οπίσθια» ζεύξη (backhaul) για τη γενικότερη αποσυμφόρηση της τηλεπικοινωνικής κίνησης. Γενικά, τα συστήματα HTS, που στοχεύουν στην παροχή ταχύτητας από εκατοντάδες Gb/s έως Tb/s, παρέχουν την επικοινωνία των δορυφορικών πυλών (gateway, GW) με τους χρήστες (user equipment, UE) μέσω του δορυφόρου. Οι ζεύξεις μεταξύ GW και δορυφόρου ονομάζονται ζεύξεις τροφοδοσίας (feeder links) και χρησιμοποιούν τις υψηλότερες RF συχνότητες, όπως οι ζώνες Q/V ή W, ενώ χαμηλότερες συχνότητες, όπως η Ka ζώνη, χρησιμοποιούνται για την επικοινωνία δορυφόρου και UE, που ονομάζεται ζεύξη χρήστη (κατερχόμενη ζεύξη).

Η παρούσα εργασία επικεντρώνεται στο σχεδιασμό αποδοτικών αλγορίθμων βελτιστοποίησης για την κατάλληλη σύνδεση μεταξύ των GWs και των UEs σε δορυφορικά συστήματα υψηλής ρυθμοαπόδοσης, λαμβάνοντας υπόψη τις προσφερόμενες και ζητούμενες χωρητικότητές τους, αντίστοιχα και τις ατμοσφαιρικές συνθήκες μετάδοσης. Πρώτον, λαμβάνοντας υπόψη ότι κάθε GW προσφέρει την ίδια χωρητικότητα στους UEs, δίνοντας έμφαση στις ζεύξεις τροφοδοσίας, προτείνεται ένα ταίριασμα μεταξύ τους εφαρμόζοντας τον αλγόριθμο Gale–Shapley (GS) για την ελαχιστοποίηση των απωλειών του συστήματος. Αυτός βρίσκει μια ευσταθή λύση του «προβλήματος ταιριάσματος συζύγων» (marriage matching problem) σε πολυωνυμικό χρόνο. Στη συνέχεια, στο ίδιο σενάριο, αποδεικνύεται ότι το βέλτιστο ταίριασμα μπορεί να επιτευχθεί με έναν αλγόριθμο με χαμηλότερη πολυπλοκότητα, βασισμένο στη θεωρία των πινάκων Monge. Τέλος η συγκεκριμένη θεωρία εφαρμόζεται και σε άλλες γνωστές μετρικές επίδοσης. Επιπλέον, παρουσιάζονται εκτεταμένα αριθμητικά αποτελέσματα σε διάφορα υποθετικά δορυφορικά δίκτυα.

Ακόμα, μελετάται η περίπτωση όπου διαφορετικές χωρητικότητες προσφέρονται από κάθε GW σε κάθε UE και παρουσιάζεται μια βέλτιστη μέθοδος αντιστοίχισης βάσει του Ουγγρικού αλγορίθμου, που λύνει το πρόβλημα εκχώρησης σε πολυωνυμικό χρόνο. Σε όλα τα προαναφερθέντα σενάρια, οι GWs μπορούν να εξυπηρετήσουν έναν ή περισσότερους UEs ταυτόχρονα, καταλήγοντας στον σχηματισμό ζευγών ένα-προς-ένα (one-to-one, O2O) και ένα-προς-πολλά (one-to-many, O2M), αντίστοιχα. Ωστόσο, στις περιπτώσεις του O2M ο αριθμός των UE που εξυπηρετούνται είναι προκαθορισμένος.

Τέλος, χωρίς τη χρήση προκαθορισμένου αριθμού ταυτόχρονα εξυπηρετούμενων χρηστών, παρουσιάζονται υποβέλτιστα O2M ταιριάσματα χρησιμοποιώντας μια ευρετική διαδικασία δύο σταδίων, για την επίλυση προβλημάτων σχετικών με το επίπεδο ικανοποίησης, δυσαρέσκειας και αντιστοίχισης χωρητικοτήτων νιοστής τάξης (θετικό και ακέραιο ν) των χρηστών. Αρχικά «χαλαρώνοντας» το πρόβλημα ταιριάσματος λύνουμε ένα συνεχές πρόβλημα χρησιμοποιώντας προσεγγίσεις από τη θεωρία κλασματικού προγραμματισμού και τη διαδοχική κυρτή βελτιστοποίηση (sequential convex optimization, SCO). Στη συνέχεια η συνεχής λύση μετατρέπεται σε διακριτή και έτσι καταλήγουμε σε μια εφικτή λύση του αρχικού προβλήματος.

Λέξεις Κλειδιά— ασύρματα δίκτυα, δορυφορικές επικοινωνίες, δορυφορικά συστήματα υψηλής ρυθμοαπόδοσης, κατανομή πόρων, βελτιστοποίηση, διαδοχική κυρτή βελτιστοποίηση, κλασματικός προγραμματισμός, αλγόριθμος Gale-Shapley, πρόβλημα ταιριάσματος συζύγων, Monge πίνακες, Ουγγρικός αλγόριθμος, ταίριασμα πύλης διαδικτύου και χρήστη.

Abstract

The huge increase in the demands of wireless users for very high data rate broadband services is a common realization. In addition, there is need to boost the performance of mobile backhaul networks in terms of capacity and resilience against link failure or congestion. Considering also that one of the main targets in fifth generation (5G) wireless networks is the satisfaction of high traffic demand of users, the satellite networks play a vital role on this. Specifically, High Throughput Satellite (HTS) systems are rendered as a reliable part toward this direction mainly providing communication services in rural and remote areas where the terrestrial networks have limited connectivity and also through the support of terrestrial infrastructure of 5G networks for backhauling and traffic offload. Generally, HTS systems, targeting to provide speed from hundreds of Gb/s to Tb/s, contain the communication of gateways (GWs) and user equipment (UE) beams through the satellite. The links between the GWs and the satellite are called feeder links and are using higher RF frequencies, such as the Q/V or W bands. Lower frequencies, such as the Ka band, are exploited for the links between the satellites and the UE beam, called user links (downlinks).

This dissertation focuses on the design of effective optimization schemes for the appropriate pairing in HTS systems among GWs and UEs, considering their offered and requested capacities respectively and the atmospheric transmission conditions. Firstly, considering that each GW offers the same capacity to UEs, focusing on the feeder links, an allocation scheme is proposed applying the Gale–Shapley (GS) algorithm for minimizing the system's losses. This algorithm finds a stable solution of the marriage matching problem in polynomial time. Afterwards, under the same scenario, it is proven that the optimal allocation can be achieved by an algorithm with lower complexity, based on the theory of Monge arrays. This theory is also applied to other known performance metrics. Moreover, extended numerical results for various hypothetical scenarios are presented.

Furthermore, we study the case where different capacities are offered by each GW to every UE and an optimal matching scheme is presented based on Hungarian algorithm, that solves the assignment problem in polynomial time. In all the aforementioned scenarios, GWs can serve one or more UEs simultaneously, resulting in one-to-one (O2O) and one-to-many (O2M) pairings, respectively. However, in O2M cases the number of served UEs is predetermined.

Finally, without predetermining the simultaneous served UEs, we show suboptimal O2M allocation schemes using a two-step heuristic approach in problems related with the satisfaction, dissatisfaction ratios and n^{th} (positive, integer) order rate matching of UEs. Firstly, solving a relaxed continuous allocation problem, we apply approximations from fractional programming and the sequential convex optimization (SCO) and then the continuous to discrete conversion of pairing solution is made, resulting in a feasible solution for the initial problem.

Index Terms— wireless networks, satellite communications, high-throughput satellite systems, resource allocation, optimization, sequential convex optimization, fractional programming, Gale-Shapley Algorithm, marriage matching problem, Monge arrays, Hungarian algorithm, gateway–user pairing

Ευχαριστίες

Με την ολοκλήρωση μιας διδακτορικής διατριβής, σίγουρα πλέον οι προκλήσεις που ανακύπτουν στην επαγγελματική και προσωπική καθημερινότητα αντιμετωπίζονται με άλλον τρόπο. Η επίπονη διαδικασία περάτωσής της διδάσκει πως η μεθοδικότητα, η επιμονή και φυσικά η σκληρή προσπάθεια τελικά ανταμείβονται. Επιπλέον το αίσθημα χαράς και ανακούφισης έρχεται και καλύπτει τις θυσίες όλων αυτών των χρόνων, όσον αφορά την απουσία από διάφορες προσωπικές στιγμές απόλαυσης. Τέλος, το κάτωθι κείμενο αποτελεί μια ελάχιστη έκφραση ευγνωμοσύνης προς όλα τα πρόσωπα που ήταν αρωγοί στην ολοκλήρωση της διατριβής μου.

Αρχικά, θα ήθελα να εκφράσω τις εγκάρδιες ευχαριστίες μου στον επιβλέποντα καθηγητή της παρούσας διδακτορικής διατριβής, τον κύριο Αθανάσιο Δ. Παναγόπουλο. Ο κ. Παναγόπουλος μου έδωσε πλήρη ελευθερία κινήσεων στα πλαίσια της έρευνας, ώστε να επιλέξω ένα ερευνητικό πεδίο που πραγματικά μου αρέσει. Επιπλέον ήταν παρών σε όλες τις περιπτώσεις που τον χρειάστηκα συζητώντας σαν φίλοι και προσπαθώντας να βρούμε λύση στις ανακύπτουσες δυσκολίες. Τον ευχαριστώ για όλες εκείνες τις στιγμές που του εξέφραζα τους προβληματισμούς μου και με ενθάρρυνε με τον δικό του μοναδικό τρόπο να συνεχίσω την προσπάθεια μου. Επίσης είμαι ευγνώμων για την δυνατότητα που μου παρείχε να ολοκληρώσω παράλληλα μεταπτυχιακές σπουδές στο Οικονομικό Πανεπιστήμιο Αθηνών. Στο μυαλό μου θα είναι πάντα ο «αγαθός γίγαντας», καθώς έχει σπάνιο χαρακτήρα εκτός από την ευρύτατη επιστημονική κατάρτιση.

Στη συνέχεια θα ήθελα να δηλώσω πως είμαι ευγνώμων απέναντι στα μέλη της εξεταστικής επιτροπής μου, τους καθηγητές Ε.Μ.Π. κ.κ. Π. Κωττή, Γ. Φικιώρη, Χ. Καψάλη, Η. Γλύτση, την επίκουρη καθηγήτρια Ε.Μ.Π. κα. Ι. Ρουσσάκη και τον καθηγητή Παν. Δυτ. Αττικής κ. Σ. Σαββαΐδη για το χρόνο που αφιέρωσαν και τη βοήθειά τους στη βελτίωση της διατριβής. Επιπλέον ευχαριστώ τον Ειδικό Λογαριασμό Κονδυλίων Έρευνας (Ε.Λ.Κ.Ε.) Ε.Μ.Π. για τη χρηματική υποστήριξη της έρευνάς μου κατά τα έτη 2017-2020.

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Στη συνέχεια επιθυμώ να ευχαριστήσω τους υπόλοιπους συνεργάτες και φίλους που συνυπήρξαμε, λιγότερο ή περισσότερο, στις ίδιες εγκαταστάσεις των Παλαιών Κτιρίων της Η.Μ.Μ.Υ. Ε.Μ.Π. και μοιραστήκαμε όμορφες στιγμές και πιο συγκεριμένα, τους Δρα. Ν. Λύρα, Δρα. Χρ. Εφραίμ, Θ. Καψή, Δρα. Αντ. Γκότση, Νίκο Φτυλιτάκη, Δρα. Γ. Πιτσιλαδή, Δ. Παπανικολάου, Δρα. Ν. Μωραΐτη, Δρα. Ι. Popescu, Δρα. Αθ. Μαρούση, Αλ. Ρογάρη και Φ. Ρογάρη. Επίσης, η συνύπαρξή μου με τον Δρα. Απ. Παπαφραγκάκη πολλές χειμερινές και καλοκαιρινές βραδιές και Σαββατοκύριακα θα μείνει ανεξίτηλη στη μνήμη μου, καθώς εργαζόμασταν ο καθένας για την έρευνά του. Επιπλέον, θα ήθελα να ευχαριστήσω την ερευνήτρια ΕΠΙΣΕΥ Δρα. Ροδούλα Μακρή και τους κυρίους Ν. Μπούζη και Π. Κελέφα για την εποικοδομητική συνεργασία μας.

Στο σημείο αυτό θα ήθελα να εκφράσω τις ευχαριστίες μου σε πρόσωπα της προσωπικής μου ζωής, οι οποίοι πάντα ήταν δίπλα μου παρέχοντάς μου συμβουλές και πολύτιμη στήριξη ανιδιοτελώς, όποτε το ζητούσα, σ’ αυτή την περίοδο της ζωής μου. Συγκεκριμένα οι Ευθύμης, Χρίστος, Αλέξανδρος, Γιάννης και η Βάγια είναι οι άνθρωποι που έχουν σεβαστεί την απουσία μου, λόγω φόρτου εργασίας, από διάφορες προσωπικές στιγμές μας ψυχαγωγίας και τους ευχαριστώ για αυτό.

Ολοκληρώνοντας θέλω να εκφράσω βαθιά ευγνωμοσύνη στους δύο πιο σημαντικούς ανθρώπους της ζωής μου, τους γονείς μου Ιωάννη Ρουμελιώτη και Βασιλική Γκρούτση. Αποτελούν τους πυλώνες μου σε κάθε επιλογή, παρέχοντας ανιδιοτελή αγάπη και απόλυτη εμπιστοσύνη. Μάλιστα στη συνεχή και αγωνιώδη προσπάθειά μου για επίτευξη νέων στόχων στέκονται με πραότητα στο πλάι μου υπομένοντας τα άγχη και παρέχοντας χρήσιμες συμβουλές στους προβληματισμούς μου. Τους ευχαριστώ για τη μόρφωση και φυσικά τον πολύτιμο πλούτο των αξιών και του ήθους που μου έχουν παράσχει και συνεχίζουν να παρέχουν στην καθημερινή συναναστροφή μας. Τους υπόσχομαι πως δε θα παραβιάσω ποτέ τις αρχές που μου έχουν διδάξει. Ευελπιστώ να είναι υπερήφανοι με τις μέχρι τώρα προσπάθειές μου και να βρω τον τρόπο, έστω και μερικώς, κάποια στιγμή, να τους ανταποδώσω την αμέριστη υλική και ψυχολογική στήριξη όλων αυτών των χρόνων. Τους αγαπώ πολύ και τους ευχαριστώ για όλα.

Ανάργυρος Ι. Ρουμελιώτης

Αθήνα, Ιανουάριος 2022

Στους πολυαγαπημένους μου γονείς,

Ιωάννη και Βασιλική.

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Αγγλικά	**Ελληνικά**
Artificial Intelligence	Τεχνητή Νοημοσύνη
5G Wireless Networks	Ασύρματα Δίκτυα 5^{ης} Γενιάς
Backhaul	Ζεύξη Υποστήριξης
Beam	Δέσμη
Binomial Formula	Διωνυμικό Ανάπτυγμα
Cloud	Νεφοϋπολογιστική Δομή
College Admissions Matching Problem	Πρόβλημα Ταιριάσματος Εισαγωγών στο Κολέγιο
Cumulative Distribution Function	Αθροιστική Συνάρτηση Κατανομής
Data Rate	Ρυθμός Δεδομένων
Downlink	Κατερχόμενη Ζεύξη
Feeder Link	Ζεύξη Τροφοδοσίας
Fractional Programming	Κλασματικός Προγραμματισμός
Gateway	Πύλη Διαδικτύου
Geostationary Satellite	Γεωστατικός Δορυφόρος
High Throughput Satellite System	Δορυφορικό Σύστημα Υψηλής Ρυθμοαπόδοσης
Internet of Things	Διαδίκτυο των Πραγμάτων
Linear Bottleneck Assignment Problem	Γραμμικό Συμφορημένο Πρόβλημα Ανάθεσης
Linear Sum Assignment Problem	Γραμμικό Αθροιστικό Πρόβλημα Ανάθεσης
Low-Earth-Orbit Satellite	Δορυφόρος Χαμηλής Τροχιάς
Medium-Earth-Orbit Satellite	Δορυφόρος Μέσης Τροχιάς
Marriage Matching Problem	Πρόβλημα ταιριάσματος συζύγων
Quadratic Programming	Τετραγωνικός Προγραμματισμός
Quality of Service	Ποιότητα Υπηρεσίας
Quotas	Αριθμός Ταυτόχρονα Εξυπηρετούμενων Χρηστών
Rate Matching	Αντιστοίχιση Χωρητικοτήτων
Reinforcement Learning	Ενισχυτική Μάθηση
Satellite Communications	Δορυφορικές Επικοινωνίες
Sequential Convex Optimization	Διαδοχική Κυρτή Βελτιστοποίηση
Smart Gateway Diversity	Διαφορισμός Έξυπνων Πυλών Διαδικτύου
User Equipment	Συσκευή Χρήστη

Abbreviations

Table 2: Abbreviations

5G	5^{th} Generation
AI	Artificial Intelligence
ARTES	Advanced Research in Telecommunications Systems
BS	Base Station
CNIR	Carrier-to-Noise-plus-Interference Ratio
CCDF	Complementary Cumulative Distribution Function
CCP	Convex-Concave Procedure
CDF	Cumulative Distribution Function
DRL	Deep Reinforcement Learning
DA	Deferred Acceptance
DC	Difference of Convex
E2E	End-to-End
eMBB	Enhanced Mobile Broadband
ESA	European Space Agency
EU	European Union
FM	Fairness Method
FP	Fractional Programming
GS	Gale-Shapley
GW	Gateway
GEO	Geostationary Earth Orbit
HAP	High Altitude Platform
HTS	High Throughput Satellites
HA	Hungarian Algorithm
IMT	International Mobile Telecommunications
IoT	Internet of Things
LSAP	Linear Sum Assignment Problem
LBAP	Linear Bottleneck Assignment Problem
L	Losses
LAP	Low Amplitude Platform
LEO	Low Earth Orbit
M2M	Machine-to-Machine
mMTC	Massive Machine-Type Communication
MEO	Medium Earth Orbit
OC	Offered Capacity
O2M	One-to-Many
O2O	One-to-One
OTS	Optimal Transport Theory
OFDMA	Orthogonal Frequency Division Multiple Access
q	Quotas
QoS	Quality of Service
QCI	Quantum Communication Infrastructure
QKD	Quantum Key Distribution
RRM	Radio Resource Management
RM	Rate Matching
RC	Requested Capacity

SF	Satisfaction Ratio
SatComs	Satellite Communications
SCO	Sequential Convex Optimization
SGD	Smart Gateway Diversity
s.t.	subject to
uRLLC	Ultra Reliable and Low Latency Communication
UAV	Unmanned Aerial Vehicle
UE	User Equipment
VLEO	Very Low Earth Orbit

Chapter 1

Extended Greek Summary-Εκτεταμένη Περίληψη

1.1 Εισαγωγή

Στο Κεφάλαιο (Chapter) 2 της παρούσας Διατριβής παρουσιάζεται μια εισαγωγή που περιλαμβάνει: α) την τρέχουσα κατάσταση στις δορυφορικές επικοινωνίες όσον αφορά τη σύνδεσή τους με τα δίκτυα 5^{ης} γενιάς (5G), μια σύντομη αναφορά στις δορυφορικές οπτικές επικοινωνίες και στα θέματα ασφαλείας των επικοινωνιών, β) την παράθεση διαφόρων επιστημονικών μελετών που έχουν διεξαχθεί παγκοσμίως ως προς τη διαχείριση πόρων στα δορυφορικά δίκτυα και την παρουσίαση κάποιων παραδειγμάτων σχετικά με την τρέχουσα χρήση της τεχνητής νοημοσύνης στον συγκεκριμένο τομέα και γ) μια περιγραφή της διάρθρωσης της διατριβής.

Όσον αφορά τις τάσεις στην εκμετάλλευση των δορυφορικών επικοινωνιών (Satellite Communications, SatComs), αυτές σχετίζονται κυρίως με την παροχή ευρυζωνικής συνδεσιμότητας των δορυφορικών δικτύων λειτουργώντας τα τελευταία μόνα τους ή σε συνδυασμό με τα επίγεια δίκτυα. Μάλιστα κατά την ενσωμάτωσή τους στα 5G δίκτυα η βασική υποστήριξη που παρέχουν, όπως παρουσιάζεται στο Σχήμα (Figure) 1, σχετίζεται [Kodheli21]: α) για τις αστικές περιοχές με τη συνδεσιμότητα IoT συσκευών (Διαδίκτυο των Πραγμάτων), την παροχή ζεύξης υποστήριξης (backhaul) σε σταθερά δίκτυα, την ευρυεκπομπή δημοφιλούς περιεχομένου και πολυμέσων, τη συνδεσιμότητα μεταξύ οχημάτων και τη διαχείριση κινδύνου, β) για τις αγροτικές περιοχές με τη ζεύξη υποστήριξης, την απευθείας συνδεσιμότητα και την παρακολούθηση και γ) για τις απομακρυσμένες περιοχές με το θαλάσσιο τομέα και τη σύνδεση M2M (μηχανή-προς-μηχανή), την εναέρια ευρυζωνικότητα και την παροχή ασφάλειας σε περιπτώσεις έκτακτης ανάγκης.

Επιπλέον, καθώς αναπτύσσεται η τεχνολογία, διαφορετικά συστήματα επικοινωνίας σε αρχιτεκτονικές πολλαπλών επιπέδων, όπως φαίνεται στο Σχήμα (Figure) 2, μπορούν να συνδυαστούν για να εγγυηθούν υπηρεσίες υψηλής ταχύτητας δεδομένων, όπως σε εξαιρετικά πυκνές περιοχές. Αυτά τα δίκτυα περιλαμβάνουν δορυφόρους, δορυφόρους χαμηλής/πολύ χαμηλής τροχιάς (very low earth orbit, VLEO), πλατφόρμες μεγάλου υψομέτρου (high altitude platforms, HAPs) και πλατφόρμες χαμηλού υψομέτρου (low altitude platforms, LAPs) όπως τα μη επανδρωμένα εναέρια συστήματα (unmanned aerial vehicles, UAV). Τα αντίστοιχα υψομετρικά εύρη τους είναι 100 έως 450 km για τους VLEO, 15 έως 25 km για τα HAPs και έως 4 km για τα LAPs [Kodheli21].

Επίσης έχει αναπτυχθεί η έννοια του «Νέου Διαστήματος» (“New Space”) [Kodheli21] που δεν αναφέρεται σε μια συγκεκριμένη τεχνολογία, αλλά σε μια γενικότερη νοοτροπία και βασίζεται σε τρεις κύριες πτυχές: 1) την ιδιωτικοποίηση του διαστήματος, 2) τη σμίκρυνση των δορυφόρων και 3) τις νέες υπηρεσίες βασισμένες σε διαστημικά δεδομένα. Η ιδιωτικοποίηση αναφέρεται στην κατασκευή και ειδικά στην εκτόξευση δορυφόρων από ιδιωτικές εταιρείες, όπως η SpaceX, σε αντίθεση με την παραδοσιακή προσέγγιση που την εκτόξευση αναλάμβαναν διάφοροι οργανισμοί. Παράλληλα η σμίκρυνση των δορυφόρων και των εξαρτημάτων επιτρέπει την εύκολη πρόσβαση στο διάστημα με πολλαπλούς συνδυασμούς κύβο/μίκρο/νάνο-δορυφόρων σε έναν εκτοξευτή. Έτσι οι δυο πρώτες πτυχές έχουν οδηγήσει στην τελευταία, επιτρέποντας γρήγορη και σχετικά φθηνή πρόσβαση στο διάστημα και μικρότερους κύκλους παραγωγής, που επιτρέπουν την ταχύτερη εισαγωγή της καινοτομίας. Σχετικά με τις επικοινωνίες, το “New Space” έχει δημιουργήσει νέες ευκαιρίες στη συλλογή δεδομένων και πολλές εταιρείες ανταγωνίζονται για να ξεκινήσουν μια βιώσιμη εμπορική υπηρεσία και στηρίζονται σε χαμηλές τροχιές, που δημιουργούν προκλήσεις στη συλλογή των δεδομένων για επεξεργασία στο έδαφος. Ωστόσο, υπηρεσίες που βασίζονται σε τεχνολογία «σύννεφου» (cloud), όπως η Amazon Web Services, έχουν αναπτύξει δίκτυα επίγειων σταθμών που μπορεί να είναι σε κοινή χρήση μεταξύ των διαφόρων σχηματισμών, παρέχοντας παράλληλα εύκολη πρόσβαση σε υπολογιστές υψηλής απόδοσης για την επεξεργασία των δεδομένων.

Με την τεχνολογία cloud οι ενδιαφερόμενοι πελάτες θα έχουν πρόσβαση σε αυτό, χωρίς να χρειάζονται μακροπρόθεσμη επένδυση σε προσωπική υποδομή επίγειου σταθμού, μειώνοντας το κόστος αποστολής δεδομένων από το διάστημα στη Γη, αλλά και μειώνοντας σημαντικά την καθυστέρηση πρόσβασης στα δεδομένα.

Επιπρόσθετα σημαντική είναι η εξασφάλιση ασφαλών επικοινωνιών με τη χρήση τεχνολογιών blockchain και quantum key distribution (QKD) για τη δημιουργία του κβαντικού διαδικτύου, καθώς με την αύξηση της υπολογιστικής ισχύος οι τρέχουσες τεχνικές κρυπτογράφησης των επικοινωνιών θα είναι τρωτές.

Εκτός από την προσπάθεια ενσωμάτωσης των δορυφορικών επικοινωνιών στα δίκτυα 5G υπάρχει στροφή στη δημιουργία οπτικών δικτύων υψηλής επίδοσης. Η μελέτη των δορυφορικών οπτικών επικοινωνιών ξεκίνησε από τον Ευρωπαϊκό Οργανισμό Διαστήματος (ΕΟΔ) το Δεκέμβριο 2016, στο πλαίσιο του προγράμματος Advanced Research in Telecommunications Systems (ARTES) με όνομα έργου “SeCure and Laser communication Technology (ScyLight)”. Το πρόγραμμα ScyLight εστιάζει τις προσπάθειες της Ευρωπαϊκής και της Καναδικής βιομηχανίας στις τεχνολογίες οπτικών επικοινωνιών και συγκεκριμένα στους ακόλουθους τομείς: α) τεχνολογία οπτικής επικοινωνίας σε επίπεδο συστήματος, β) τεχνολογία τερματικών οπτικής επικοινωνίας, ενδο-δορυφορική φωτονική και οπτικά payloads και γ) τεχνολογίες κβαντοκρυπτογραφίας στις διαστημικές επικοινωνίες. Μάλιστα για να βοηθηθούν η Ευρωπαϊκή και η Καναδική βιομηχανία να δοκιμάσουν τις τεχνολογίες τους σε τροχιά, ο ΕΟΔ προετοίμασε ένα έργο που ονομάζεται "High thRoughput Optical Network (HydRON)” και στοχεύει στην απρόσκοπτη ενσωμάτωση επίγειων και δορυφορικών υποδομών σε μια terabit-οπτική αρχιτεκτονική δικτύου επονομαζόμενη ως “Fiber in the Sky”.

Το πρόγραμμα HydRON στοχεύει να καταδείξει πως: α) όλοι οι οπτικοί δορυφορικοί κόμβοι (γεωστατικοί και μη) μπορούν να παράγουν εξαιρετικά υψηλούς ρυθμούς δεδομένων, β) τα δορυφορικά δίκτυα λέιζερ με δυνατότητες σύνδεσης terabit, πολύ μεγαλύτερες από 100 Gbps και δυνατότητα οπτικής επαναδρομολόγησης/μεταγωγής ροών δεδομένων, μπορούν να αποδώσουν όμοια με τις τυπικές οπτικές ίνες που χρησιμοποιούνται ευρέως σε επίγεια συστήματα, γ) ο αντίκτυπος των ατμοσφαιρικών συνθηκών μπορεί να μειωθεί κάνοντας χρήση των δυνατοτήτων του δικτύου HydRON για αναδιανομή δεδομένων σε τροχιά, επειδή οι σταθμοί της προς-τα-άνω/κάτω ζεύξης μπορούν να βρίσκονται σε γεωγραφικές περιοχές με υψηλή διαθεσιμότητα σύνδεσης (καλές καιρικές συνθήκες) ή τα κατανεμημένα οπτικά δίκτυα επίγειων σταθμών μπορούν να εξυπηρετούν περισσότερους από έναν δορυφόρους παράλληλα και να αποφεύγονται οι ακριβοί χρόνοι αναμονής, δ) οι εγγενείς δυνατότητες διανομής δεδομένων του HydRON θα επιτρέψουν τη συλλογή και διανομή των δεδομένων του χρήστη εντός του δικτύου, παρόμοια με ένα επίγειο δίκτυο οπτικών ινών και ε) η χρήση τεχνητής νοημοσύνης θα ωφελήσει τις νέες δικτυακές μορφές να ενσωματωθούν με τα επίγεια δίκτυα [Hauschildt18].

Καθώς οι υπηρεσίες τηλεπικοινωνιών προσφέρονται τόσο από εθνικές όσο και από εμπορικές δορυφορικές υποδομές, βασικές λειτουργίες και υποδομές της Ευρωπαϊκής Ένωσης (ΕΕ) και των κρατών μελών της εκτίθενται σε κινδύνους ασφαλείας. Οι ασφαλείς δορυφορικές επικοινωνίες που μπορούν να χρησιμοποιηθούν έγκαιρα και αποτελεσματικά είναι κρίσιμες για κυβερνητικούς φορείς ασφαλείας όπως αστυνομία, συνοριοφύλακες, πυροσβέστες, πολιτικές και στρατιωτικές δυνάμεις. Οι υπηρεσίες αυτές μπορούν να βοηθήσουν στην ασφαλή λειτουργία αποστολών, οι οποίες δύναται να μην μπορούν να βασίζονται στα παραδοσιακά δίκτυα ή να υπόκεινται σε απειλές στον κυβερνοχώρο. Έτσι δημιουργήθηκε το πρόγραμμα Κυβερνητικών Δορυφορικών Επικοινωνιών της ΕΕ (GOVSATCOM) στο οποίο συνεργάζονται ο ΕΟΔ, τα κράτη μέλη και η Ευρωπαϊκή Επιτροπή. Αυτό στοχεύει στην παροχή ασφαλών και οικονομικά αποδοτικών δυνατοτήτων επικοινωνίας σε κρίσιμες αποστολές και λειτουργίες, όσον αφορά την ασφάλεια, που διαχειρίζονται η ΕΕ και τα κράτη μέλη της, συμπεριλαμβανομένων των εθνικών φορέων ασφαλείας και των οργανισμών και θεσμών της ΕΕ.

Επιπλέον στο πλαίσιο Ορίζοντας 2020 της ΕΕ, τον Σεπτέμβριο 2020 ξεκίνησε το πρόγραμμα "European Networking for satellite Telecommunication Roadmap for the governmental Users requiring Secure, inTeroperable, innovativE and standardiseD services (ENTRUSTED)" με χρηματοδότηση περίπου 3 εκατομμύρια ευρώ, το οποίο θα ολοκληρωθεί τον Φεβρουάριο 2023 και αποτελείται από σχεδόν 20 ιδρύματα που εκπροσωπούν κράτη μέλη και οργανισμούς της ΕΕ. Σκοπός του ENTRUSTED είναι να παρέχει συστάσεις για την Ευρωπαϊκή Επιτροπή, όσον αφορά θέματα που θα μπορούσαν να επηρεάσουν τους χρήστες στον τομέα των ασφαλών υπηρεσιών δορυφορικής επικοινωνίας. Αυτές μπορεί να σχετίζονται με τις απαραίτητες επενδύσεις, τον εξοπλισμό του χρήστη και, κατά περίπτωση, τις τεχνολογικές πτυχές που είναι σημαντικές για το σχεδιασμό των μελλοντικών υπηρεσιών.

Οι προβληματισμοί για την ασφάλεια των επικοινωνιών οδήγησαν τον Απρίλιο 2019 να υπογραφεί τεχνική συμφωνία για ένα Ευρωπαϊκό σχέδιο για την κβαντική επικοινωνιακή υποδομή (quantum communication infrastructure, QCI). Χρησιμοποιείται η τεχνολογία του QKD βασισμένη στις αρχές της κβαντικής μηχανικής για την εκτέλεση κρυπτογραφικών εργασιών και δεν μπορεί να παραβιαστεί από κβαντικούς υπολογιστές, επιτρέποντας κατ' αυτόν τον τρόπο τη μακροπρόθεσμη ασφάλεια δεδομένων και μηνυμάτων επικοινωνίας. Έτσι με την υποστήριξη του QKD, η άκρο-προς-άκρο κβαντική επικοινωνιακή υποδομή θα αποτελείται από στοιχεία στη Γη και στο διάστημα και θα ενισχύσει σημαντικά τις δυνατότητες της Ευρώπης για την κυβερνοασφάλεια και τις επικοινωνίες. Μάλιστα η συγκεκριμένη υποδομή θα μπορεί να ωφελήσει τις ψηφιακές υπογραφές και την αυθεντικοποίηση. Πιο συγκεκριμένα, το επίγειο συστατικό του QCI θα αποτελείται από μια σειρά κβαντικών δικτύων επικοινωνίας που θα συνδέουν κρίσιμες υποδομές και ευαίσθητα κέντρα δεδομένων στην Ευρώπη. Το διαστημικό στοιχείο, γνωστό ως SAGA (Security and cryptoGrAphic Mission), θα είναι υπό την ευθύνη του

ΕΟΔ και θα αποτελείται από δορυφορικά κβαντικά συστήματα επικοινωνίας με πανευρωπαϊκή κάλυψη [QKD19]

Γενικότερα, ο ρόλος που έχουν τα δορυφορικά συστήματα στο οικοσύστημα 5G είναι ζωτικής σημασίας και έχει αναγνωριστεί ευρέως και το 3rd Generation Partnership Project (3GPP) ξεκίνησε τον Μάρτιο 2017 να τον μελετά. Επιπλέον στις 21 Ιουνίου 2017, στο Paris Air and Space Show, ο ΕΟΔ και 16 ηγέτες της δορυφορικής βιομηχανίας υπέγραψαν μια κοινή συνθήκη σχετικά με τη συνεργασία τους στον τομέα του “Satellite for 5G”. Μάλιστα στο έγγραφο “Assessing satellite-terrestrial integration opportunities in the 5G environment”, το οποίο συντάχθηκε τον Σεπτέμβριο 2016 με την υποστήριξη του ΕΟΔ στα πλαίσια των μελλοντικών προετοιμασιών του ARTES, αναφέρθηκαν ως καινοτομίες των δορυφορικών συστημάτων τα δορυφορικά συστήματα υψηλής ρυθμοαπόδοσης (high throughput satellite systems, HTS) και η νέα γενιά αστερισμών χαμηλής τροχιάς. Τα τελευταία μειώνουν τον χρόνο καθυστέρησης στις δορυφορικές επικοινωνίες, ενώ παράλληλα αναφέρθηκε η ανάγκη για γρήγορη τυποποίηση των απαραίτητων διεπαφών, ώστε να επιτρέπεται η ενοποιημένη διαχείριση και λειτουργία υβριδικών δορυφορικών-επίγειων δικτύων 5G.

Η τεράστια αύξηση της ζήτησης των χρηστών για ευρυζωνικές υπηρεσίες διαδικτύου είναι κοινός τόπος. Στην έκθεση της Cisco [Cisco19] παρατηρούμε ότι ο μηνιαίος παγκόσμιος όγκος δεδομένων κινητών συσκευών θα είναι 77 exabytes έως το 2022 και η ετήσια κίνηση θα φτάσει σχεδόν το ένα zettabyte. Στην εποχή των 5G ασύρματων δικτύων, οι δορυφόροι αποτελούν αναπόσπαστο μέρος του δικτύου για την παροχή υπηρεσιών διαδικτύου και πολυμέσων. Μάλιστα τα συστήματα HTS αποτελούν αξιόπιστη λύση προς αυτή την κατεύθυνση παρέχοντας υπηρεσίες κυρίως σε αγροτικές και προαστιακές περιοχές, όπου τα επίγεια δίκτυα έχουν περιορισμένη συνδεσιμότητα και μέσω της υποστήριξης επίγειας υποδομής σε δίκτυα 5G για backhaul και αποσυμφόρηση της τηλεπικοινωνιακής κίνησης [Evans15].

Για να μπορέσουν να ικανοποιήσουν τους υψηλούς ρυθμούς δεδομένων πρόσβασης στο διαδίκτυο, τα συστήματα HTS στοχεύουν σε εκατοντάδες Gbps έως Tbps [Jeannin14]. Αυτές οι απαιτήσεις ρυθμών δεδομένων απαιτούν την εκμετάλλευση υψηλότερων συχνοτήτων, όπως η ζώνη Ka (20/30 GHz) και η ζώνη Q/V (40/50 GHz). Συγκεκριμένα, η ζώνη Q/V χρησιμοποιείται στη σύνδεση μεταξύ της πύλης διαδικτύου (GW) και του δορυφόρου, η οποία ονομάζεται ζεύξη τροφοδοσίας και η ζώνη Ka αξιοποιείται στη σύνδεση μεταξύ του δορυφόρου και της συσκευής του χρήστη (user’s equipment, UE), η οποία ονομάζεται κατερχόμενη ζεύξη ή ζεύξη χρήστη. Είναι γνωστό ότι τα ατμοσφαιρικά φαινόμενα επιδεινώνουν την απόδοση των συστημάτων επικοινωνίας για συχνότητες λειτουργίας άνω των 10 GHz [Panagopoulos04] και αυτό καθιστά το σύστημα ευάλωτο σε εξασθενήσεις που μπορούν να επηρεάσουν καθοριστικά τη διαθεσιμότητά του.

Οι σοβαρές εξασθενήσεις του σήματος στις ζώνες υψηλών συχνοτήτων μπορούν να μετριαστούν με την τεχνική του διαφορισμού έξυπνων πυλών διαδικτύου (smart gateway diversity, SGD). Ειδικότερα αξιοποιώντας τη χωρική ποικιλομορφία των ζεύξεων τροφοδοσίας, λόγω της μεγάλης γεωγραφικής απόστασης μεταξύ των GWs, μπορεί να αλλάξει η εξυπηρέτηση ενός UE και ο τελευταίος να εξυπηρετηθεί από μια άλλη GW, της οποίας η ζεύξη τροφοδοσίας αντιμετωπίζει λιγότερο σοβαρές συνθήκες εξασθένησης. Για παράδειγμα στο [Kyrgiazos14] οι συγγραφείς μελετούν το σχήμα χρονικής πολυπλεξίας SGD, όπου οι UEs εξυπηρετούνται από διαφορετικά GWs σε διαφορετικές χρονικές σχισμές.

Όσον αφορά τον τομέα διαχείρισης πόρων, που αφορά πόρους όπως το εύρος ζώνης, την κατανομή ισχύος και το ταίριασμα των χρηστών, υπάρχει μεγάλη επιστημονική βιβλιογραφία και παρέχονται σύγχρονες προσεγγίσεις όχι μόνο σε ασύρματα δίκτυα [Manap20], αλλά και σε δορυφορικά συστήματα επικοινωνίας [Kisseleff21]. Με βάση τους [Elsayed19] οι προσεγγίσεις στον συγκεκριμένο τομέα μπορούν να διαχωριστούν ως:

1) κεντρικές ή αποκεντρωμένες: Εάν οι αποφάσεις προέρχονται από μια οντότητα (agent) που συγκεντρώνει όλες τις πληροφορίες, τότε μιλάμε για μια κεντρική προσέγγιση, διαφορετικά ακολουθείται μια αποκεντρωμένη διαδικασία όπου οι οντότητες λαμβάνουν αποφάσεις αυτόνομα.

2) βελτιστοποίησης, ευρετικές, θεωρίας παιγνίων ή βασιζόμενες στην τεχνητή νοημοσύνη (artificial intelligence, AI), ανάλογα με τη μαθηματική θεωρία που χρησιμοποιείται. Συγκεκριμένα, τα προβλήματα βελτιστοποίησης είναι συνήθως πολύπλοκα επειδή υπάρχουν πολλές παράμετροι, πολλές συνδυαζόμενες συναρτήσεις και αρκετοί περιορισμοί. Έτσι μπορεί να εφαρμοστεί μια ευρετική λύση χωρίς γενικά θεωρητικές εγγυήσεις. Στην περίπτωση προσεγγίσεων της θεωρίας παιγνίων, οι οντότητες στο δίκτυο αλληλεπιδρούν και επηρεάζουν τις αποφάσεις άλλων οντοτήτων. Ειδικότερα, οι μέθοδοι αυτές μπορούν να προσαρμοστούν αποτελεσματικά στις μεταβολές του δικτύου.

Τέλος, ακολουθώντας το δρόμο προς τις μελλοντικές ασύρματες επικοινωνίες, η τεχνητή νοημοσύνη είναι αναπόσπαστο μέρος της διαχείρισης των πόρων τους [Elsayed19, Lin20]. Στις δορυφορικές επικοινωνίες υπάρχουν επιστημονικές μελέτες που χρησιμοποιούν τέτοιες μεθόδους, όπως η βαθιά ενισχυτική μάθηση (deep reinforcement learning). Σύμφωνα με αυτό το πλαίσιο υπάρχουν οντότητες, καταστάσεις και δράσεις και χρησιμοποιώντας ανατροφοδότηση από το περιβάλλον, η πρόθεση της οντότητας είναι να επιλέξει τη δράση που οδηγεί σε μεγαλύτερη τελική ανταμοιβή. Το περιβάλλον και η οντότητα συνδέονται μέσω των δράσεων της οντότητας και των καταστάσεων και των ανταμοιβών του περιβάλλοντος. Ειδικότερα, η οντότητα λαμβάνει μια σειρά από αποφάσεις βάσει μιας πολιτικής ενεργειών σε σχέση με την κατάσταση του παρατηρούμενου περιβάλλοντος. Αυτό το πλαίσιο είναι πολύτιμο για τα ασύρματα δίκτυα λόγω του δυναμικού οικοσυστήματός τους [Elsayed19].

1.2 Βέλτιστες Μέθοδοι Ταιριάσματος Θεωρώντας τις Ζεύξεις Τροφοδοσίας

Στο Κεφάλαιο (Chapter) 3 μελετάται ένα HTS σύστημα όπου M GWs εξυπηρετούν N UEs και οι GWs μπορεί να είναι ίσες ή λιγότερες σε αριθμό από τους UEs. Επιπλέον όλα τα ζεύγη μεταξύ των GWs και UEs είναι πιθανά. Τα ταιριάσματα εξετάζονται σε χρονικές σχισμές που απαρτίζουν ένα ευρύτερο χρονικό πλαίσιο, θεωρώντας τη χρονική πολυπλεξία SGD. Σε κάθε χρονική σχισμή οι GWs μπορούν να εξυπηρετήσουν έναν ($M=N$) ή περισσότερους UEs ($M<N$) και κάθε UE μπορεί να εξυπηρετηθεί από μια GW. Στην πρώτη περίπτωση ο αριθμός ταυτόχρονα εξυπηρετούμενων UEs (quotas, q) είναι $q=1$, ενώ στην τελευταία $q>1$. Το σενάριο όπου οι UEs είναι περισσότερα από τα GW είναι ένα ρεαλιστικό και σημαντικό σενάριο για το σχεδιασμό δορυφορικών συστημάτων. Δίνοντας έμφαση στις ζεύξεις τροφοδοσίας η κάθε GW παρέχει μια κοινή προσφερόμενη χωρητικότητα (offered capacity, OC) στους UEs και επιπλέον κάθε UE έχει μια ζητούμενη χωρητικότητα (requested capacity, RC) σε bps, για να ικανοποιήσει την ανάγκη του για δεδομένα. Σε όλα τα παρακάτω προβλήματα τα ταιριάσματα γίνονται βάσει των προσφερόμενων και ζητούμενων χωρητικοτήτων.

Τέλος, οι εξεταζόμενες μετρικές επίδοσης είναι οι απώλειες του συστήματος (losses), η αντιστοίχιση των χωρητικοτήτων (rate matching) και ο λόγος ικανοποίησης (satisfaction ratio), όλες ευρέως γνωστές στη σχετική βιβλιογραφία [Kyrgiazos13, Kyrgiazos14, Lei11]. Συγκεκριμένα, οι απώλειες προσδιορίζονται ως η μη αρνητική διαφορά μεταξύ της ζητούμενης και της προσφερόμενης χωρητικότητας, ενώ το rate matching σαν την νιοστή τάξη της μεταξύ τους απόκλισης, στην περίπτωσή μας $v=1$ που περιγράφει την απόλυτη διαφορά. Τέλος, ο λόγος ικανοποίησης είναι ο λόγος της προσφερόμενης προς τη ζητούμενη χωρητικότητα.

Αρχικά στην Ενότητα (Section) 3.1 γίνεται χρήση της θεωρίας ταιριάσματος με σκοπό την ελαχιστοποίηση των απωλειών του συστήματος. Η συγκεκριμένη θεωρία περιλαμβάνει δυο διαφορετικά σύνολα οντοτήτων (agents) τα οποία ταιριάζουν μεταξύ τους μέσω ενός αποδοτικού ευσταθούς αλγορίθμου, γνωστού ως Gale-Shapley (GS) [Gale62]. Ο τελευταίος έχει πολυπλοκότητα $O(N^2)$, όπου N είναι ο αριθμός των οντοτήτων στο σύστημα. Ειδικότερα σε ένα περιβάλλον ταιριάσματος (matching market) κάθε οντότητα του ενός συνόλου κατατάσσει τις οντότητες του άλλου συνόλου, σύμφωνα με μια σχέση προτίμησης με βάση τις συναρτήσεις χρησιμότητάς τους. Στην περίπτωσή μας, το περιβάλλον ταιριάσματος είναι το σύστημα HTS που περιλαμβάνει τα ξεχωριστά σύνολα των GWs και UEs, όπου κάθε GW/UE κατατάσσει τους UEs/GWs, αντίστοιχα, σύμφωνα με τις συναρτήσεις χρησιμότητάς τους.

Υπάρχουν διάφορες ταξινομήσεις των προβλημάτων ταιριάσματος που εξαρτώνται είτε από τον αριθμό των quotas των οντοτήτων, είτε από τον τρόπο κατασκευής των λιστών προτιμήσεών τους. Βασιζόμενοι στα quotas, δηλαδή σύμφωνα με το μέγιστο αριθμό των ζευγών που μπορεί να σχηματίσει μια οντότητα, υπάρχει η αντιστοίχιση ενός-προς-έναν (one-to-one, O2O), όπως το πρόβλημα ταιριάσματος συζύγων, ενός-προς-πολλούς (one-to-many, O2M), όπως το πρόβλημα εισαγωγής σπουδαστών στο κολέγιο [Roth89] και πολλών-προς-πολλούς. Ενδεικτικά, στο πρόβλημα ταιριάσματος συζύγων κάθε άντρας ταιριάζει το πολύ με μία γυναίκα και αντιστρόφως, στο πρόβλημα εισαγωγής στο κολέγιο κάθε σπουδαστής αντιστοιχεί το πολύ σε ένα κολέγιο και το τελευταίο αντιστοιχίζεται το πολύ με το μέγιστο αριθμό σπουδαστών του και πολλές οντότητες ενός συνόλου μπορούν να αντιστοιχιστούν με πολλές οντότητες ενός άλλου συνόλου στα ζεύγη πολλών-προς-πολλούς. Τέλος, βάσει των συναρτήσεων χρησιμότητας υπάρχουν δύο υποκατηγορίες που χρησιμοποιούνται περισσότερο [Gu15], η κανονική αντιστοίχιση, όπου οι προτιμήσεις εξαρτώνται αποκλειστικά από τις διαθέσιμες πληροφορίες σε κάθε συγκεκριμένη οντότητα και η αντιστοίχιση με externalities [Bando12, Namvar14]. Στην τελευταία υποκατηγορία υπάρχουν αλληλεξαρτήσεις μεταξύ των προτιμήσεων των οντοτήτων, δηλαδή οι προτιμήσεις των μεμονωμένων οντοτήτων επηρεάζονται από τις προτιμήσεις των άλλων οντοτήτων και επίσης από το τρέχον ταίριασμα.

Η χρήση του GS αλγορίθμου οδηγεί σε διαφορετικό ταίριασμα ανάλογα από ποιό σύνολο θα ξεκινήσει. Στην περίπτωσή μας οι λίστες προτίμησης των GWs δομούνται θέτοντας σε φθίνουσα σειρά τους UEs, βάσει των ζητούμενων χωρητικοτήτων τους και οι UEs θέτουν σε φθίνουσα σειρά τους GWs, βάσει των προσφερόμενων χωρητικοτήτων τους. Έτσι οι λίστες προτίμησης σε κάθε σύνολο οντοτήτων είναι οι ίδιες και αποδεικνύεται πως το ταίριασμα είναι το ίδιο ανεξαρτήτως του συνόλου εκκίνησης και διαπιστώνουμε πως οδηγεί στην ελαχιστοποίηση των απωλειών του συστήματος.

Μάλιστα στις προσομοιώσεις γίνεται σύγκριση του συγκεκριμένου αλγορίθμου και με άλλους μηχανισμούς ταιριάσματος, δηλαδή τον εξαντλητικό μηχανισμό, τον μηχανισμό δικαιοσύνης, έναν σταθερό μηχανισμό και έναν τυχαίο μηχανισμό. Συγκεκριμένα ο προτεινόμενος μηχανισμός αντιστοίχισης έχει την ίδια απόδοση με τον εξαντλητικό μηχανισμό τόσο στο ένα-προς-ένα, αλλά και στο ένα-προς-πολλά ταιριάσματα, που σημαίνει ότι η προτεινόμενη διαδικασία έχει ως αποτέλεσμα την ελαχιστοποίηση των απωλειών του συστήματος. Επιπλέον, στην περίπτωση όπου μια GW εξυπηρετεί έναν UE, ο αλγόριθμός μας επιτυγχάνει καλύτερη απόδοση σε σύγκριση με τον μηχανισμό δικαιοσύνης, τον σταθερό μηχανισμό και τη διαδικασία τυχαίου ταιριάσματος.

Όσον αφορά στην Ενότητα (Section) 3.2, χρησιμοποιώντας τη θεωρία των πινάκων Monge [Villani03, Park91], παρατίθενται βέλτιστα ταιριάσματα για την ελαχιστοποίηση των losses και του rate matching, καθώς και για τη μεγιστοποίηση του satisfaction ratio του συστήματος και του χειρότερου UE. Αυτά τα βέλτιστα σχήματα καταλήγουν σε ταιριάσματα βάσει μιας κατάλληλης ταξινόμησης των προσφερόμενων και των ζητούμενων χωρητικοτήτων και έχουν χαμηλή πολυπλοκότητα. Ο Monge συνδέεται με τη γενικότερη θεωρία της βέλτιστης μεταφοράς και διατύπωσε το 1781 το εξής πρόβλημα [Villani03]: με δεδομένους σωρούς άμμου και τρύπες με τον ίδιο όγκο, αναζητούμε την καλύτερη κίνηση για να γεμίσουμε πλήρως τις τρύπες με το ελάχιστο συνολικό κόστος μεταφοράς. Ένα άλλο απλό παράδειγμα ονομάζεται πρόβλημα εξόρυξης μεταλλεύματος [Mozaffari19]. Δεδομένης μιας ομάδας ορυχείων εξόρυξης σιδηρομεταλλεύματος και μιας ομάδας εργοστασίων που καταναλώνουν το σιδηρομετάλλευμα που παράγουν τα ορυχεία, ο στόχος είναι να βρεθεί ο βέλτιστος τρόπος μεταφοράς του μεταλλεύματος από τα ορυχεία στα εργοστάσια. Αυτό γίνεται με την ελαχιστοποίηση μιας συνάρτησης κόστους που μπορεί να περιέχει το κόστος μεταφοράς, την τοποθεσία των ορυχείων και την παραγωγικότητα των εργοστασίων.

Τα εξεταζόμενα προβλήματα ανήκουν στην κατηγορία των γραμμικών αθροιστικών προβλημάτων ανάθεσης (linear sum assignment problems, LSAPs), εκτός από τη μεγιστοποίηση του satisfaction ratio του χειρότερου UE που είναι ένα γραμμικό συμφορημένο πρόβλημα ανάθεσης (linear bottleneck assignment problems, LBAP). Αυτά αποδεικνύουμε πως ικανοποιούν τις ιδιότητες των πινάκων Monge (τα τρια πρώτα) και bottleneck Monge (το τελευταίο) για κάθε 2×2 υποπίνακα του αρχικού πίνακα των προβλημάτων. ‘Ετσι οδηγούμαστε σε βέλτιστη λύση ταξινομώντας και ταιριάζοντας κατάλληλα τους GWs και UEs βάσει των προσφερόμενων και ζητούμενων χωρητικοτήτων τους με πολυπλοκότητα $O(N\log(N))$. Μάλιστα αποδεικνύουμε θεωρητικά πως το ταίριασμα που οδηγεί στη μεγιστοποίηση του satisfaction ratio του χειρότερου UE, ταυτόχρονα προκαλεί την ελαχιστοποίηση του αντίστοιχου συνολικού και το ανάποδο.

Τέλος, οι παραπάνω μέθοδοι εξετάζονται τόσο στις περιπτώσεις των O2O όσο και των O2M ζευγών, όπου στην τελευταία ο αριθμός των UEs που εξυπηρετούνται ταυτόχρονα από κάθε GW έχει προσδιοριστεί πριν από τη διαδικασία ταιριάσματος.

1.3 Βέλτιστες Μέθοδοι Ταιριάσματος Θεωρώντας τις Κατερχόμενες Ζεύξεις

Στο Κεφάλαιο (Chapter) 4 λαμβάνονται υπόψη τόσο οι ζεύξεις τροφοδοσίας, όσο και οι κατερχόμενες ζεύξεις του HTS συστήματος, ενώ οι γενικές παραδοχές του μοντέλου είναι ίδιες με αυτές στο Κεφάλαιο (Chapter) 3. Ειδικότερα οι βασικές έννοιες παραμένουν ίδιες με αυτές στο Κεφάλαιο (Chapter) 3 και οι ορολογίες που αλλάζουν αφορούν την περίπτωση των $M=N$ και $M<N$, όπου το πρόβλημα καλείται σαν «ισορροπημένο» και «μη ισορροπημένο», αντίστοιχα. Στη δεύτερη περίπτωση υπάρχουν N-M μη εξυπηρετούμενοι χρήστες και μελετώνται επιπλέον O2M ταιριάσματα για να εξυπηρετηθούν τελικά όλοι οι χρήστες.

Συγκεκριμένα παρέχονται βέλτιστα ταιριάσματα για την ελαχιστοποίηση των losses και του rate matching, καθώς και για τη μεγιστοποίηση του satisfaction ratio του συστήματος με τη χρήση του Ουγγρικού αλγορίθμου (Hungarian algorithm, HA). Ο HA έχει πολυπλοκότητα $O(N^4)$ και επιτυγχάνει $O(N^3)$ [Tomizawa71] με κατάλληλες τροποποιήσεις. Επιπλέον, στην περίπτωση μεγάλων πινάκων αυτή η πολυπλοκότητα είναι απαγορευτική και μια σειρά τεχνικών επιτάχυνσης και παραλληλοποίησης μελετώνται στο [Cui16]. Τα βήματα εκτέλεσής του περιγράφονται παρακάτω θεωρώντας πως οι πίνακες των υπό εξέταση προβλημάτων είναι N x N [Winston04]:

α) Βρείτε το ελάχιστο στοιχείο σε κάθε γραμμή του πίνακα. Κατασκευάστε έναν νέο πίνακα αφαιρώντας από κάθε στοιχείο το ελάχιστο στοιχείο στη γραμμή του. Για αυτόν τον νέο πίνακα, βρείτε το ελάχιστο στοιχείο σε κάθε στήλη. Κατασκευάστε έναν νέο πίνακα αφαιρώντας από κάθε στοιχείο το ελάχιστο στοιχείο στη στήλη του.

β) Σχηματίστε τον ελάχιστο αριθμό γραμμών (οριζόντιες, κάθετες ή και οι δύο) που χρειάζονται για να καλύψουν όλα τα μηδενικά στον πίνακα Εάν απαιτούνται N γραμμές, υπάρχει μια βέλτιστη λύση μεταξύ των καλυμμένων μηδενικών και σταματά ο αλγόριθμος. Εάν χρειάζονται λιγότερες από N γραμμές, συνεχίστε με το γ).

γ) Βρείτε το μικρότερο μη μηδενικό στοιχείο (ονομάστε το κ) που δεν καλύπτεται από τις γραμμές στο (β). Αφαιρέστε το κ από όλα τα ακάλυπτα στοιχεία του πίνακα και προσθέστε κ σε όλα τα στοιχεία που καλύπτονται από 2 γραμμές. Συνεχίστε με τη διαδικασία από το β).

Για την εφαρμογή του HA, όσον αφορά τα μη ισορροπημένα σενάρια προστίθενται N-M σειρές «εικονικών» GWs στους πίνακες των υπό εξέταση προβλημάτων, για τις O2O περιπτώσεις. Στις O2M περιπτώσεις επαναλαμβάνονται οι γραμμές της κάθε GW τόσες φορές, όσο είναι το αντίστοιχο quota της συγκεκριμένης GW. Τέλος, ο HA παρέχει βέλτιστα ταιριάσματα και στις περιπτώσεις που δεν μπορεί να γίνει κάποιο ταίριασμα μεταξύ συγκεκριμένων GWs και UEs, οπότε εξαιρείται το συγκεκριμένο ζεύγος από τη διαδικασία ταιριάσματος. Βέβαια παρατηρήθηκε στις προσομοιώσεις πως η βέλτιστη απόδοση του συστήματος στη συγκεκριμένη περίπτωση, όσον αφορά όλες τις μετρικές, είναι χειρότερη από την αντίστοιχη βέλτιστη απόδοση στην περίπτωση που κάθε μια GW μπορεί να ταιριάξει με οποιοδήποτε UE.

1.4 Υποβέλτιστες Μέθοδοι Ταιριάσματος για την Περίπτωση Ενός-προς-Πολλά Ζεύγη

Στο Κεφάλαιο (Chapter) 5 ισχύουν όμοιες υποθέσεις με αυτές του Κεφαλαίου (Chapter) 4 αλλά πλέον στα ένα-προς-πολλά ταιριάσματα ο αριθμός των ταυτοχρόνως εξυπηρετούμενων UEs από κάθε GW αποτελεί μέρος των εξεταζόμενων προβλημάτων και δεν είναι προκαθορισμένος.

Αυτό το στοιχείο κάνει τα προβλήματα πιο περίπλοκα και παρέχουμε μια ευρετική διαδικασία επίλυσης δύο βημάτων: (α) το συνεχές βήμα που περιλαμβάνει τη «χαλάρωση» των προβλημάτων ταιριάσματος αναζητώντας λύση στο συνεχές σύνολο [0, 1] και την εφαρμογή επαναληπτικών αλγορίθμων που καταλήγουν σε μια συνεχή λύση και (β) το διακριτό βήμα που περιλαμβάνει τη δυαδική μετατροπή της λύσης από το βήμα (α) και καταλήγει σε μια εφικτή λύση του αρχικού προβλήματος ταιριάσματος.

Ειδικότερα, εξετάζονται τα προβλήματα μεγιστοποίησης τόσο του ελάχιστου, όσο και του συνολικού λόγου ικανοποίησης, αλλά και της ελαχιστοποίησης τόσο του μέγιστου, όσο και του συνολικού λόγου δυσαρέσκειας. Ο λόγος δυσαρέσκειας ορίζεται σαν το αντίστροφο του λόγου ικανοποίησης. Στο προαναφερθέν στάδιο (α) για τα προβλήματα ικανοποίησης ο προτεινόμενος μηχανισμός βασίζεται στη θεωρία κλασματικού προγραμματισμού και χρησιμοποιείται μια κοίλη προσέγγιση που προτείνεται στο [Shen18], ενώ για τα προβλήματα δυσαρέσκειας εφαρμόζεται η διαφορά κυρτών συναρτήσεων [Lipp16]. ʻΕτσι οι επαναληπτικοί αλγόριθμοι στο βήμα (α) λύνουν σε κάθε επανάληψη κοίλα και κυρτά προβλήματα, αντίστοιχα. Μέσα από τις προσομοιώσεις παρουσιάζεται το μικρό σχετικό σφάλμα, σε σχέση με την αντίστοιχη επίδοση του εξαντλητικού αλγορίθμου που εξετάζει όλα τα πιθανά ζεύγη. Επιπλέον παρατηρείται μικρός αριθμός επαναλήψεων σύγκλισης των αλγορίθμων στο στάδιο (α).

Στο σημείο αυτό πρέπει να τονισθεί πως στην περίπτωση των προβλημάτων δυσαρέσκειας δημιουργούνται τετραγωνικές μορφές πινάκων στα προβλήματα βελτιστοποίησης. Έτσι παρουσιάζουμε μια γενική μέθοδο αντιμετώπισης αυτών μέσω της διαφοράς κυρτών συναρτήσεων. Συγκεκριμένα γράφουμε τους πίνακες των προβλημάτων σαν αθροίσματα ενός συμμετρικού και ενός αντισυμμετρικού πίνακα, όπου η τετραγωνική μορφή του τελευταίου είναι μηδενική. Επομένως στην επίλυση απομένει ο συμμετρικός πίνακας. Στη συνέχεια καθώς το πρόβλημα παραμένει μη κυρτό, αφού οι ιδιοτιμές του συμμετρικού πίνακα είναι πραγματικές, προσθέτουμε και αφαιρούμε κατάλληλο πίνακα βάσει των ιδιοτιμών του συμμετρικού πίνακα. Κατ' αυτόν τον τρόπο καταλήγουμε σε διαφορά κυρτών συναρτήσεων και εφαρμόζουμε άμεσα τον αντίστοιχο αλγόριθμο. Συμπερασματικά, τα προβλήματα με τετραγωνικές μορφές είτε στις συναρτήσεις βελτιστοποίησης είτε στους περιορισμούς, μπορούν να επιλυθούν με τη βοήθεια της διαφοράς των κυρτών συναρτήσεων.

Τέλος, παρέχεται θεωρητική ανάλυση για την ελαχιστοποίηση της n-ιοστής τάξης του rate matching, όπου το n είναι θετικός και ακέραιος αριθμός. Δείχνουμε πως μπορεί να αντιμετωπιστεί αυτή και πάλι μέσω της διαφοράς κυρτών συναρτήσεων. Ειδικότερα αναπτύσσονται τετραγωνικές μορφές που αντιμετωπίζονται όπως παραπάνω, αλλά επιπλέον το διωνυμικό ανάπτυγμα περιέχει όρους που είναι είτε κυρτοί, είτε κοίλοι. Ως εκ τούτου, τα κυρτά και κοίλα μέρη από τις τετραγωνικές μορφές ομαδοποιούνται μαζί με τους κυρτούς και κοίλους όρους, αντίστοιχα, από το διωνυμικό ανάπτυγμα και εφαρμόζεται άμεσα ο αλγόριθμος της διαφοράς κυρτών συναρτήσεων.

1.5 Συμπεράσματα–Προεκτάσεις

Στο Κεφάλαιο (Chapter) 6 παρέχουμε τα γενικά συμπεράσματα της διατριβής, που παρουσιάζονται παρακάτω ανά κεφάλαιο, και προτάσεις για μελλοντική έρευνα.

Ειδικότερα, στο Κεφάλαιο (Chapter) 3 εστιάζουμε στις ζεύξεις τροφοδοσίας και σε διαφορετικές θεωρίες ταιριάσματος, δηλαδή ο αλγόριθμος Gale-Shapley και οι πίνακες Monge, εφαρμόζονται σε μετρικές επίδοσης που περιλαμβάνουν την ελαχιστοποίηση των απωλειών του συστήματος και της αντιστοίχισης των χωρητικοτήτων και της μεγιστοποίησης του συνολικού και ελάχιστου λόγου ικανοποίησης.

Συγκεκριμένα, στην Ενότητα (Section) 3.1 κύρια συνεισφορά είναι η εφαρμογή ενός ευέλικτου αλγορίθμου ταιριάσματος βασισμένου στις αρχές της θεωρίας αντιστοίχισης, που αντιμετωπίζει το πρόβλημα ταιριάσματος συζύγων. Στην περίπτωσή μας επιλύει το πρόβλημα ελαχιστοποίησης των απωλειών στο HTS σύστημα, στις περιπτώσεις που μια GW μπορεί να εξυπηρετήσει ταυτοχρόνως έναν ή περισσότερους UEs.

Όσον αφορά την Ενότητα (Section) 3.2 χρησιμοποιείται το ίδιο γενικό σενάριο όπως και παραπάνω αλλά τώρα παρέχονται βέλτιστα ταιριάσματα χρησιμοποιώντας τη θεωρία των πινάκων Monge. Συγκεκριμένα αυτά τα ταιριάσματα βασίζονται στις κατάλληλες ταξινομήσεις των GWs και UEs, βάσει των προσφερόμενων και ζητούμενων χωρητικοτήτων τους.

Σχετικά με τις μετρικές των απωλειών του συστήματος, της αντιστοίχισης των χωρητικοτήτων και της μεγιστοποίησης του συνολικού λόγου ικανοποίησης αποδεικνύουμε πως ικανοποιούν την ιδιότητα των πινάκων Monge, ενώ η μεγιστοποίηση του ελάχιστου λόγου ικανοποίησης ικανοποιεί την ιδιότητα των bottleneck πινάκων Monge. Τέλος προκύπτει ένας σημαντικός θεωρητικός συμβιβασμός που αφορά το γεγονός ότι το ταίριασμα που οδηγεί στη μεγιστοποίηση του συνολικού λόγου ικανοποίησης καταλήγει στην ελαχιστοποίση της ικανοποίησης του χειρότερου UE και αντιστρόφως.

Στα πλαίσια του Κεφαλαίου (Chapter) 4 λαμβάνονται υπόψη τόσο οι ζεύξεις τροφοδοσίας, όσο και οι κατερχόμενες ζεύξεις και χρησιμοποιείται ο Ουγγρικός αλγόριθμος. Εξετάζονται οι μετρικές των απωλειών του συστήματος, της αντιστοίχισης των χωρητικοτήτων και του συνολικού λόγου ικανοποίησης και παρέχονται βέλτιστα ταιριάσματα στις O2O και O2M περιπτώσεις. Βέλτιστα ταιριάσματα παρέχονται και στην περίπτωση που δεν είναι δυνατόν να σχηματιστούν όλα τα ζευγή GW-UE.

Τέλος, στο Κεφάλαιο (Chapter) 5 παρέχονται υποβέλτιστες λύσεις στα προβλήματα μεγιστοποίησης τόσο του ελάχιστου, όσο και του συνολικού λόγου ικανοποίησης, αλλά και της ελαχιστοποίησης τόσο του μέγιστου, όσο και του συνολικού λόγου δυσαρέσκειας. Ο τελευταίος προτείνεται για πρώτη φορά στη βιβλιογραφία, εξ’ όσων γνωρίζουμε, σαν μια εναλλακτική απλή μετρική για την αξιολόγηση της επίδοσης των συστημάτων. Στα συγκεκριμένα προβλήματα κάθε GW δεν έχει προκαθορισμένο αριθμό εξυπηρετούμενων χρηστών, όπως συνέβαινε μέχρι τώρα, και οδηγούμαστε στη χρήση προσεγγίσεων από τον κλασματικό προγραμματισμό και τη διαφορά κυρτών συναρτήσεων. Μάλιστα στην τελευταία περίπτωση παρέχεται μια γενική μέθοδος επίλυσης προβλημάτων με τετραγωνικές μορφές πινάκων, μέσω της διαφοράς κυρτών συναρτήσεων.

Επιπλέον, στο Κεφάλαιο (Chapter) 5 παρουσιάζουμε μια θεωρητική ανάλυση για να προσεγγίσουμε την ελαχιστοποίηση της n-ιοστής τάξης του rate matching, όπου το n είναι θετικός και ακέραιος αριθμός, εφαρμόζοντας τον αλγόριθμο διαφοράς κυρτών συναρτήσεων. Για να επιτευχθεί αυτό, εκμεταλλευόμαστε κατάλληλα τις τετραγωνικές μορφές που εμφανίζονται μαζί με τους κυρτούς και κοίλους όρους του διωνυμικού αναπτύγματος.

Με βάση τις υποθέσεις των μοντέλων που αναπτύχθηκαν στο πλαίσιο αυτής της Διατριβής υπάρχουν σημεία που μπορούν να ληφθούν υπόψη για περαιτέρω έρευνα στο μέλλον, στο πεδίο της διαχείρισης πόρων σε δορυφορικά δίκτυα [Kuang17], [Kisseleff21].

Αρχικά, η απόδοση της μεθόδου που περιγράφεται για την ελαχιστοποίηση της n-ιοστής τάξης του rate matching πρέπει να αξιολογηθεί μέσω της σύγκρισής της με τον εξαντλητικό μηχανισμό, βάσει προσομοιώσεων. Συγκεκριμένα πρέπει να εξεταστούν τόσο η απόκλιση της προτεινόμενης λύσης από τη βέλτιστη, όσο και οι επαναλήψεις που απαιτούνται για τη σύγκλιση του αλγορίθμου.

Επιπρόσθετα, υποθέτουμε στις προσομοιώσεις μια ομοιόμορφη κατανομή για την ζητούμενη χωρητικότητα των UEs. Παρόλο που οι παρουσιαζόμενες μαθηματικές θεωρίες μπορούν να εφαρμοστούν ανεξαρτήτως των μορφών των προσφερόμενων και ζητούμενων χωρητικοτήτων, είναι σημαντικό να εξεταστούν διαφορετικές κατανομές για τις ζητούμενες χωρητικότητες [Al-Hraishawi20], [Ortiz-Gomez21]. Επιπλέον, τα πραγματικά δεδομένα είναι υψίστης σημασίας και αντί για τη χρήση μαθηματικών τύπων, οι προσφερόμενες και ζητούμενες χωρητικότητες μπορούν να προέρχονται από αυτά και να γίνει μια μελέτη όπως για τις απώλειες του συστήματος βάσει αυτών. Επίσης, εκτός από τις περιπτώσεις O2O και O2M, μπορούν να ληφθούν υπόψη κατάλληλα σενάρια όπου κάθε GW μπορεί να εξυπηρετεί πολλούς UEs και κάθε UE μπορεί να εξυπηρετείται από πολλές GWs.

Μια λογική επέκταση του μοντέλου που αναπτύχθηκε στο Κεφάλαιο (Chapter) 5 είναι η υπόθεση ότι μια GW δεν μπορεί να εξυπηρετήσει όλους τους UEs. Έτσι μπορεί να γίνει η μελέτη ενός πιο πολύπλοκου σεναρίου που θα λαμβάνει υπόψη τις διαφορετικές κατερχόμενες ζεύξεις, τον μη προκαθορισμένο αριθμό των UE που εξυπηρετούνται ταυτόχρονα από κάθε μια GW αλλά και τον παραπάνω περιορισμό.

Η μελέτη των προβλημάτων της από κοινού κατανομής πόρων είναι ζωτικής σημασίας στα δορυφορικά δίκτυα, όπου υπάρχει ανάγκη χρήσης όλων των δυνατών πόρων. Καθώς τα σενάρια γίνονται πιο περίπλοκα λαμβάνοντας υπόψη περισσότερες παραμέτρους, η εφαρμογή της τεχνητής νοημοσύνης είναι ένας πιθανός σύμμαχος για την αντιμετώπιση αυτών των προβλημάτων. Στην τελευταία περίπτωση, η εκπαιδευτική διαδικασία είναι χρονοβόρα και γίνεται offline. Στη συνέχεια, το εκπαιδευμένο μοντέλο παρέχει απαντήσεις σε σύντομο χρονικό διάστημα και μπορεί να χρησιμοποιηθεί σε πραγματικές συνθήκες. Τέλος, ενώ τα μοντέλα μηχανικής μάθησης μπορούν να «κατανοήσουν» πολύπλοκες σχέσεις και είναι σε θέση να λύσουν σε αποδεκτό επίπεδο πολλά προβλήματα σε ένα ευρύ φάσμα επιστημονικών πεδίων, δεν υπάρχουν θεωρητικές εγγυήσεις για την απόδοσή τους λόγω της μορφής των συναρτήσεων τις οποίες καταβάλλουν προσπάθεια να προσεγγίσουν.

Chapter 2

Introduction

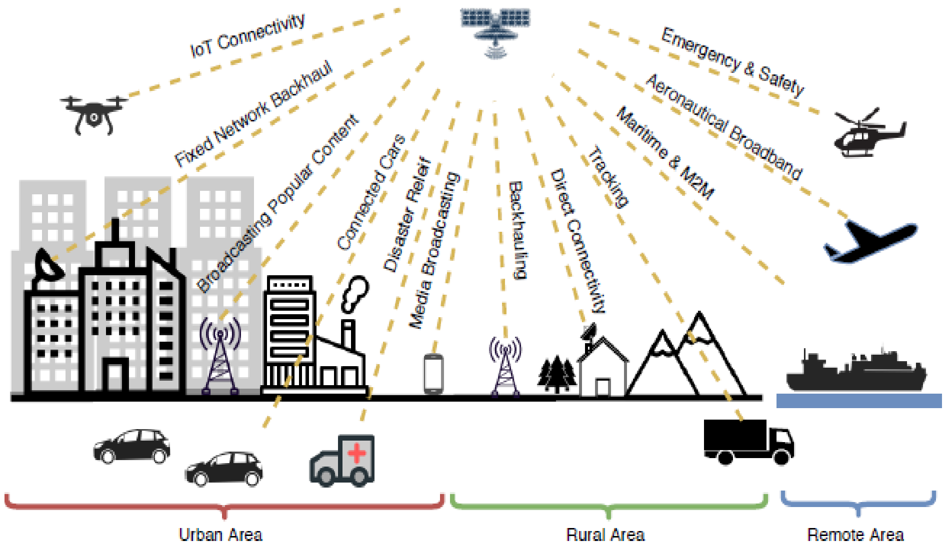


Figure 1: Satellite Services in the 5G networks [Kodheli21].

The special features and technical advances in satellite communications (SatComs) make them necessary to support a wide range of applications, either as a standalone solution or through their integration in the fifth generation (5G) networks [Kodheli21, Völk19]. In summary, considering Figure 1, the assistance of SatComs in 5G ecosystem includes: (a) for urban areas the Internet of Things (IoT) device connectivity, backhaul support over fixed networks, popular content and media broadcasting, vehicle connectivity and emergency response, b) for rural areas backhauling, direct connectivity and monitoring and c) for remote areas the communication in maritime sector, machine-to-machine (M2M) connectivity, aeronautical broadband and emergency communications.

Moreover, as technology is developed, different communication systems in multi-layer architectures, as shown in Figure 2, can be combined to guarantee high data rate services such as in ultra-dense regions. These networks include satellites, low/very low earth orbit (VLEO) satellites, high altitude platforms (HAPs) and low altitude platforms (LAPs) like unmanned aerial systems (UAVs). Their respective altitude ranges are 100 to 450 km for VLEO, 15 to 25 km for HAPs and up to 4 km for LAPs [Kodheli21].

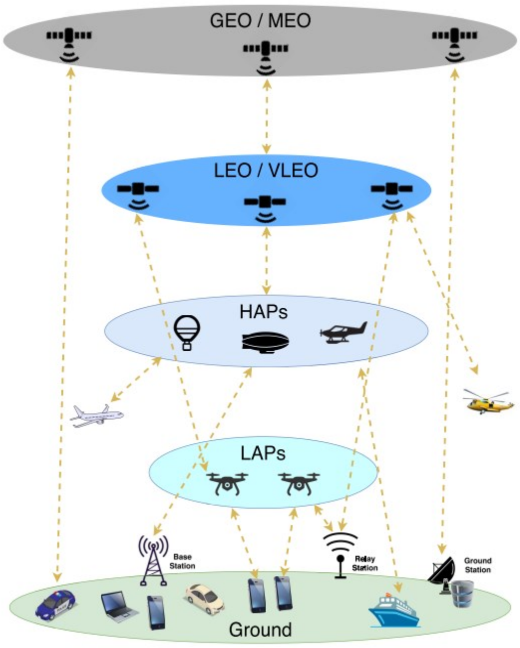


Figure 2: Multi-layer communications ecosystem [Kodheli21].

2.1 Current Status of Satellite Communications

Nowadays, the notion of "New Space" has been emerged meaning: 1) the space privatization, 2) satellite miniaturization and 3) services based on data from space [Kodheli21]. Specifically, companies such as SpaceX launch satellites, while until recently this was done only by institutions. Moreover, the satellite miniaturization helps the multiplexing of multiple cube/micro/nano-satellites into a single launcher and these innovations make simpler the access to space and give the ability to gather a large amount of data. Towards this direction services based on 'cloud' technology have been developed, such as Amazon Web Services, having ground stations that are shareable among the constellations and data processing can be done under high computing facilities.

In the same context, Microsoft Azure Space cooperates with SpaceX Starlink to have a high-speed, low-latency satellite broadband connection for the Azure Modular Datacenter and, based on its existing partnership with Société Européenne des Satellites (SES), will support its O3b medium earth orbit (MEO) constellation to extend the connectivity between its cloud data centers and cloud edge devices. With cloud technology, interested customers will be able to access it, without the need for long-term investment in personal ground station infrastructure, reducing the cost of sending data from space to Earth, but also significantly reducing data access delays.

Continuing the description of trends in SatComs, their integration with the 5G networks is of utmost importance. In International Mobile Telecommunications for 2020 and beyond (IMT2020) are defined three major groups of 5G usage cases by ITU-R [ITU-R15]: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC) and ultra reliable and low latency communication (uRLLC). The satellite usage cases for mMTC involve the IoT where high network load is generated and the satellites assist the terrestrial networks by providing the backhaul or continuous service when they fail. In the case of uRLLC the satellite can assist with broadcast of content, in case of non-critical data and edge caching, i.e. processing delay-intolerant information and only non–critical data transmitted through satellite. In terms of caching, the problem is how to prefetch the high volume of popular content to the caches. The satellite backhauling with its beams' wide area coverage is a possible solution [Kodheli21]. Finally, specific paradigms for satellites in eMBB can be found in [Liolis19].

European Space Agency (ESA) and the European space industry have joined forces to develop and demonstrate the added value that satellite brings to 5G since June 2017, at the Paris Air and Space show, where ESA and 16 satellite industry leaders signed a Joint Statement on their collaboration in the “Satellite for 5G”. In fact, in the document “Assessing satellite-terrestrial integration opportunities in the 5G environment”, which was prepared in September 2016 with the support of ESA in the future preparations of the Advanced Research in Telecommunications Systems (ARTES) program, the high throughput satellite (HTS) systems and non-geostationary constellations were mentioned as innovations of satellite systems. The latter reduce dramatically the latency of satellite communications. Finally, the need for rapid standardization of the necessary interfaces to allow integrated management and operation of 5G hybrid satellite-terrestrial networks was also stated.

In addition to the efforts for integration of satellite communications into 5G networks, there is a shift in the creation of high-performance optical networks. The study of satellite optical communications started by ESA in December 2016, under the ARTES program with the project name "SeCure and Laser communication Technology (ScyLight)". The ScyLight project focuses the European and the Canadian industry's efforts on optical communications technologies, specifically in the following areas: a) system-level optical communication technology, b) optical communication terminal technology, intra-satellite photonics and optical payloads and c) quantum cryptography technologies in space. Furthermore, ESA has prepared a project called “High thRoughput Optical Network (HydRON)”, which aims to seamlessly integrate terrestrial and satellite infrastructure into a terabit-optical network, called “Fiber in the Sky”, to help European and Canadian industry test their technologies in orbit.

The HydRON project aims to demonstrate that: a) all optical satellite nodes (geostatic and non-geostatic) can produce extremely high data throughput, b) space laser networks with terabit connectivity capabilities exceeding 100 Gbps and capable of optically rerouting/switching data streams can perform similarly to standard fiber optics widely used in terrestrial systems, c) the impact of atmospheric conditions can be reduced by utilizing the capabilities of the HydRON network to redistribute data, as up/downlink stations can be located at geographical areas with high link availability (good weather conditions) or distributed ground station optical networks can serve more than one satellite at a time and avoid expensive waiting times, d) HydRON's inherent data distribution capabilities will enable the collection and distribution of user data within the network, similar to a terrestrial fiber network and e) the use of artificial intelligence (AI) will benefit the new network formats to integrate with terrestrial networks [Hauschildt18].

As telecommunication services are provided by both national and commercial satellite infrastructure, key operations and infrastructures of the European Union (EU) and its Member States are exposed to security risks. Secure satellite communications that can be used in a timely and effective manner are critical to government security agencies such as the police, border guards, firefighters, civilian and military crisis forces. These services can assist in the safe operation of missions that may not be able to rely on traditional communication networks or be subject to cyber threats. This is how the EU Governmental Satellite Communication (GOVSATCOM) program was created, in which the ESA, the Member States and the European Commission work together. This aims to provide secure and cost-effective communication capabilities to critical security missions and operations managed by the EU and its Member States, including national security agencies and EU agencies and institutions.

In addition, in the framework of EU Horizon 2020, in September 2020 the program "European Networking for satellite Telecommunication Roadmap for government Users requiring Secure, inTeroperable, innovative and standardized services (ENTRUSTED)" was launched with funding of about 3 million euros which will be completed in February 2023 and consists of almost 20 institutions representing Member States and EU agencies. ENTRUSTED aims to provide recommendations to the European Commission on issues that could affect users in the area of secure satellite communications services. These may be related to the necessary investments, the user equipment and the appropriate technological aspects that are important for the design of future services.

Concerns about communications’ security led in April 2019 to the signing of a technical agreement for a European project for Quantum Communication Infrastructure (QCI). Quantum Key Distribution (QKD) technology based on the principles of quantum mechanics is used to perform cryptographic tasks and cannot be compromised by quantum computers, thus allowing long-term security of data and communication messages. With the support of the QKD, the end-to-end quantum communication infrastructure will be composed of elements on Earth and in space and will significantly enhance Europe's capabilities for cybersecurity and communications. In fact, this infrastructure will be able to benefit from digital signatures and authentication. In particular, the QCI terrestrial component will consist of a series of quantum communication networks connecting critical infrastructures and sensitive data centers in Europe. The space component, known as SAGA (Security and cryptoGrAphic mission), will be under the responsibility of ESA and will consist of satellite quantum communication systems with pan-European coverage [QKD19].

2.2 Radio Resource Management Framework

The huge increase in the demand of wireless users for very high data rate broadband internet services is a common knowledge. In Cisco’s report [Cisco19] we remark that monthly global mobile data traffic will be 77 exabytes by 2022 and annual traffic will reach almost one zettabyte. In addition, there is need to boost the performance of mobile backhaul networks in terms of capacity resilience against link failure or congestion. In the upcoming 5G era of wireless networks, satellites will be an integral part of the network of the future for the delivery of internet and multimedia services, as also stated in aforementioned Section. The HTS systems are rendered as a reliable part towards this direction, mainly providing services in rural and suburban areas, where the terrestrial networks have limited connectivity and through the support of terrestrial infrastructure in 5G networks for backhauling and traffic offload [Evans15]. Generally, the application of satellite networks for broadband internet services has been included in the second generation of Digital Video Broadcasting for Satellite Transmission DVB-S2 standard and in its extension DVB-S2X [ETSI14].

In order to be able to satisfy the high data rates of internet access, the HTS systems target to hundreds Gbps up to Tbps [Jeannin14]. These bit rate requirements need the exploitation of large portions of bandwidth which are available at higher frequency bands, such as Ka Band (20/30GHz) and Q/V Band (40/50GHz). Specifically, the Q/V Band is used at the link between the gateway (GW) and the satellite, which is called as feeder link and the Ka Band is exploited at the link between the satellite and user (UE) beam, which is called as user link.

It is well known that the atmospheric effects deteriorate the performance of communication systems for operating frequencies above 10GHz [Panagopoulos04]. Specifically, this makes the system more vulnerable to fading mechanisms that can crucially influence the availability of the system.

These severe signal degradations in high frequency bands can be mitigated by the smart gateway diversity (SGD) technique, which treats the ground and space resources appropriately. Especially, by exploiting the spatial diversity of the feeder links, due to the large geographical distance among the gateways, the service of a user beam can be changed and the latter can be served by another GW, whose feeder link faces less severe fading conditions. Specifically, in [Kyrgiazos14] authors study the assignment of a number of time slots that each gateway is connected to a user beam under the type of time multiplexing N-active SGD scheme. In the latter scheme, calling as N the number of GWs in the system, the UE beams can be served by different GWs in different time slots, which together constitute a frame. Additionally, three different optimization problems, i.e. rate matching, load balance and fairness method, are examined. Particularly, due to the combinatorial form of problems, for the rate matching and load balance methods the GLPK software tool is used.

In literature the concept of HTS networks is of utmost importance since it may help the satellite operators to achieve the high throughput requirements of their customers. In [Vasavada16] new architectures for next generation HTS systems are proposed, while in [Tani17] a flexibility-enhanced HTS network is investigated as a viable solution in case of disaster management because its operation is independent of the availability of terrestrial networks. The idea of SGD techniques and their combination with appropriate resource allocation mechanisms are examined thoroughly for current and future HTS systems, making the satellite operators able to achieve the high throughput requirements of their customers. Especially, in [Rossi17] the outage analysis in a SGD scheme is examined in order to allow the use of the Q/V Band in the feeder link for commercial purposes, while in [Muhammad16] a SGD multi-gateway multi-beam satellite network is considered and a Quality of Service (QoS) management framework is proposed to control congestion and packet losses, that deteriorate the performance of delay-sensitive and delay-insensitive traffic flows.

In terms of radio resource management (RRM) field, containing resources such as bandwidth, power allocation and user scheduling, there is a wide scientific literature and state of the art approaches are provided not only in wireless networks [Manap20], but also in satellite communication systems [Kisseleff21]. Based on [Elsayed19] the RRM approaches can be separated as:

1) centralized or decentralized: If the RRM decisions are originated by an agent that gathers all the information then we talk about a centralized RRM approach, otherwise a decentralized process is followed, where users make decisions autonomously. Generally, centralized approaches have more overhead.

2) optimized, heuristic, game theoretic, or AI-enabled according to the mathematical theory. Specifically, optimization problems are usually much complicated, because there are several parameters in multiobjective functions that have several constraints. Afterwards a heuristic solution can be applied generally without having any theoretical guarantees. In case of game theory approaches, the agents in the network interact and influence the decisions of other agents. Particularly, the latter methods can effectively adapt to network dynamics. Finally, a brief list of works for AI-enabled processes is cited in the end of this Section.

An indicative list about the RRM cases in SatComs is given in paragraphs below. Various RRM mechanisms have been concerned either for the cooperation of satellite and terrestrial networks, such as [Lagunas17], [Rosati06], or the resource allocation in satellite downlinks, such as [Choi05], [Choi09], [Destounis11], or the cognitive satellite networks [Lagunas15]. In [Lagunas17] authors study a hybrid satellite-terrestrial backhaul network and propose a joint satellite and terrestrial carrier assignment algorithm, targeting to the maximization of the satellite and terrestrial links' sum-rate, considering in parallel the minimization of interference impact in the links' performance. Due to the intractability of the initial problem the carrier assignment for the satellite backhaul network is firstly determined and, based on this allocation, a sub-optimal carrier assignment for the terrestrial network is proposed. Finally, in [Rosati06] a joint routing and resource allocation mechanism is proposed in a hybrid satellite-terrestrial network. Especially, a cross-layer approach in the protocol stack is investigated for the coordination of the network and the link layer and a decentralized and distributed solution based on the Lagrange dual decomposition method is implemented, resulting in a pricing strategy related with bandwidth.

Considering the satellite downlinks, in [Choi05] the optimum satellite downlink multi-beam power and spotbeam allocation based on demands and link qualities is provided, using the Lagrangian approach, while in [Choi09] the optimal solution for joint resource allocation and congestion control based on incoming traffic, link qualities, and average delay constraints is extracted. Finally, in [Destounis11] a heuristic dynamic power allocation among the beams of a multi-beam satellite antenna for a broadband satellite communication network operating at Ka band and above has been proposed. For cognitive satellite networks in [Lagunas15] resource management mechanisms, including carrier, power and bandwidth allocation, for a cognitive spectrum utilization satellite scenario with incumbent terrestrial network are investigated. The scope is the exploitation of the spectrum allocated to the terrestrial networks, which are the incumbent users, by the satellite system without causing harmful interference to the former.

Continuing the brief discussion about the RRM approaches in SatComs, in [Takahashi19] authors propose an adaptive power resource allocation with multi-beam directivity control in an HTS system with digital beam forming, in order to solve the trade-off, accrued from physical restrictions, between the transmit power and beam directivity. Moreover, in [Chen19] a joint power and subchannel allocation algorithm from the perspective of efficiency and fairness in cognitive satellite network is examined, applying the Lagrange multiplier method. Authors show its efficiency through simulations. Furthermore, in [Li20a] a game-theoretical approach, containing both spectrum pricing and auction, for enhancement of spectral efficiency in satellite mobile communications is implemented. Especially, a satellite spectrum pricing scheme is proposed considering the spectrum reuse in multi-beam satellite systems, the heterogeneous nature of satellite transmission links in different spectrum bands and predictable and periodic satellite switching from one non-Geostationary Earth Orbit (GEO) satellite link to another.

Additionally, in [Li20b] a power control method for the IoT terminals in satellite-based IoT environment is applied, with close approach to the optimization solution and the Poisson Point Process is used to model the IoT users’ distribution. Finally, in [Lin19] a joint beamforming and power allocation mechanism for satellite-terrestrial networks with non-orthogonal multiple access is considered. The maximization of sum rate of satellite-terrestrial network considering the constraints of per-antenna transmit power and the QoS requirements of satellite and cellular users is approximated, by applying appropriate user clustering. Then the problem is transformed to an equivalent convex one and an iterative algorithm with fast convergence is provided.

Paving the way towards future wireless communications, AI is an integral part of RRM in them [Elsayed19, Lin20]. In SatComs there are studies that use AI-enabled techniques such as the deep reinforcement learning (DRL) and an indicative list of them follows. In this concept there are agents, states and actions and using feedback from the environment the intention of agent is to choose the action that results in larger final reward. The environment and agent are connected through the agent’s actions and the environment’s states and rewards. Especially, the agent makes a series of decisions based on a policy of actions with respect to the observed environment’s state. This framework is valuable for wireless networks due their dynamic ecosystem [Elsayed19].

Specifically, in [Hu18] a DRL for dynamic resource allocation is proposed in multi-beam satellite systems, where the states are reformulated as 2D tensors to consider both spatial and temporal traffic features. In [Hu20a], a multi-objective reinforcement learning concept, in satellite broadband systems, for beam hopping management is proposed. The target is to match the demand of system capacity with the efficient utilization of beams considering the fairness of beam’s services, the delay minimization of real-time services transmission and the maximization of throughput of transmission of non-instant services. Additionally, in [Liuis19] a DRL method to allocate power in multi-beam satellite systems is applied, where the problem is described with continuous state and action spaces and the actions are based on the power that is the optimization parameter.

In parallel in [Hu20b] the authors consider the inter-beam interference and resource utilization variance and build a game-theoretic model for bandwidth allocation in the forward link. Then a multi-agent deep reinforcement learning-based bandwidth allocation scheme is proposed, to satisfy the requested capacity. The results reveal that the proposed method is more efficient than other traditional bandwidth allocation schemes, in matching the requested capacity across the beams.

Moreover, in [Deng20] the promising usage of DRL for the next generation heterogeneous satellite networks is presented, in order to achieve appropriate matching between resources and services. Specifically, the problems of multi-objective and multi-agent reinforcement learning are investigated. Finally, in [Jiang20] a reinforcement learning capacity management mechanism in a three-layer, including GEO, MEO and low earth orbit (LEO) satellites, heterogeneous network is studied. Authors propose an algorithm with low-complexity to compute the capacities among source and destination satellites and a capacity allocation algorithm to optimize the long-term utility when sharing capacity between the users.

2.3 Structure of the Thesis

In Chapter 3 of this thesis optimal pairing schemes among GWs and UE beams are considered in HTS systems, focusing on the feeder links, based on matching theory, applying the Gale–Shapley (GS) algorithm and the theory of Monge arrays. The examined performance metrics, based on GWs' offered and UEs' requested capacities, are the minimization of system's losses and rate matching and maximization of minimum and total systems' satisfaction ratio. Moreover in Chapter 4, considering also the downlinks of HTS system, optimal pairings are presented based on Hungarian algorithm for the minimization of system's losses and rate matching and maximization of systems' satisfaction ratio. In all above cases one-to-one and one-to-many pairings are assumed and the number of simultaneously served UEs by each GW is predetermined. The latter assumption is removed in Chapter 5 and suboptimal one-to-many pairings are presented for maximization of minimum and total systems' satisfaction ratio and minimization of maximum and total systems' dissatisfaction ratio. Iterative algorithms from fractional programming and difference of convex functions are used. Furthermore, the application of difference of convex functions is presented theoretically in order to solve the minimization of n^{th} order rate matching where *n* is positive, even and integer. Finally, Chapter 6 concludes the thesis where the main conclusions are depicted and some points for further research are outlined.

Chapter 3

Optimal Allocation Schemes Focusing on Feeder Links[1,2,3]

In this Chapter we investigate a multi-beam HTS system with *M* GWs that can serve *N* UE beams as presented in Figure 3 and no particular payload constraints are assumed, i.e. all possible pairings among GWs and UEs are feasible. A frame period separated in different time-slots is considered, based on the time multiplexing SGD context. At every time-slot each UE is served by one GW and each GW serves only one UE, assuming *M=N*. More UEs are served in case *M<N*. In the former case each GW_k, with *k=1,…,M*, serves $q_k=1$ UE, while in the latter case $q_k>1$ UEs are served at the same time by GW_k satisfying the relation $\sum_{k=1}^{M} q_k = N$. Hereafter, the number of each GW_k in the system “virtually” increases from one to q_k by offering at the same time capacity $OC_k = OC_k^{"} / q_k$ to UEs where $OC_k^{"}$ in bps is the total offered capacity of GW_k.

Specifically, the total offered capacity is calculated using the Shannon expression, i.e. $OC_k^{"} = B_C \log_2(1+\gamma_k)$ where B_C is the bandwidth and $\gamma_k^{-1} = CNIR_{up,k}^{-1} + CNIR_{dn}^{-1}$. Especially, γ_k is the end-to-end (E2E) or total carrier to noise plus interference ratio $CNIR_k$, with $CNIR = C/(N+I)$, that includes both CNIR of feeder link *k* and CNIR of downlink which is considered same for all UEs since we focus on the feeder links. Finally, $CNIR_{up,k} = CNIR_{CS,k} 10^{-Att_k/10}$ where the $CNIR_{CS,k}$ is CNIR in clear sky conditions for the feeder link *k* and Att_k is the total atmospheric induced attenuation. The total atmospheric attenuation includes gaseous attenuation, scintillation, attenuation due to clouds and rain attenuation [Karagiannis12, Kourogiorgas17].

From the aforementioned analysis, in the system there are *N* GWs each of them offering OC_i capacity with *i=1,…,N*. Moreover, there are *N* UEs where each UE_j with *j=1,…,N* requests capacity

RC_j in bps to satisfy its need for data. The scenario where UEs are more than the GWs is a realistic and important scenario for the design of satellite systems.

Finally, the examined performance metrics are the system's losses, rate matching and satisfaction ratio, all widely known in the related literature [Kyrgiazos13, Kyrgiazos14, Lei11]. Specifically, losses are determined as the non-negative difference among the requested and offered capacities, while rate matching as an n^{th} order deviation of them, in our case $n=1$, describing the absolute difference. To conclude the fraction of offered over requested capacities determine the satisfaction ratio.

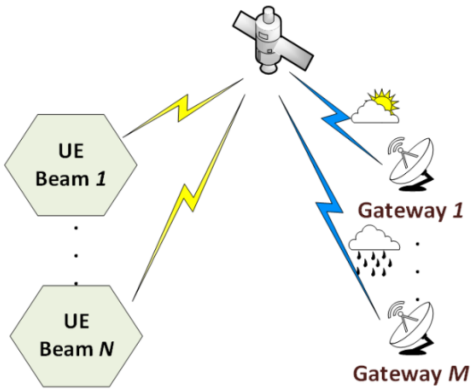


Figure 3: System Configuration focusing on Feeder Links

3.1 Pairing Allocation based on Gale-Shapley Algorithm

In this Section the minimization of total system's capacity losses is studied considering the offered capacities of gateways and requested capacities of users' beams, in the scenario described above. To do that we exploit the matching theory that has been largely used in economics, as a mathematical framework attempting to describe the formation of mutually beneficial relationships between different sets of agents. Especially, matching theory [Roth89, Gale62] helps to take resource management decisions efficiently and has recently been involved in synchronous wireless networks [Gu15, Bayat16] with very promising results. There are many paradigms about the application of this theory, such as in cognitive radio networks [Leshem12], orthogonal frequency-division multiple access (OFDMA) networks [Jorswieck11] and heterogeneous small cell networks [Bayat14].

This theory includes a two sided approach, which contains two different sets of agents in a matching market and a way to make the agents' pairing provided by the application of an efficient stable matching algorithm, known as Gale-Shapley or deferred acceptance (DA) algorithm [Gale62]. In the matching market each agent of one set ranks the agents of the other set according to a preference relation based on their utility functions. In our case the matching market is the HTS system that involves the disjoint sets of GWs and UE beams, where each GW/UE beam ranks the UEs' beams/GWs (correspondingly) according to their utility functions. Finally, the deferred acceptance algorithms have many practical applications such as the National

Resident Matching Program of U.S. for medical school graduates and the school choice systems in Boston and New York City [Roth08].

There are various classifications of matching models depending either on the agents’ quotas or the construction of the agents’ preference lists. According to the agents’ quotas, which indicate the maximum number of pairings that an agent can make, there is the one-to-one (O2O) matching, such as classical marriage problem, one-to-many (O2M), such as college admission problem and many-to-many matching models [Xu11, Hamidouche14]. Indicatively, in marriage problem each man is matched with at most one woman and reversely, in college admission problem each student is matched to at most one college and the latter is matched to at most its quota of students and many agents of one set can be matched to many agents of another set, in many-to-many pairings.

Based on the agents’ preferences, i.e. utility functions, there are two mostly used subcategories [Gu15], the canonical matching, where the preferences depend solely on the information available at each specific agent and the matching with externalities [Bando12, Namvar14]. In the latter subcategory, there are interdependencies between the agents’ preferences, i.e. individual agents’ preferences are affected by the other agents’ preferences and also by the current matching. An indicative example, given in [Bayat16], describes a user-subchannel pairing in an ad hoc network where a subchannel can be accessed by many users. A user may choose a specific subchannel as its favorite, but as more users exploit the same channel the level of interference increases and this user may choose another subchannel as most preferred. This means that the preference of a user for a subchannel is directly related with other users’ preferences.

3.1.1 Capacity Allocation Scheme

Our objective is to propose optimal GWs-UEs pairings with low complexity in order to minimize in each time slot, the total system’s capacity losses, L, defined as:

$$\mathrm{L} = \sum_{j=1}^{N} \max\left\{ RC_j - OC_j , 0 \right\} \tag{1}$$

where OC_j is the offered capacity to j^{th} UE. From the analysis in Sections 3.1.1.1 and 3.1.1.2, we conclude that our algorithm results in the minimization of losses, considering two basic factors: a) the more demanding UEs are served by the GWs which offer higher capacities and b) this matching is the same and unique for both sides of matching process [Eeckhout00].

3.1.1.1 Matching Theory Concepts

In the following analysis, we use the terms UE and UE beam interchangeably to have a more compact and clarified analysis. Before presenting the proposed algorithm based on matching theory, the fundamentals of matching theory are given using the terminology of the capacity allocation problem under consideration.

At this point some basic concepts of matching theory are provided. The matching theory is applied to two different finite sets of agents, i.e. the set of GWs (**GWs**={GW_1,GW_2,…,GW_M}) and the set of UE beams (**UEs**={UE_1,UE_2,…,UE_N}) and is based on specific utility functions according to their preferences. We examine the case where each GW is able to serve many UE beams simultaneously (i.e. each GW has quota q_{GW}, which indicates the number of UE beams that can serve satisfying the relation $q_{GW} > 1$) in order to study the performance of HTS networks in more realistic scenarios where the UE beams are more than the GWs, called as O2M matching [Roth89]. Moreover, as special case of O2M matching we investigate the O2O matching [Roth89] in which each GW can serve at most one UE beam (i.e. the GW's quota satisfies the relation $q_{GW} = 1$).

The core of matching theory is the matching function *μ*, which is defined as follows, considering that $|P|$ indicates the size of P:

Definition [Roth89]: A matching *μ* is a function from the set $\mathbf{GWs} \cup \mathbf{UEs}$ into the set of unordered families of elements of $\mathbf{GWs} \cup \mathbf{UEs}$ such that:

1. $|\mu(\mathrm{UE})| = 1$ for every $\mathrm{UE} \in \mathbf{UEs}$ and $\mu(\mathrm{UE}) = \mathrm{UE}$ if $\mu(\mathrm{UE}) \notin \mathbf{GWs}$.

2. $|\mu(\mathrm{GW})| = q_{GW}$ for every $\mathrm{GW} \in \mathbf{GWs}$ and if the number of UEs in $\mu(\mathrm{GW})$, say *r*, is less than q_{GW}, then $\mu(\mathrm{GW})$ contains $q_{GW} - r$ copies of GW.

3. $\mu(\mathrm{UE}) = \mathrm{GW}$ if and only if UE is in $\mu(\mathrm{GW})$.

The matching *μ* among the *M* GWs and *N* UEs depends on their utility functions which include the UEs' requested and GWs' offered capacities, respectively. In case that a GW is able to serve simultaneously q_{GW} UEs then each of these UEs can exploit a portion of $1/q_{GW}$ of GW's offered capacity. Afterwards, the GW_i's/UE_j's utility functions for a given UE_j/GW_i, with $i = 1,\dots,M$ and $j = 1,\dots,N$, are defined as (2)/(3), respectively, considering the aforementioned assumptions:

$$U_{GW,ij} = RC_j, \tag{2}$$

$$U_{UE,ji} = \frac{1}{q_{GW,i}} OC_i. \tag{3}$$

According to the proposed matching scheme the GWs are more willing to serve UEs that request higher capacities and the UEs want to be served by GWs which offer higher capacities, in order to share smartly the system's resources (i.e. OCs) based on the corresponding UEs' beams demands (i.e. RCs). Based on these remarks and the utility functions described above, the preference list of GW_i is defined as:

$$prefGW_i = \{UE_{\sigma(k)}\}_{k=1}^{N}, \tag{4}$$

where $\sigma(\bullet$ refers to a mapping function $\sigma : \{1,\dots,N\} \to \{1,\dots,N\}$ that sets each UE in a descent ordered list, based on each GW's utility function according to the inequality (5):

$$U_{GW,i\sigma(1)} > U_{GW,i\sigma(2)} > \dots > U_{GW,i\sigma(N)}. \tag{5}$$

Moreover, considering the UE beams, the preference list of UE_j is described as:

$$prefUE_j = \{GW_{\lambda(k)}\}_{k=1}^{M}, \tag{6}$$

where $\lambda(\bullet$ refers to a mapping function $\lambda : \{1,...,M\} \rightarrow \{1,...,M\}$ that sets each GW in a descent ordered list based on each UE's utility function according to the following inequality:

$$U_{UE,j\lambda(1)} > U_{UE,j\lambda(2)} > ... > U_{UE,j\lambda(M)}, \tag{7}$$

where in the above notions the notation *σ(1)* (*λ(1)*) denotes the most preferable UE (GW), i.e. the UE with highest RC (GW with the highest OC), for the corresponding GW_i (UE_j).

3.1.1.2 Proposed Matching Scheme

The corresponding GWs-UEs pairing can be found by the proposed matching algorithm, as described in Figure 4 and afterwards this matching is considered in (1) to find the system's capacity losses.

It is noticeable that the solution of the GWs-UEs matching concept produces a stable matching and has low complexity as it is based on the GS or DA algorithm, that leads to a stable matching [Gale62]. Its runtime complexity is polynomial, especially $O(N^2)$, where *N* is the number of both GWs and UEs in our system. Particularly, the matching is stable for the marriage problem when there does not exist any other matching under which both matched agents would be more benefited than current matching. An assignment of UEs to GWs will be called unstable if there are two UEs *a* and *b* which are assigned to GWs *A* and *B*, respectively, although *b* prefers *A* to *B* and *A* prefers *b* to *a*.

The matching process, based on the DA algorithm, can be started either by the GWs or by the UEs changing the result of the matching algorithm while leaving invariant the core of the algorithm's formulation. Considering that the GWs' and UEs' preference lists are strict (as expressed in (5), (7)), it is proven [Roth89] that if the GWs start the matching process (GW-proposing matching) the result is the optimal stable matching for them, called as GW-optimal, meaning that every GW likes this matching at least as well as any other stable matching. Finally, the application of **O2M matching algorithm**, described in Figure 4, in the **O2O matching** is direct with the only assumption that $q_{GW,i} = 1$. Generally, it should be noted that in our system model the GWs–UEs pairing, through the application of scheme of Figure 4, based on the DA algorithm, is stable, as stated in [Roth89].

The system's assumptions about the invariance among the conditions of user links, due to the focus on the feeder links as stated in the beginning of this Chapter and the fact that each UE has

Input: number of GWs (*M*), number of UE beams (*N*), GWs' quotas (vector $\boldsymbol{q_{GW}}= [q_{GW,1}\ldots q_{GW,M}]$)

Matching Determination:

Step a (Initialization)

1) Each GW_i with *i=1,..,M* constructs its preference list $prefGW_i$ based on (2) and preference relation according to (5).
2) Each GW_i is replaced by its replicas $GW_{i,1}, GW_{i,2} \ldots GW_{i,q_{GW,i}}$ with the same preference lists as determined in **Step a.1**.
3) Each UE_j with *j=1,…,N* constructs its preference list $prefUE_j$ based on (3) and preference relation according to (7).
4) Each UE_j incorporates in its preference list, determined in **Step a.3**, the replicas $GW_{i,1}, GW_{i,2} \ldots GW_{i,q_{GW,i}}$ in the corresponding position of GW_i.

Step b (Matching Process)

1) Each *GW* proposes to its most preferred *UE* according to (4) that has not yet rejected it.
2) Each *UE* keeps the most preferred *GW*, according to (6), considering the proposed *GWs* to this specific *UE* and its current matching *μ*. The *UE* rejects the previous matching as well as the rest of proposed *GWs*, if this is imposed by (7).

Step c (Iteration Step)

Repeat **Step b** for each *GW* that has been rejected in the previous step until

- $|\mu(GW)| > q_{GW}$ (*GW* reaches its quotas) or
- $\mu(GW) = GW$ (i.e. *GW* has made a proposal to all the *UEs* of its preference list and results in remaining unmatched).

Output: stable matching *μ**

Figure 4: GWs to UE beams Matching Process (O2M Approach).

a specific requested capacity, results in an important characteristic for the preferences based on (2)-(5). All GWs have identical preferences over the UEs and all UEs have identical preferences over the GWs. Hence, the proposed algorithm results in a unique stable pairing [Eeckhout00].

3.1.2 Numerical Results

Table 3: Gateway Locations

	Location	Latitude (degrees North)	Longitude (degrees East)
Gateway 1	Nemea, Greece	37.81^o	22.67^o
Gateway 2	Sintra, Portugal	38.80^o	-9.38^o
Gateway 3	Harwell, UK	51.60^o	-1.29^o
Gateway 4	SES, Luxembourg	49.69^o	6.27^o

Table 4: Simulation Parameters

Parameter	Value
Feeder Link Frequency	V Band (50 GHz)
GEO Satellite Position	9^o East
Bandwidth (B_c)	1 GHz
Clear Sky Uplink CNIR($CNIR_{CS,up}$)	25 dB
Clear Sky Downlink CNIR($CNIR_{CS,dn}$)	13 dB

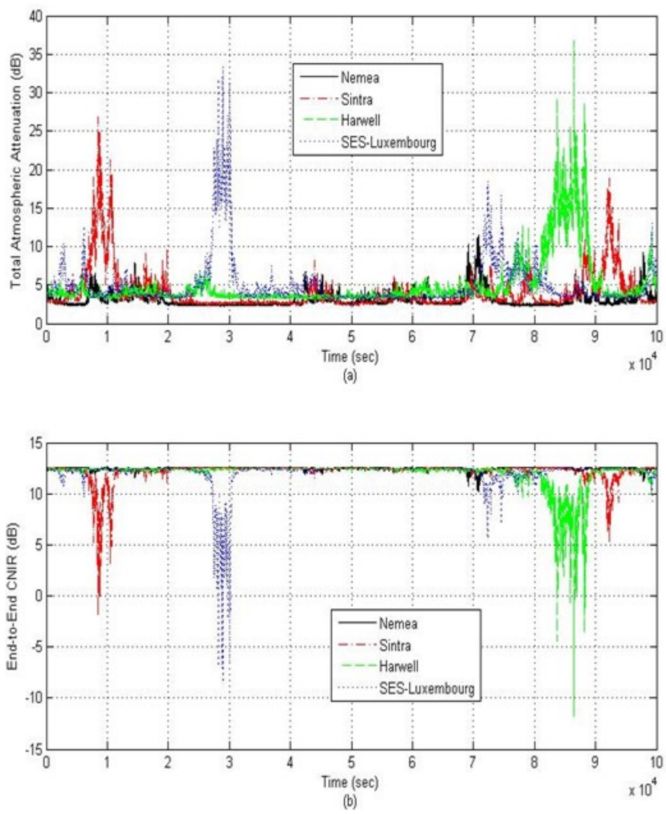


Figure 5: A time series snapshot of (a) Total atmospheric attenuation for the four feeder links and (b) end-to-end CNIR for the links from the four GWs.

We investigate a GEO HTS system, assuming four gateways in locations shown in Table 3 and four UE beams and the time series of total atmospheric attenuation derived using multi-dimensional stochastic differential equations [Karagiannis12]. The simulation parameters are summarized in Table 4. We assume constant links' propagation conditions during the frame period of *1 sec* and the RCs in the same period are drawn from a uniform distribution, as in [Kyrgiazos14], in the range $\left(0,(B_C/q)\log_2(1+CNIR_{total\_\max})\right)$ bps, where $q=q_{GW}$ is the number of simultaneously served UEs by each GW and the upper bound $CNIR_{total\_\max}^{-1}=CNIR_{CS,up}^{-1}+CNIR_{CS,dn}^{-1}$. Thus the capacity losses are estimated in this time duration. Finally the corresponding system's performance under different RRM mechanisms is investigated over a year.

In Figure 5 (a) the total atmospheric attenuation time series (correlated in space and time) are shown for the four GWs, while in Figure 5 (b) the end-to-end CNIR is presented. Furthermore, Figure 6 depicts the cumulative distribution functions (CDFs) of the gateways' offered capacities and proves that different atmospheric conditions, which characterize the four specified locations, result in different values of gateways' offered capacities. Thus, it is obvious that in general higher capacity values are offered by the GW in Greece, followed by the GW in UK, the GW in Portugal and finally the GW in Luxembourg.

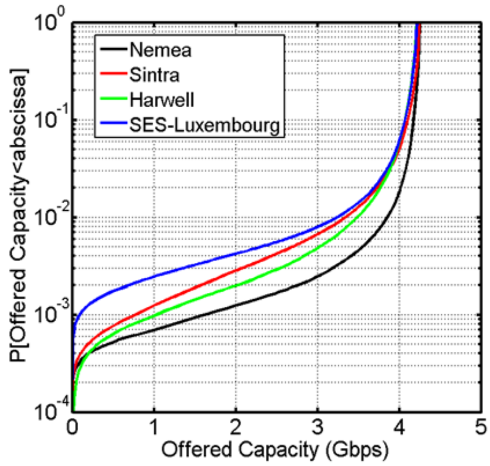


Figure 6: Cumulative distribution functions of the offered capacities of each gateway considering the corresponding GW locations given in Table 3.

We continue the performance analysis of the proposed matching scheme comparing it with the following RRM schemes: Fairness method, the Exhaustive mechanism, a less sophisticated Fixed scheme and a Random process. More specifically, the GWs-UE beams pairs are originated in Fairness method by the objective:

$$\max_{X}\left\{\min_{1\le j\le N}\left(\frac{OC_j(X)}{RC_j}\right)\right\}, \tag{8}$$

where the appropriate matching X* that satisfies (8) is extracted from all the possible pairing combinations of GWs and UE beams and then the losses are estimated for this specific *X** according to (1). Moreover, in Exhaustive technique we examine all the possible system's capacity losses, originated by all the possible pairing combinations among the GWs and UEs beams, in order to find the minimum one. Additionally, in Fixed scheme different GW-UE beam pairings are examined changing after equal number of frames, without requiring any particular resource management and in Random mechanism the pairing takes place in a random way.

Figure 7 presents the total gateways’ offered capacities and the system’s capacity losses, based on (1), over time for a time series snapshot of $3*10^6$ samples. In the first subfigure the total transmitted capacity by gateways is illustrated, while in the rest subfigures the capacity losses of proposed O2O matching, Exhaustive and Fixed mechanisms are depicted. It is obvious that the performances of O2O matching and Exhaustive mechanisms are the same and better than the corresponding system losses of Fixed mechanism. Finally, the losses increase for all RRM schemes in deep fades, however the system’s capacity losses are lower for the O2O matching and Exhaustive mechanisms compared with the less sophisticated Fixed mechanism.

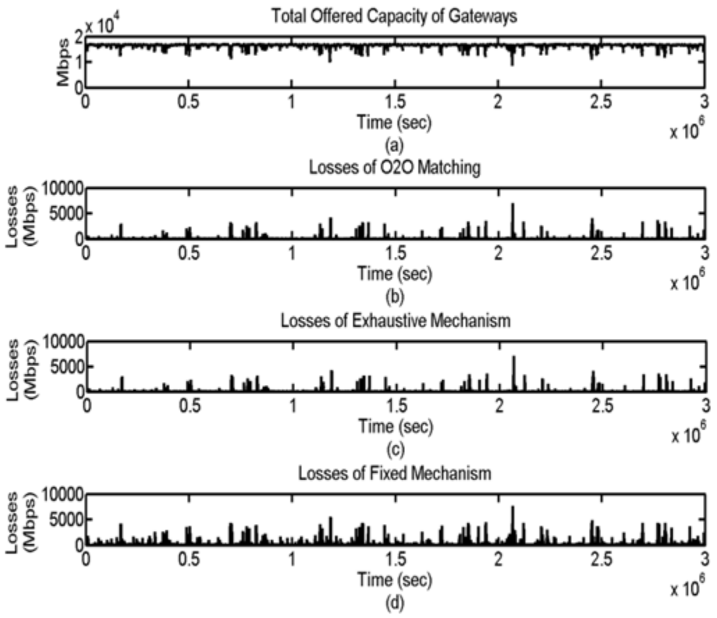


Figure 7: A time series snapshot of (a) Total Offered Capacities, (b) Losses of O2O Matching, (c) Losses of Exhaustive Mechanism and (d) Losses of Fixed Mechanism.

Figure 8 (a) presents the complementary cumulative distribution (CCDF) of the system’s capacity losses for the proposed O2O matching, Fixed, Exhaustive and Fairness RRM algorithms as a percentage of instantaneous traffic demands. Moreover, in Figure 8 (b), considering the same metric, the performance of O2O matching is illustrated as the latter is implemented after, or remains constant for, larger periods of time i.e. indicatively for two and four frames corresponding to 2 and 4 seconds respectively. In terms of Figure 8 (a) the proposed O2O matching has identical performance with the Exhaustive mechanism. Additionally, the O2O matching scheme has slightly better performance compared with the Fairness method. Furthermore, the Fixed allocation scheme has the worst performance. Finally, it is noticeable in Figure 8 (b) that if the O2O matching is less “dynamic”, namely repeated less times, or repeated after more frames, this leads to more capacity losses in the system.

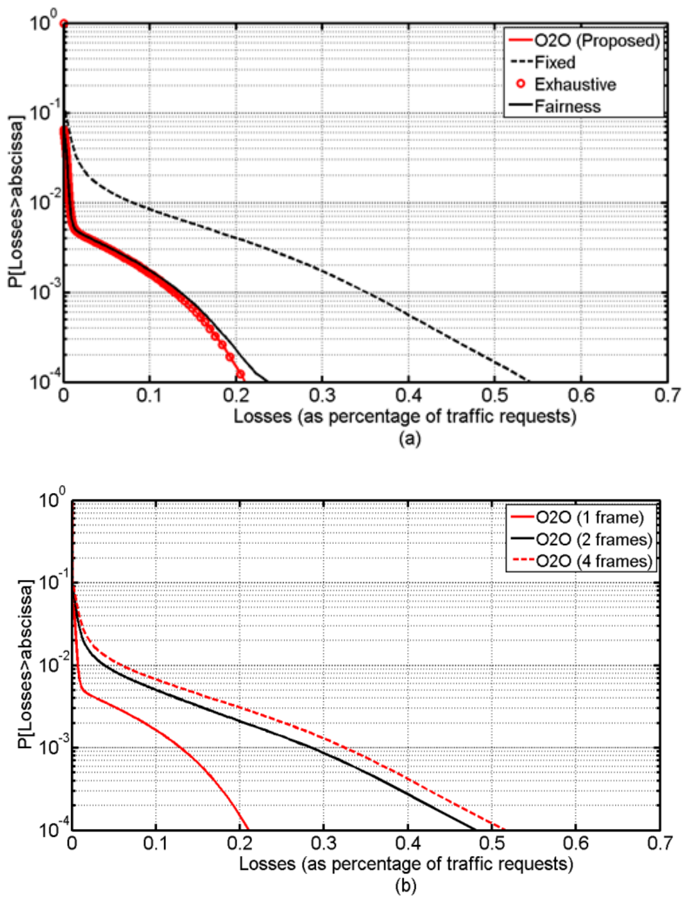


Figure 8: Comparison between (a) O2O, Fixed, Exhaustive and Fairness RRM Mechanisms, and (b) O2O Mechanism applied in different frames, based on the CCDF of their capacity losses.

Figure 9 presents the CCDF of the system's capacity losses as percentage of instantaneous traffic demands for the O2O matching and a Random matching scheme as the number of active GWs in the system decreases from four to three. We emphasize in the case that for some reason one GW stops its operation, i.e. the system has three and not four active GWs and the remaining GWs have to serve a larger number of UE beams. In this situation the capacity losses increase because one UE beam remains unmatched, namely unserved, considering that each GW can serve only one UE beam. Finally, our proposed sophisticated algorithm outperforms a naive Random matching scheme, where GW-UE beam pairs are constructed in a random way, in both cases as expected.

Figure 10 shows the CCDF of the system's capacity losses for the proposed O2M matching and Exhaustive RRM algorithms in three different cases, where each GW can serve simultaneously $q = q_{GW} = \{1, 3, 4\}$ UE beams. At this scenario, without loss of generality, we consider that there are two GWs and {2, 6, 8}, respectively, UE beams in order to study the realistic case that fewer GWs have to serve a larger number of UE beams. The considered gateways are located in Greece and Portugal, based on Table 3, respectively. It is obvious that in all three cases, where the GWs can simultaneously serve different number q of UE beams, the performance of O2M RRM algorithm is identical with the Exhaustive mechanism, while the former's complexity is lower because the latter investigates all the possible GW-UE beams matching combinations, in order to estimate the minimum losses.

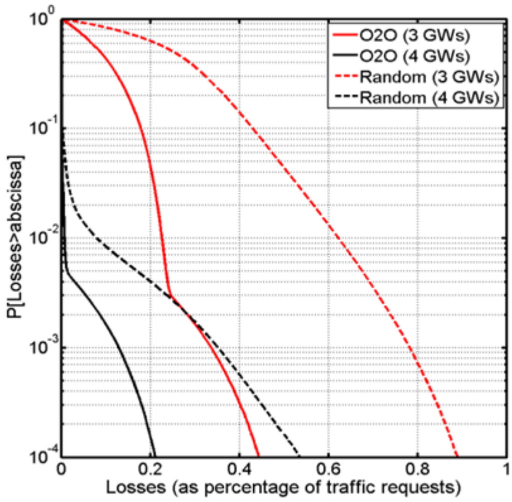


Figure 9: CCDF of the losses as the number of Gateways changes, for O2O and Random RRM mechanisms.

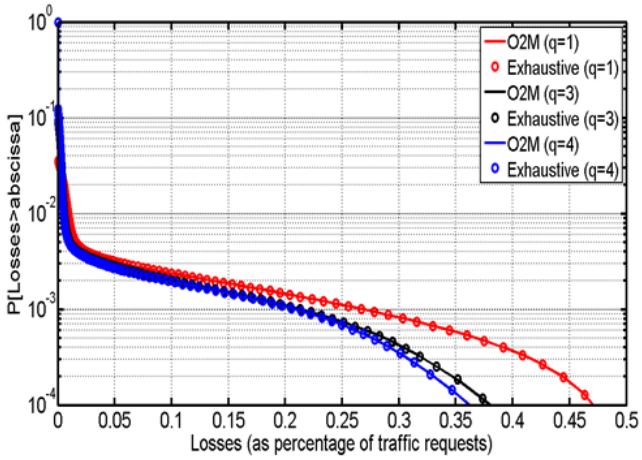


Figure 10: CCDF of the losses for different quotas, for the O2M and Exhaustive RRM mechanisms.

3.2 Pairing Allocation based on Monge Arrays

In this Section we propose a theoretically optimal, based on Monge arrays [Villani03, Park91], capacity allocation scheme for minimization of both total system's capacity losses and rate matching performance metrics. Moreover, we apply the same theory for maximization of minimum and total system's satisfaction ratios. These optimal schemes result in an appropriate sorting of offered and requested capacities that has very low complexity.

Monge is connected with the general concept of optimal transport theory (OTS). According to the Monge's problem stated in 1781 [Villani03], given piles of sands and holes with the same volume, we look for the best move to entirely fill up the holes with the minimum total transportation cost. Another simple example is called as ore mining problem [Mozaffari19]. Given a collection of mines mining iron ore and a collection of factories which consume the iron ore that the mines produce, the target is to find the optimal way to transport the ore from the mines to the factories. This is done under the minimization of a cost function that may contain the costs of transportation, the location of the mines and the productivity of the factories.

The OTS can be applied to solve problems such as user association and resource allocation and has already been used in wireless networks, such as UAV-enabled cellular networks. Specifically in [Mozaffari17a] a delay-optimal cell association in UAVs cellular networks is proposed. Authors use the OTS to minimize the average network delay subject to arbitrary spatial distribution of the ground users and the optimal cell partitions of UAVs and terrestrial base stations (BSs) are derived. Finally, in [Mozaffari17b] the optimization through the OTS of average number of bits (data service) transmitted to users as well as the UAVs' hover (flight) duration is presented.

3.2.1 Capacity Allocation Schemes

3.2.1.1 Losses and Rate Matching

Under the similar concept of Section 3.1.1 our objective is to propose low complexity optimal GWs-UEs pairings, in order to minimize both the total system's capacity losses, L, defined in (1) and the rate matching, RM, defined as:

$$\mathrm{RM} = \sum_{j=1}^{N} \left| RC_j - OC_j \right| , \tag{9}$$

where OC_j is the offered capacity to j[th] UE. The aforementioned minimization problems can be formally written as in (10) constituting linear sum assignment problems (LSAPs), considering the constraints: (a) the *N x N* pairing array $\mathbf{X^m} = (\mathrm{x}_{ij}^{m})$ is binary and $x_{ij}^{m} = 1$ only for the *GW$_i$-UE$_j$* pair, (b) $\sum_{j=1}^{N} x_{ij}^{m} = 1, \ \forall i$ and (c) $\sum_{i=1}^{N} x_{ij}^{m} = 1, \ \forall j$ declaring (b)/(c) that each GW/UE is paired with one UE/GW, respectively, and index *m* is L or RM representing problems (1) or (9), respectively.

$$\min_{\mathbf{X}^m} \ \sum_{i=1}^{N} \sum_{j=1}^{N} c_{ij}^{m} x_{ij}^{m}, \ s.t. \ (a),(b),(c) , \tag{10}$$

where the elements of *N x N* array $\mathbf{C^m} = (c_{ij}^{m})$ take the form (11), (12) considering the problems (1), (9), respectively.

$$c_{ij}^{L} = \max \left\{ RC_j - OC_i \ , 0 \right\} , \tag{11}$$

$$c_{ij}^{RM} = \left| RC_j - OC_i \right|. \tag{12}$$

Generally, solution of LSAP problems has more complexity than our scenario that belongs to a special case in which the optimal pairing is easily extracted and known in advance, because the cost array $\mathbf{C^m}$, as shown in Appendix 3.2.3.1, has the specific formation of a Monge array. Specifically, its elements satisfy the Monge property depicted in (13), described in (2.11) of [Brucker07], for all i_1, i_2, j_1, j_2 with $i_1 < i_2$ and $j_1 < j_2$, namely for every 2 × 2 sub-array of $\mathbf{C^m}$ inequality (13) is valid.

$$c_{i_1 j_1}^{m} + c_{i_2 j_2}^{m} \leq c_{i_1 j_2}^{m} + c_{i_2 j_1}^{m} \tag{13}$$

For proving that $\mathbf{C^m}$ is a Monge array, based on (13), in order to solve optimally problems in (10), we sort all OCs and RCs in ascending ordered lists, as follows:

$$OC_{\sigma(1)} \leq OC_{\sigma(2)} \leq \ldots \leq OC_{\sigma(N)}, \tag{14}$$

$$RC_{\lambda(1)} \leq RC_{\lambda(2)} \leq \ldots \leq RC_{\lambda(N)}. \tag{15}$$

In (14), (15) $\sigma(\bullet$ and $\lambda(\bullet$ refer to mapping functions $\sigma, \lambda : \{1, \ldots, N\} \rightarrow \{1, \ldots, N\}$ that set *OC*s and *RC*s in ascending ordered lists, respectively. These can be also set in descending ordered lists, without loss of generality. To prove that (14), (15) result in optimal solution for problems in (10), we construct the arrays $\boldsymbol{C^L}$, $\boldsymbol{C^{RM}}$ assuming that *1,…,N* rows represent the *σ(1),…,σ(N)* GWs and the *1,…,N* columns represent the *λ(1),…,λ(N)* UEs meaning that i^th^ row corresponds to $OC_{\sigma(i)}$ and j^th^ column to $RC_{\lambda(j)}$, i.e. $i \triangleq$ and $j \triangleq$ in the following analysis. In the Appendix 3.2.3.1 we prove that these arrays are Monge arrays and their p^th^ diagonal element corresponds to the *σ(p)* GW and *λ(p)* UE. Hence considering the Corollary 2.3 of [Brucker07], presenting the identical permutation as an optimal pairing in the assignment problem with a Monge cost array, the optimal ($GW_{\sigma(p)}$, $UE_{\lambda(p)}$) pairing with *p=1,…,N*, originated by (14), (15) with complexity of *O(Nlog(N))*, minimizes both systems' capacity losses and rate matching, i.e. $\mathbf{X}^L \triangleq$.

3.2.1.2 Satisfaction Ratio

In this Section, similar to the process of Section 3.2.1.1, the maximization of minimum satisfaction ratio considering the system's GW-UE pairs and the maximization of system's total satisfaction ratio are examined. The former metric is generally described as fairness method, called as FM, and defined as:

$$FM = \min_{1 \leq j \leq N} \left(OC_j \big/ RC_j \right), \tag{16}$$

while the total satisfaction ratio, called as SF, takes the form:

$$SF = \sum_{j=1}^{N} \left(OC_j \big/ RC_j \right), \tag{17}$$

where OC_j is the offered capacity to j[th] UE. The aforementioned maximization problems can be formally written as in (18), (19) where they are also transformed appropriately to linear bottleneck and linear sum assignment problems, defined in Chapter 1 of [Burkard09], called as LBAP and LSAP respectively. In problems (18) and (19) we have $w_{ij}^{m} = OC_i \big/ RC_j$, where index *m* is FM or SF representing problems (16) or (17), respectively and the constraints (a)-(c) are the same with the Section 3.2.1.1.

$$\max_{\mathbf{X}^{FM}} \left\{ \min_{1\le i,j\le N} \left\{ w_{ij}^{FM} x_{ij}^{FM} \right\} \right\} \triangleq \qquad \max_{1\le i,j\le N} \left\{ c_{ij}^{FM} x_{ij}^{FM} \right\} \Big\}, s.t.(a),(b),(c) , \tag{18}$$

$$\max_{\mathbf{X}^{SF}} \sum_{i=1}^{N} \sum_{j=1}^{N} \left\{ w_{ij}^{SF} x_{ij}^{SF} \right\} \triangleq \qquad \sum_{i=1}^{N} \sum_{j=1}^{N} \left\{ c_{ij}^{SF} x_{ij}^{SF} \right\}, s.t.(a),(b),(c) , \tag{19}$$

where the elements of *N x N* array $\mathbf{C^m} = \left(c_{ij}^{m}\right)$ are defined as:

$$c_{ij}^{m} = -w_{ij}^{m} = -OC_i \big/ RC_j \ . \tag{20}$$

Dealing with problems (18), (19), two strategies have been defined, namely **Strategy A** and **Strategy B**, respectively.

Strategy A: We sort the OCs and RCs as follows:

$$OC_{\sigma(1)} \le OC_{\sigma(2)} \le \ldots \le OC_{\sigma(N)} , \tag{21}$$

$$RC_{\lambda(1)} \le RC_{\lambda(2)} \le \ldots \le RC_{\lambda(N)} . \tag{22}$$

S**trategy B**: We sort the OCs as in (21) and RCs as:

$$RC_{\mu(1)} \ge RC_{\mu(2)} \ge \ldots \ge RC_{\mu(N)} , \tag{23}$$

where $\sigma(\bullet$, $\lambda(\bullet$, $\mu(\bullet$ are mapping functions $\sigma, \lambda, \mu : \{1,\ldots,N\} \to \{1,\ldots,N\}$ that set the corresponding values in ordered lists as described in (21), (22) and (23), i.e. *σ(1)*, *λ(1)* represent the smallest OC, RC, respectively and *μ(1)* the largest RC.

Same optimal pairings are extracted setting both of (21), (22) or both of (21), (23) in reverse ordered lists. In **Strategy A** the optimal pairings are ($GW_{\sigma(p)}$,$UE_{\lambda(p)}$), while in **Strategy B** the optimal parings come from ($GW_{\sigma(p)}$,$UE_{\mu(p)}$) considering in both that *p=1,…,N*. To show that **Strategies A**, **B** are optimal for problems (18), (19), respectively, we construct the arrays $\boldsymbol{C^{FM}}$, $\boldsymbol{C^{SF}}$ assuming that in both the *1,…,N* rows represent the *σ(1),…,σ(N)* GWs and the *1,…,N* columns represent the *λ(1),…,λ(N)* UEs for the $\boldsymbol{C^{FM}}$ and *μ(1),…,μ(N)* UEs for the $\boldsymbol{C^{SF}}$ respectively.

In both arrays the i[th] row corresponds to $OC_{\sigma(i)}$, i.e $i \triangleq$ and the j[th] column to $RC_{\lambda(j)}$ in the $\boldsymbol{C^{FM}}$, i.e. $j \triangleq$ and to $RC_{\mu(j)}$ in the $\boldsymbol{C^{SF}}$, i.e. $j \triangleq$. In Appendix 3.2.3.2 we prove that $\boldsymbol{C^{FM}}$ is a bottleneck Monge array and $\boldsymbol{C^{SF}}$ is a Monge array. Considering the Proposition 6.14 of [Burkard09] for $\boldsymbol{C^{FM}}$ of problem (18) and Corollary 2.3 of [Brucker07] for $\boldsymbol{C^{SF}}$ of problem (19), the **Strategies A**, **B**, both with very low complexity of *O(Nlog(N))*, result to optimal GWs-UEs pairings in terms of problems (18) and (19), respectively, while the corresponding Exhaustive schemes have to examine all the possible GWs-UEs combinations, to find the optimal result.

At this point, we remark an important tradeoff originated from theory. On the one hand, **Strategy A** that results in the maximization of minimum satisfaction ratio of a GW-UE pair, causes minimization to system's total satisfaction ratio as proven in the end of Appendix 3.2.3.2. On the other hand, the application of **Strategy B** results in maximization of system's total satisfaction ratio and causes the minimum satisfaction ratio of a pair, i.e. minimization of FM in (16), that is $OC_{\sigma(1)}/RC_{\mu(1)}$.

3.2.2 Numerical Results

3.2.2.1 Losses and Rate Matching

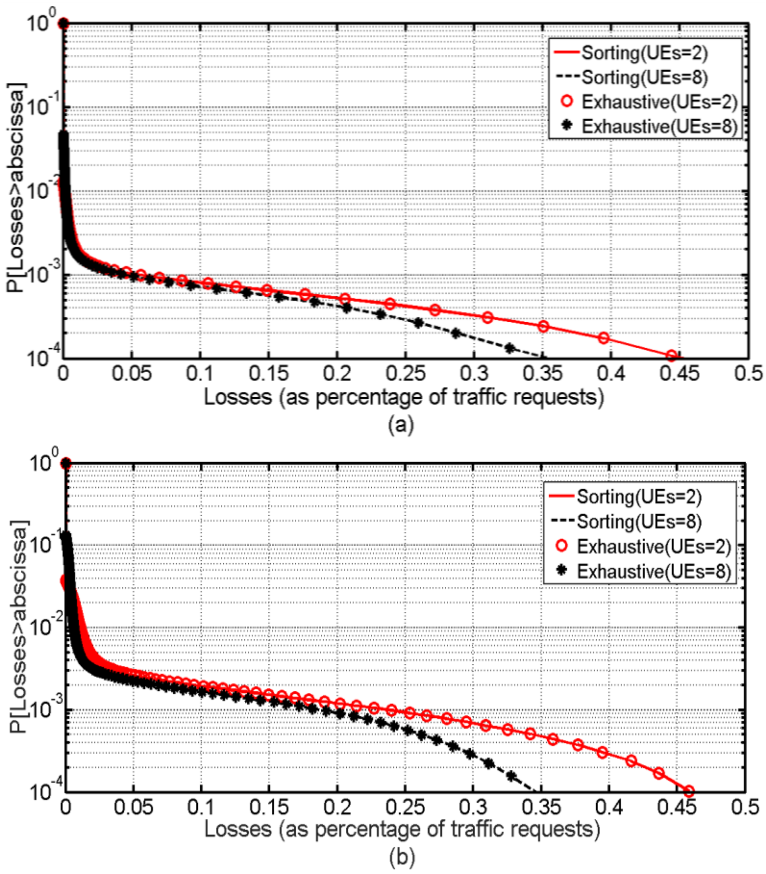


Figure 11: CCDF of losses for different number of UEs for Sorting and Exhaustive mechanisms in: (a) MEO and (b) GEO HTS systems.

We investigate Geostationary and Medium Earth Orbit, i.e. GEO and MEO, HTS systems. For MEO satellite scenario we assume 2 GWs in Nemea in Greece and for GEO satellite scenario one in Nemea and another in Harwell in UK. For the MEO scenario, an 8-MEO constellation at equatorial plane is considered and the time series of total atmospheric attenuation are derived using the multi-dimensional synthesizer presented in [Kourogiorgas17]. The separation distance between the 2 GWs of the MEO scenarios is 20 km in the North-South direction. For the scenario of the GEO system, the satellite is in 9° East as also given in Table 4, where the values of current simulation parameters are also provided. The total atmospheric attenuation time series are derived by employing multi-dimensional Stochastic Differential Equations [Karagiannis12].

We study two different scenarios: a) with equal number of GWs and UEs, i.e. 2 UEs in the system, and b) with 8 UEs in the system, where each GW serves simultaneously 4 UEs. The simulation concept is similar to Section 3.1.2, where UEs' requested capacities in bps are drawn from a uniform distribution.

The CCDF of system's capacity losses and rate matching for both scenarios are presented in Figure 11 (a), Figure 12 (a) for MEO satellite and in Figure 11 (b), Figure 12 (b) for GEO satellite. It is obvious that the same Sorting of OCs and RCs and pairing of GWs and UEs as proposed in Section 3.2.1.1, has identical performance, as proven in Appendix 3.2.3.1, with the much more complicated Exhaustive technique, which examines all the possible system's capacity losses and rate matchings, originated by all the possible GWs-UEs pairing combinations, in order to find the minimum ones.

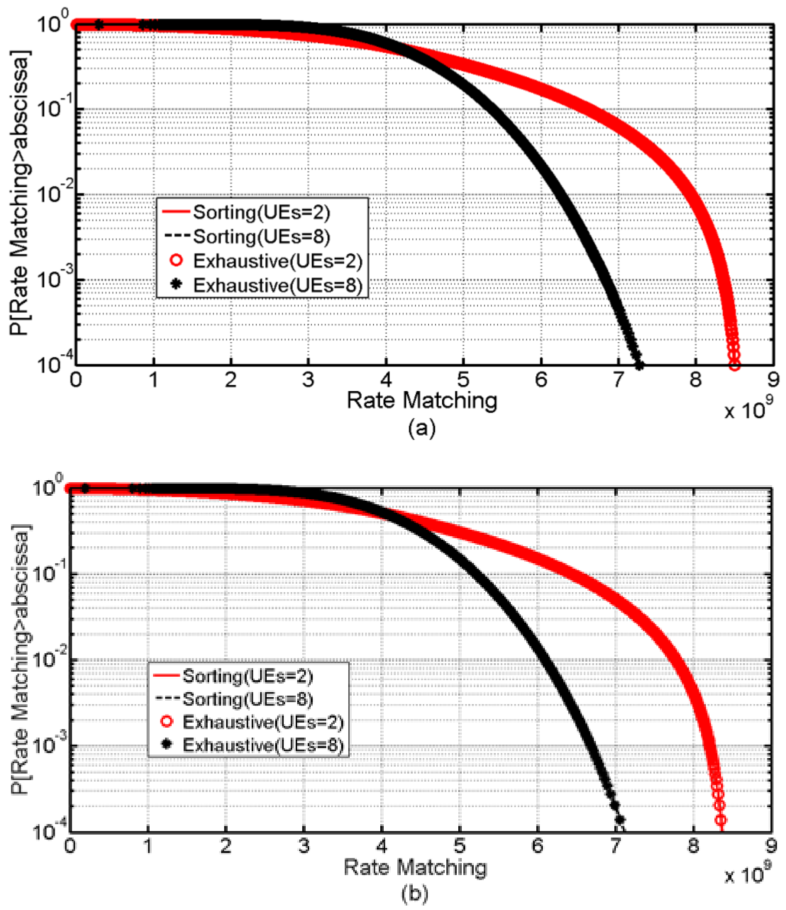


Figure 12: CCDF of rate matching for different number of UEs for Sorting and Exhaustive mechanisms in: (a) MEO and (b) GEO HTS systems.

3.2.2.2 Satisfaction Ratio

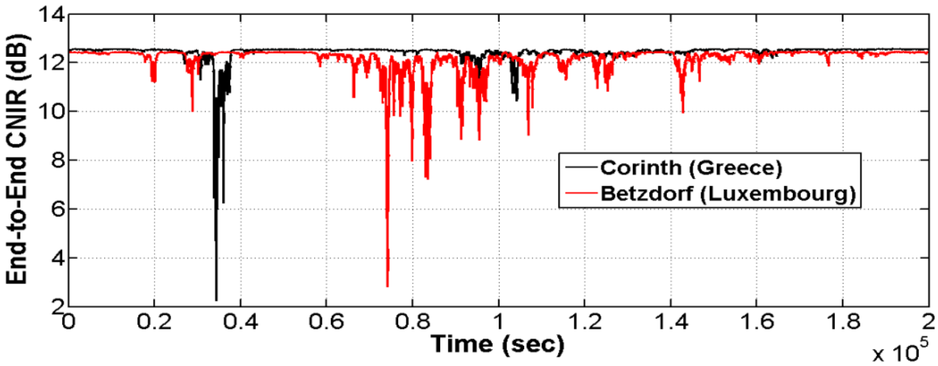


Figure 13: A time series snapshot of links’ E2E CNIR from both Gateways.

We assume a GEO HTS system with two different GWs in Greece and Luxembourg, respectively, that serve eight UEs, i.e. each GW serves $q_{1,2}=q=4$ UEs, hence the system has $N=8$ GWs-UEs pairs. The system’s parameters, presented in Table 4 and simulation concept are similar with Section 3.1.2 and UEs’ requested capacities in bps are drawn from a uniform distribution in the range (x,y), where x is maximum OC and $y=(B_C/q)\log_2(1+CNIR_{total\_\max})$, considering without loss of generality that $OC_j \le RC_j, \forall j$ [Lei11].

In Figure 13, a snapshot of the E2E CNIR time series, being correlated in space and time, is shown for both GWs. Moreover the CDF of FM and normalized, i.e. divided by *N*, SF is presented in Figure 14 and Figure 15, respectively. In Figure 14 (a), Figure 15 (a) **Strategies A, B** result in maximization of FM and normalized SF, respectively, and have same performance with the corresponding Exhaustive schemes. Finally, assuming the tradeoff cited in Section 3.2.1.2 in Figure 14 (b), Figure 15 (b) **Strategies B, A** result in minimization of FM and normalized SF, respectively, compared also with the corresponding Exhaustive schemes.

3.2.3 Appendix

3.2.3.1 Losses and Rate Matching

Firstly, we prove that $\boldsymbol{C}^L$ is a Monge array and to do that we show that its elements c_{ij}^L based on (11) satisfy inequality (2.11) of [Brucker07], that is defined as follows setting *w/v* equal to right/left hand sides of (24), respectively, for simpler mathematical notation:

$$c_{i_1 j_1}^L + c_{i_2 j_2}^L \le c_{i_1 j_2}^L + c_{i_2 j_1}^L \Leftrightarrow \mathrm{v} \le \mathrm{w}, \forall\ i_1 < i_2\ \&\ j_1 < j_2, \tag{24}$$

We prove (24) for random i_1, i_2, j_1, j_2 with $i_1<i_2$ and $j_1<j_2$, hence this can be generalized for all $i_1<i_2$ and $j_1<j_2$. Considering the specific construction of $\boldsymbol{C}^L$ as described in Section 3.2.1.1 and that $i \triangleq$, $j \triangleq$, we have for $i_1<i_2$ that $OC_{\sigma(i_1)} \le OC_{\sigma(i_2)}$ and for $j_1<j_2$ that $RC_{\lambda(j_1)} \le RC_{\lambda(j_2)}$.

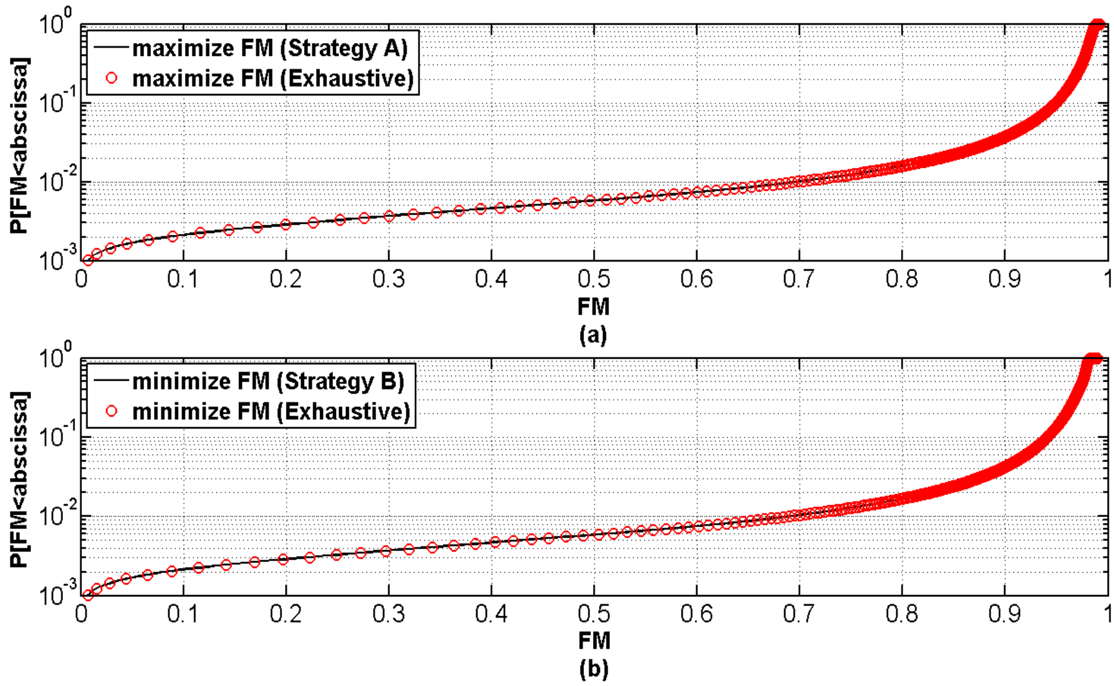


Figure 14: CDF of minimum satisfaction ratio, FM, considering (a) its maximization through Strategy A and (b) its minimization through Strategy B, compared both with the corresponding Exhaustive schemes.

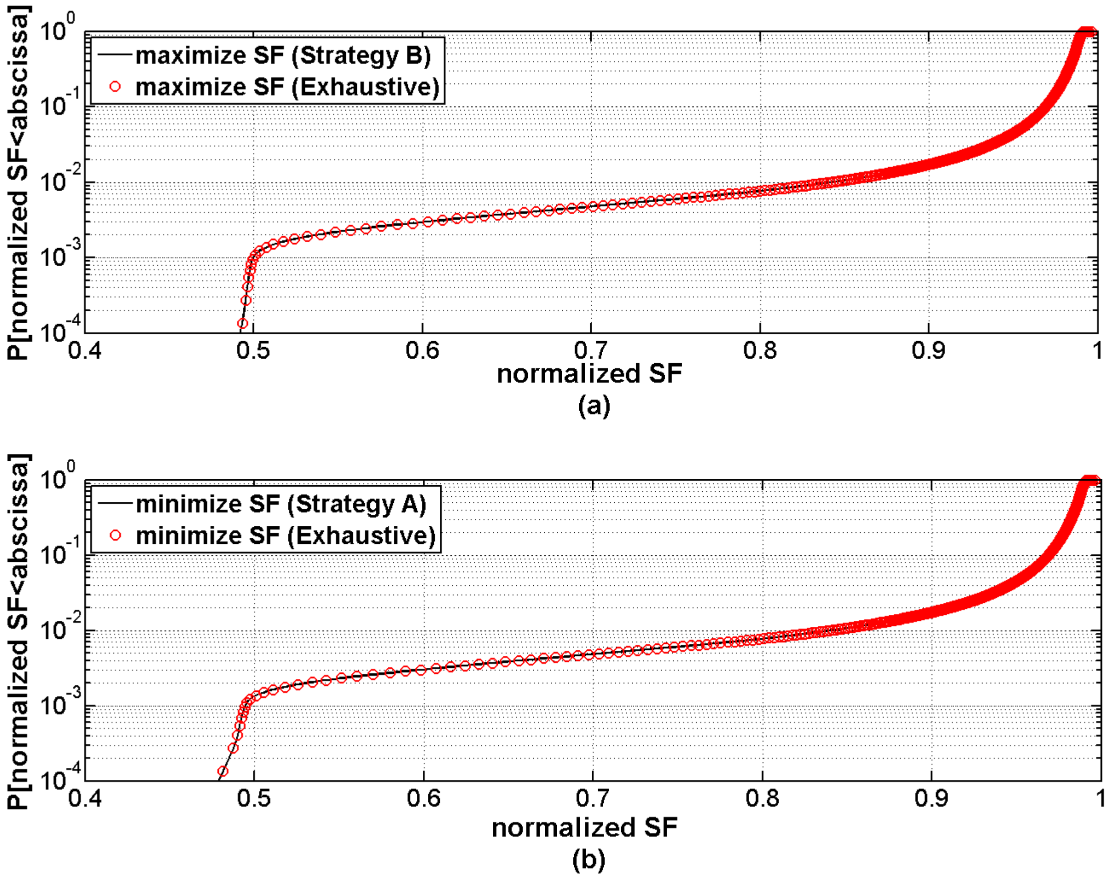


Figure 15: CDF of normalized total satisfaction ratio SF considering (a) its maximization through Strategy B and (b) its minimization through Strategy A, compared both with the corresponding Exhaustive schemes.

Afterwards, the inequalities (25)-(28) are easily extracted.

$$RC_{\lambda(j_1)} - OC_{\sigma(i_1)} \geq RC_{\lambda(j_1)} - OC_{\sigma(i_2)}, \tag{25}$$

$$RC_{\lambda(j_2)} - OC_{\sigma(i_1)} \geq RC_{\lambda(j_2)} - OC_{\sigma(i_2)}, \tag{26}$$

$$RC_{\lambda(j_2)} - OC_{\sigma(i_1)} \geq RC_{\lambda(j_1)} - OC_{\sigma(i_1)}, \tag{27}$$

$$RC_{\lambda(j_2)} - OC_{\sigma(i_2)} \geq RC_{\lambda(j_1)} - OC_{\sigma(i_2)}. \tag{28}$$

Regarding (11), (24) and setting $d_{\sigma(i),\lambda(j)} = RC_{\lambda(j)} - OC_{\sigma(i)}$ for a more compact analysis we have:

$$v = \max\left\{d_{\sigma(i_1),\lambda(j_1)}, 0\right\} + \max\left\{d_{\sigma(i_2),\lambda(j_2)}, 0\right\}, \tag{29}$$

$$w = \max\left\{d_{\sigma(i_1),\lambda(j_2)}, 0\right\} + \max\left\{d_{\sigma(i_2),\lambda(j_1)}, 0\right\}. \tag{30}$$

We prove that $w \geq v$ according to (24) starting without loss of generality from (30) and examining all the possible cases.

<u>**Case I:**</u> $d_{\sigma(i_1),\lambda(j_2)} > 0$ (31) & $d_{\sigma(i_2),\lambda(j_1)} > 0$ (32)

From (32) and (25) we have $d_{\sigma(i_1),\lambda(j_1)} > 0$ (33) and from (32) and (28) that $d_{\sigma(i_2),\lambda(j_2)} > 0$ (34). Thus substituting (31), (32) in (30) and (33), (34) in (29) we conclude to $w = v$ from the commutative property.

<u>**Case II:**</u> (31) & $d_{\sigma(i_2),\lambda(j_1)} \leq 0$ (35)

Substituting (31), (35) in (30) we have $w = d_{\sigma(i_1),\lambda(j_2)}$ (36). Due to the fact that (31), (35) do not influence (29), the different possible values of (29) considering four different cases of *v* and the corresponding comparisons with (36) are:

1) For (33) and (34) and using commutative property we have $v = d_{\sigma(i_1),\lambda(j_2)} + d_{\sigma(i_2),\lambda(j_1)}$, hence $v \leq w$ due to (31) and (35).

2) For (34) and $d_{\sigma(i_1),\lambda(j_1)} \leq 0$ (37) we have $v = d_{\sigma(i_2),\lambda(j_2)}$, hence $v \leq w$, due to (26),

3) For (33) and $d_{\sigma(i_2),\lambda(j_2)} \leq 0$ (38) we have $v = d_{\sigma(i_1),\lambda(j_1)}$, hence $v \leq w$, due to (27),

4) For (37) and (38) we have $v = 0 < w$ due to (31).

<u>**Case III:**</u> $d_{\sigma(i_1),\lambda(j_2)} \leq 0$ (39)

From (39) and (27) we obtain (37), from (39) and (26) we obtain (38) and from (37) and (25) we obtain (35). Substituting (37), (38) in (29) and (35), (39) in (30) we conclude to *w=v=0*.

In all the above cases we have shown that $v \le w$ is valid for random i_1, i_2, j_1, j_2 with $i_1<i_2$ and $j_1<j_2$, hence the same happens for all $i_1<i_2$ and $j_1<j_2$, concluding that $\boldsymbol{C^L}$ is a Monge array.

Now, we prove that $\boldsymbol{C^{RM}}$ is a Monge array showing that its elements c_{ij}^{RM}, based on (12), satisfy inequality (2.11) of [Brucker07]. In the following analysis we use the relations (40), (41):

$$c_{ij}^{RM} = \left| RC_j - OC_i \right| = 2\max\left(RC_j, OC_i \right) - RC_j - OC_i \ , \tag{40}$$

$$\max\left(RC_j, OC_i \right) = \max\left(RC_j - OC_i, 0 \right) + OC_i \ . \tag{41}$$

Considering the same sorting as in (14), (15) the array $\boldsymbol{C^{RM}}$ is a Monge array if and only if for random i_1, i_2, j_1, j_2 with $i_1<i_2$ and $j_1<j_2$:

$$c_{i_1 j_1}^{RM} + c_{i_2 j_2}^{RM} \le c_{i_1 j_2}^{RM} + c_{i_2 j_1}^{RM} \ . \tag{42}$$

Substituting (40) in (42) we result in:

$$\max\left(RC_{j_1}, OC_{i_1} \right) + \max\left(RC_{j_2}, OC_{i_2} \right) \le \max\left(RC_{j_2}, OC_{i_1} \right) + \max\left(RC_{j_1}, OC_{i_2} \right) \tag{43}$$

Continuing our analysis and substituting (41) in (43) we have:

$$\begin{aligned} &\max\left(RC_{j_1} - OC_{i_1}, 0 \right) + \max\left(RC_{j_2} - OC_{i_2}, 0 \right) \le \\ &\le \max\left(RC_{j_2} - OC_{i_1}, 0 \right) + \max\left(RC_{j_1} - OC_{i_2}, 0 \right) \end{aligned} \tag{44}$$

The inequality (44) is true because it is the same with (24) that was proven in the analysis for the $\boldsymbol{C^L}$ Monge array, considering the sorting in (14), (15). Due to the fact that (44) is true then (42) is also valid for random i_1, i_2, j_1, j_2 and consequently for all i_1, i_2, j_1, j_2 with $i_1<i_2$ and $j_1<j_2$ and thus we have shown that $\boldsymbol{C^{RM}}$ is a Monge array.

3.2.3.2 Satisfaction Ratio

Firstly, we prove that $\boldsymbol{C^{FM}}$ is a bottleneck Monge array showing that its elements c_{ij}^{FM} based on (20) satisfy (28) of [Burkard96] $\forall\ 1 \le i_1 < i_2 \le N,\ 1 \le j_1 < j_2 \le N$ that is defined as:

$$\max(c_{i_1 j_1}^{FM}, c_{i_2 j_2}^{FM}) \le \max(c_{i_1 j_2}^{FM}, c_{i_2 j_1}^{FM}) \tag{45}$$

We prove inequality (45) for random i_1, i_2, j_1, j_2 with $i_1<i_2$ and $j_1<j_2$ hence this is generalized for all $1 \le i_1 < i_2 \le N$ and $1 \le j_1 < j_2 \le N$. Considering the construction of $\boldsymbol{C^{FM}}$, described in Section 3.2.1.2, and that $i \triangleq$, $j \triangleq$, we have for $i_1<i_2$ that $OC_{\sigma(i_1)} \le OC_{\sigma(i_2)}$ (46) and for $j_1<j_2$ that $RC_{\lambda(j_1)} \le RC_{\lambda(j_2)}$ (47). Thus, (48)-(50) are easily extracted.

$$(-OC_{\sigma(i_2)} \big/ RC_{\lambda(j_2)}) \le (-OC_{\sigma(i_1)} \big/ RC_{\lambda(j_2)}) \ , \tag{48}$$

$$(-OC_{\sigma(i_1)} \Big/ RC_{\lambda(j_1)}) \leq (-OC_{\sigma(i_1)} \Big/ RC_{\lambda(j_2)}), \tag{49}$$

$$(-OC_{\sigma(i_2)} \Big/ RC_{\lambda(j_1)}) \leq (-OC_{\sigma(i_2)} \Big/ RC_{\lambda(j_2)}). \tag{50}$$

From (48) and (50) we have that:

$$(-OC_{\sigma(i_2)} \Big/ RC_{\lambda(j_1)}) \leq (-OC_{\sigma(i_1)} \Big/ RC_{\lambda(j_2)}) \tag{51}$$

Inequality (45), considering (51), takes the form (52):

$$\max(-\frac{OC_{\sigma(i_1)}}{RC_{\lambda(j_1)}}, -\frac{OC_{\sigma(i_2)}}{RC_{\lambda(j_2)}}) \leq -\frac{OC_{\sigma(i_1)}}{RC_{\lambda(j_2)}} \tag{52}$$

Inequality (52) is true because both $-OC_{\sigma(i_1)} \Big/ RC_{\lambda(j_1)}$ and $-OC_{\sigma(i_2)} \Big/ RC_{\lambda(j_2)}$ are smaller or equal to $-OC_{\sigma(i_1)} \Big/ RC_{\lambda(j_2)}$ considering (49) and (48), respectively. Hence inequality (45) is also valid and $\boldsymbol{C}^{FM}$ is a bottleneck Monge array.

Secondly, we prove that $\boldsymbol{C}^{SF}$ is a Monge array showing that its elements c_{ij}^{SF}, based on (20), satisfy inequality (2) of [Burkard96] $\forall\ 1 \leq i_1 < i_2 \leq N,\ 1 \leq j_1 < j_2 \leq N$ that is defined as follows:

$$c_{i_1 j_1}^{SF} + c_{i_2 j_2}^{SF} \leq c_{i_1 j_2}^{SF} + c_{i_2 j_1}^{SF} \tag{53}$$

We prove (53) for random i_1, i_2, j_1, j_2 with $i_1<i_2$ and $j_1<j_2$ and hence this is generalized for all $1 \leq i_1 < i_2 \leq N$ and $1 \leq j_1 < j_2 \leq N$. Considering the construction of $\boldsymbol{C}^{SF}$ as described in Section 3.2.1.2 and that $i \triangleq$, $j \triangleq$, we have for $i_1<i_2$ that (46) is valid and for $j_1<j_2$ that $RC_{\mu(j_1)} \geq RC_{\mu(j_2)}$ (54). Thus, based on (20), (53), we have:

$$OC_{\sigma(i_1)}(RC_{\mu(j_1)}^{-1} - RC_{\mu(j_2)}^{-1}) \geq OC_{\sigma(i_2)}(RC_{\mu(j_1)}^{-1} - RC_{\mu(j_2)}^{-1}) \tag{55}$$

From (54) we get $RC_{\mu(j_1)}^{-1} - RC_{\mu(j_2)}^{-1} \leq 0$ and from (55) we conclude that (46) is valid, something that is true. Hence (55) is valid and also (53) is valid, so $\boldsymbol{C}^{SF}$ is a Monge array.

Finally we prove that **Strategy A** minimizes problem SF given in (17). To prove the minimization of problem (17) by **Strategy A** we set $c_{ij}^{\min SF} = OC_i \Big/ RC_j$ (56). Afterwards we construct the *N x N* array $\mathbf{C}^{\min SF} = (c_{ij}^{\min SF})$, where *1,...,N* rows represent the *σ(1),...,σ(N)* GWs and *1,...,N* columns represent the *λ(1),...,λ(N)* UEs, i.e. $i \triangleq$, $j \triangleq$, and based on (21), (22) we prove that $\boldsymbol{C}^{minSF}$ is a Monge array, by showing that (57) is valid for all $i_1<i_2$ and $j_1<j_2$ and so proving that this happens for random $i_1<i_2$ and $j_1<j_2$, similarly to proofs of (45), (53).

$$c_{i_1 j_1}^{\min SF} + c_{i_2 j_2}^{\min SF} \leq c_{i_1 j_2}^{\min SF} + c_{i_2 j_1}^{\min SF} \tag{57}$$

Assuming the construction of $\boldsymbol{C}^{minSF}$ we have for $i_1<i_2$ that (46) is valid and for $j_1<j_2$ that (47) is valid. Thus based on (56), (57) and after a simple analysis we result in:

$$OC_{\sigma(i_1)}(RC_{\lambda(j_1)}^{-1} - RC_{\lambda(j_2)}^{-1}) \leq OC_{\sigma(i_2)}(RC_{\lambda(j_1)}^{-1} - RC_{\lambda(j_2)}^{-1}) \tag{58}$$

From (47) we have that $RC_{\lambda(j_1)}^{-1} - RC_{\lambda(j_2)}^{-1} \geq 0$ and from (58) we conclude that (46) is valid, which is true. Hence (58) is valid and also (57) is valid. Thus $\boldsymbol{C}^{minSF}$ is a Monge array and from Corollary 2.3 of [Brucker07] **Strategy A** minimizes the total satisfaction ratio described in problem (17).

3.3 Conclusion

In this Chapter optimal capacity allocation mechanisms with low complexity in multi-beam HTS systems have been proposed considering the offered and requested capacities of GWs and UE beams. Moreover, there is the assumption that every GW can serve every UE and every UE can be served by every GW. We focus on the feeder links of the systems, hence the CNIRs of UEs' links remain identical. To estimate the GWs' offered capacities, a large-scale total atmospheric attenuation model is applied by considering the dynamic variation of atmospheric conditions, while the uniform distribution has been exploited for UEs' requested capacities. Consequently in our scenario we result in the case that every GW and UE offers and requests, respectively, a specific capacity. Finally, for the pairings, we examine both the one-to-one and the one-to many cases, where, in the latter, the number of simultaneously served UEs by each GW has been determined before the allocation process.

In terms of system's capacity losses firstly we present an algorithm of $O(N^2)$ complexity from the matching theory. The factor N is the number of system's agents. The main idea is that in the proposed matching scheme the GWs are more willing to serve UEs that request higher capacities and the UEs want to be served by GWs which offer higher capacities. Then we go a step further and prove that the sorting of offered and requested capacities solves optimally the minimization of system's capacity losses, using the theory from Monge arrays with $O(NlogN)$ complexity.

Thereafter, we have theoretically shown that appropriate sorting solves optimally the problems of minimization of rate matching and maximization of minimum and total system's satisfaction ratio. In the last case we state a dilemma for satellite operators, raising from theoretical analysis, about giving priority to maximization of the total system's satisfaction ratio or worst individual pair's satisfaction ratio. This is originated by the fact that the optimal pairing scheme for the maximization of total system's satisfaction ratio ends up in the least satisfaction of an individual pair and the opposite is also valid.

Chapter 4

Optimal Allocation Schemes Considering Users' Links [4]

In this Chapter we consider an HTS network with a GEO satellite that has *M* GWs offering services to *N* UE beams, as depicted in Figure 16. The general assumptions of model are same with the system model in Chapter 3, but now we include in analysis the UEs' links. We repeat some basic relations and notations here to be consistent with the specific problems' formulation. Assuming O2O pairings each GW_i with $i=1,..,M$ serves one UE and each UE_j with $j=1,\ldots,N$ is served by one GW in case of $M=N$ (balanced problem), while in case of $M<N$ (unbalanced problem) there are N-M unserved UEs. For the unbalanced problem O2M pairings are also investigated, resulting in a balanced problem, where each GW_i serves q_i UEs simultaneously, satisfying $\sum_{i=1}^{M} q_i = N$ and all UEs are served. In the latter scenario the existence of q_i replicas for each GW_i is considered.

Moreover, the total offered capacity in bps from GW_i to UE_j is determined by Shannon formula, similar to Chapter 3, as $OC_{ij}^{"} = B_C \log_2(1+\gamma_{ij})$, but in current case γ_{ij} is the total carrier to noise plus interference ratio $CNIR_{ij}$, including both the CNIR of feeder link *i* and the CNIR of downlink *j*, i.e. $\gamma_{ij}^{-1} = CNIR_{up,i}^{-1} + CNIR_{dn,j}^{-1}$. The rest factors remain the same as in Chapter 3.

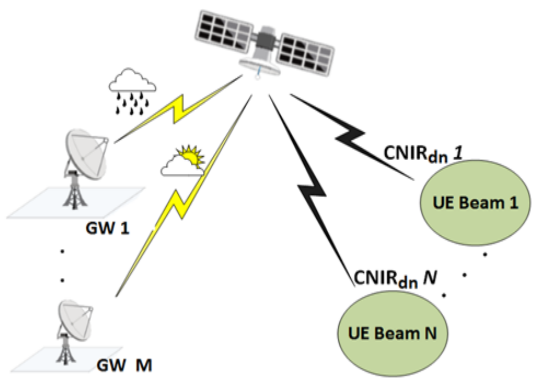


Figure 16: System Configuration considering the UEs' Links.

4.1 Pairing Allocation based on Hungarian Algorithm

At this point we have to say that the crucial difference of current Chapter with the previous one is that the assumption about identical user links is not valid anymore and different UEs' links are considered. Hence we apply the Hungarian algorithm (HA) in order to find optimal pairings. Another significant advancement that must be considered is the provision of optimal solution when there are also disallowed assignments, i.e. each GW can serve different pool of UEs. These new assumptions are realistic in satellite systems and must be taken into account in capacity allocation problems.

Generally, the HA, whose examples of execution can be found in [Winston04, Liang19, Zhu12], has been implemented in different scenarios in wireless systems, to face resource management problems. An indicative list follows. Especially, in [Zhang16] a Kuhn–Munkres, another name for the HA, parallel genetic algorithm is applied to large-scale wireless sensor networks. Furthermore, in [Mochaourab15, Zhou13] the HA is used as centralized pairing scheme in scenarios of (a) a distributed channel assignment scenario in cognitive radio networks and (b) two-hop relay networks with multiple source-destination pairs respectively. Moreover, in [Liang19] a modified distributed HA for workload balance, considering delay and energy consumption constraints, is implemented in sensor-cloud systems based on urban fog computing. Finally, in [Lagunas17] the HA is exploited in hybrid satellite-terrestrial backhaul networks, as part of a carrier allocation algorithm.

In our case the target is to provide optimal GWs-UEs assignments for minimizing total system's capacity losses, *L*, and rate matching, *RM*, and maximizing total system's satisfaction ratio, *SF*, in both balanced and unbalanced problems with O2O and O2M assignments. In case of O2O unbalanced problems only *M* UEs are served, while in balanced problems *M=N* in summations of (3.1)[5],(3.9) and (3.17) and all UEs are served. These problems are presented as unbalanced LSAP in (1) with constraints: (C1) the *M x N* assignment array $\mathbf{X^m} = (\mathrm{x}_{ij}^m)$ is binary and $x_{ij}^m = 1$ only for the GW_i-UE_j pair, considering that this pair is "active", (C2) $\sum_{j=1}^{N} x_{ij}^m = 1, \ \forall i$ and (C3) $\sum_{i=1}^{M} x_{ij}^m \in \{0,1\}, \ \forall j$ declaring (C2) that each GW serves a UE and (C3) that there are UEs remaining unserved and index *m* is *L*, *RM* or *SF* representing problems (3.1), (3.9) and (3.17) respectively.

$$\min_{\mathbf{X}^m} \ \sum_{i=1}^{M}\sum_{j=1}^{N} c_{ij}^m x_{ij}^m, \ s.t. \ (C1),(C2),(C3) \tag{1}$$

where the elements of *M x N* cost array $\mathbf{C^m} = (c_{ij}^m)$ take the form (2)-(4) considering the problems (3.1), (3.9) and (3.17), respectively.

$$c_{ij}^L = \max\left\{RC_j - OC_{ij}, 0\right\}, \tag{2}$$

$$c_{ij}^{RM} = \left|RC_j - OC_{ij}\right|, \tag{3}$$

[5] Notation (k.m) means that we make reference to mth equation of kth Chapter.

$$c_{ij}^{SF} = \max_{\forall i,j}\left(OC_{ij} \big/ RC_j\right) - OC_{ij} \big/ RC_j \;. \tag{4}$$

In (4) we show a possible transformation of maximization problem of (3.17) to an equivalent minimization problem, with same optimal pairing solution making the latter applicable for the HA

implementation. Finally, in case of balanced problems, constraint (C3) of (1) becomes $\sum_{i=1}^{M} x_{ij}^{m} = 1,\ \forall j$ declaring that there are not unserved UEs.

<u>Hungarian Algorithm</u>

Input: $N \times N$ cost matrix $\mathbf{C}^{\mathrm{m}}[\mathrm{i},\mathrm{j}]$ of LSA problem with $1 \le i, j \le N$

Step a (Construct $\mathbf{C}''$ matrix):

1) $\mathbf{C}'' = \mathbf{C}^{m}$
2) $\mathbf{C}''[\mathrm{i},\mathrm{j}] = \mathbf{C}^{\mathrm{m}}[\mathrm{i},\mathrm{j}] - \min_{j} \mathbf{C}^{\mathrm{m}}[\mathrm{i},:],\ \forall i, j$
3) $\mathbf{C}''[\mathrm{i},\mathrm{j}] = \mathbf{C}''[\mathrm{i},\mathrm{j}] - \min_{i} \mathbf{C}''[:,\mathrm{j}]\ ,\ \forall i, j$

Step b (Cover zeros in $\mathbf{C}''$ matrix):

1) $\text{cov\_rows} = \{i \mid \exists j \text{ s.t } \mathbf{C}''[\mathrm{i},\mathrm{j}] = 0\}$
   $\text{cov\_cols} = \{j \mid \exists i \text{ s.t } \mathbf{C}''[\mathrm{i},\mathrm{j}] = 0\}$
   $\text{intersect\_entries} = \{(i,j) \mid i \in \text{cov\_rows} \,\&\, j \in \text{cov\_cols}\}$
   $\text{uncov\_entries} = \{(i,j) \mid i \notin \text{cov\_rows} \,\&\, j \notin \text{cov\_cols}\}$
2) Draw the minimum number (Lines) of non-diagonal straight lines that cover each $\mathbf{C}''[\mathrm{i},\mathrm{j}] = 0$

Step c (Iteration Step):

<u>If Lines<N then:</u>

1) $d = \min_{(i,j)\in \text{uncov\_entries}} \mathbf{C}''[\mathrm{i},\mathrm{j}]$
2) $\mathbf{C}''[\mathrm{i},\mathrm{j}] = \mathbf{C}''[\mathrm{i},\mathrm{j}] - d,\ \forall (i,j) \in \text{uncov\_entries}$
3) $\mathbf{C}''[\mathrm{i},\mathrm{j}] = \mathbf{C}''[\mathrm{i},\mathrm{j}] + d,\ \forall (i,j) \in \text{intersect\_entries}$
4) Repeat the process from **Step b**.

<u>Else If Lines =N then:</u>

An optimal assignment is found among the entries for which:

$$\mathbf{C}''[\mathrm{i},\mathrm{j}] = 0,\ \forall (i,j) \notin \text{uncov\_entries}$$

Output: An optimal assignment for the minimization of the LSA problem that is represented by the $N \times N$ $\boldsymbol{C}^{\mathbf{m}}$ cost matrix.

Figure 17: Gateways to UE beams assignment process (Hungarian Algorithm)

The optimal solution in (3.1), (3.9) and (3.17) for the balanced problems can be provided by the HA originally published by H. W. Kuhn [Kuhn55] and reviewed by J. Munkres [Munkres57]. Kuhn is the godfather of the method, called as "Hungarian method", due to the fact that this algorithm is based on the earlier works of Dénes Kőnig and Jenő Egerváry who were Hungarian mathematicians [Kuhn55, Kuhn56, Martello10].

The original HA has time complexity $O(N^4)$ and it achieves $O(N^3)$ [Tomizawa71] with appropriate modifications. Moreover, in case of large matrices this complexity is prohibitive and a series of acceleration and parallel techniques are studied on [Cui16]. Furthermore, the application of HA can be represented either based on graphs, or on matrices. In Figure 17 we present a step-by step algorithm, while a description of the algorithm that has as input the $\boldsymbol{C^m}$, follows:

a) For each row find the lowest element and subtract it from each element in that row and do the same for each column of new matrix.

b) Cover the zeros in the resulting cost matrix using the minimum number of horizontal and vertical lines. If *N* lines are required, an optimal pairing exists among the zeros and algorithm stops. If less than *N* lines are needed, continue with c).

c) Find the smallest nonzero element (call it *k*) that is not covered by a line in (b). Subtract *k* from all uncovered elements and add *k* to all elements that are covered twice. Continue with process from (b).

The extension of HA to unbalanced problems needs the squaring *N x N* of the cost array $\boldsymbol{C^m}$ either by adding *N-M* rows of dummy GWs in O2O scenarios, or replicating q_i times the row of each GW_i in O2M scenarios. Furthermore, in the scenarios of disallowed GW_i-UE_j pairings the missing c_{ij}^m values can be represented by large cost *P* like $P > \max_{\forall i,j}(c_{ij}^m)$. Finally, we have to say that the application of HA in satellite networks is straightforward through the appropriate construction of $\boldsymbol{C^m}$ matrix, whose elements include the offered and requested capacities of GWs and UE beams following different functions based on (2)-(4).

4.2 Numerical Results

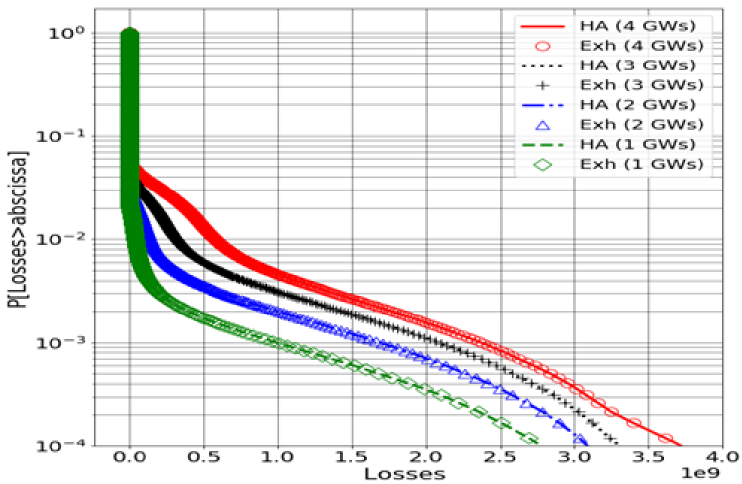
In this Section we compare the HA with the corresponding Exhaustive schemes that examine all the possible system's capacity losses, rate matching and system's satisfaction ratios, in order to find the corresponding optimal performances.

We consider a GEO multi-beam HTS network with four GWs across Europe in locations Ancient Corinth in Greece, Amadora in Portugal, Chilton in UK and the City of Luxembourg and also four UE beams. The system's parameters, presented in Table 4 and simulation concept are similar with Section 3.1.2. However instead of a common CNIR for the downlinks, we consider that $CNIR_{CS,dn,j}$ are from *[10, 13, 16, 19] dB*. Afterwards the UEs' requested capacities in bps are drawn from a uniform distribution in the range (0, $B_C \log_2(1+CNIR_{\text{tot\_max,j}})$), where $CNIR_{\text{tot\_max,j}}^{-1} = CNIR_{CS,up}^{-1} + CNIR_{CS,dn,j}^{-1}$ is the upper bound.

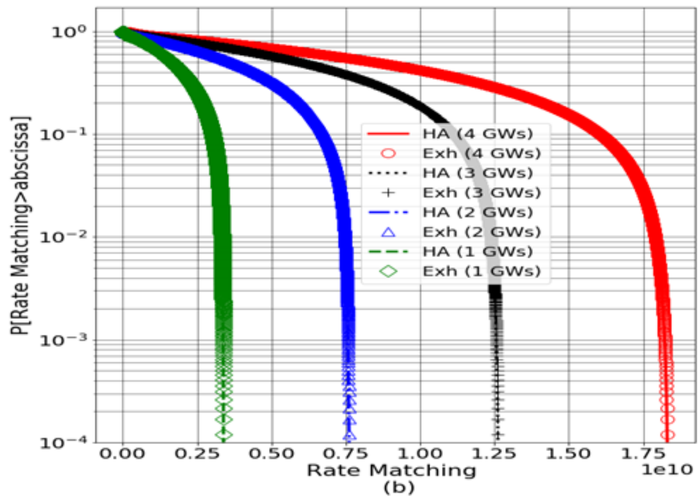
In Figure 18 the CCDFs of Losses, RM and SF performance objectives are presented for the HA and Exhaustive, called as Exh in all figures below, schemes considering balanced, with *M=N=4* and O2O unbalanced assignment problems, where number of GWs in the system increases from one to three and remains less than the UE beams. The optimality of HA is obvious through its identical performance with the corresponding Exh mechanisms.

Furthermore, in Figure 19 the balanced problem of 4 GWs and 4 UEs with different disallowed pairs, called as “constrained”, scenarios is studied. The labels describe the number of GWs with unavailable connections and the disallowed UEs’ number for each of these GWs. For a clearer view of results, the CCDF of differences of the unconstrained scenario with the rest constrained scenarios is presented for Loss, RM and SF objectives. The first red zeroed line is the bound representing the difference of unconstrained scenario’s performance from itself. We have put the red line to show that all the rest cases have a worse performance than the case with no disallowed assignments. The positive difference among the objectives of constrained and unconstrained scenarios for Losses and RM cases due to minimization problems and the opposite difference for SF due to maximization problem, demonstrates a rational conclusion that the optimum performance of HTS system is achieved, when there are not any payload or hardware constraints (no disallowed pairs) in the system. Hence each GW can serve all UEs, namely all the pairs are possible during the optimization process. Moreover, the optimality of HA is also confirmed by its full matching with the Exh scheme. The conclusion is that the HA leads again to the optimum outcome for the satellite system with the disallowed GWs-UEs pairs. Nevertheless, this optimal result is not as good as the optimal result for the case without constraints (as expected).

Concluding, in Figure 20 we consider indicatively 2 different GWs in Ancient Corinth (Greece) and Amadora (Portugal) that each serves $q_{1,2}=q=3$ UEs, hence O2M pairing is studied in system with 6 UEs and the RCs are drawn as described before, but the multiplying factor of upper bound becomes B_C/q similar to Section 3.1.2. The downlink CNIRs are *[10, 13, 15, 16, 17, 19] dB*. Finally, the results again confirm the optimality of HA compared with the Exh schemes in terms of CCDFs of Losses and RM. We result in same conclusions for the SF objective. Hence we show that in cases of unbalanced problems, where fewer GWs have to serve more UEs, the implementation of HA is appropriate to find pairings to achieve the best systems’ performance in terms of Losses, RM and SF metrics.



(a)



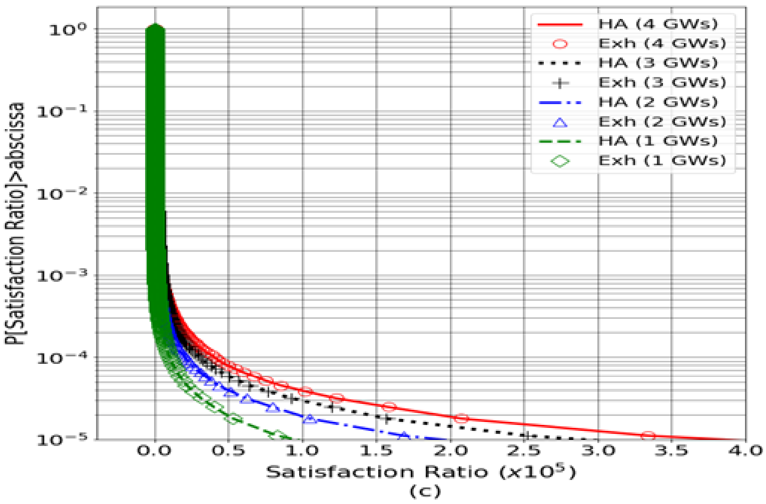
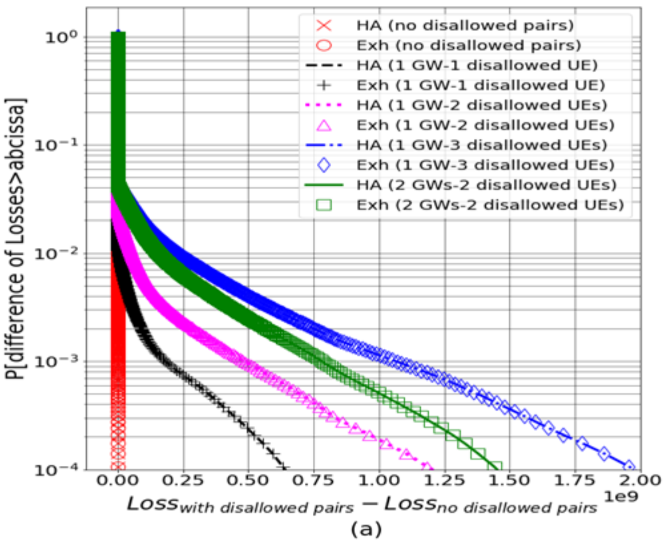
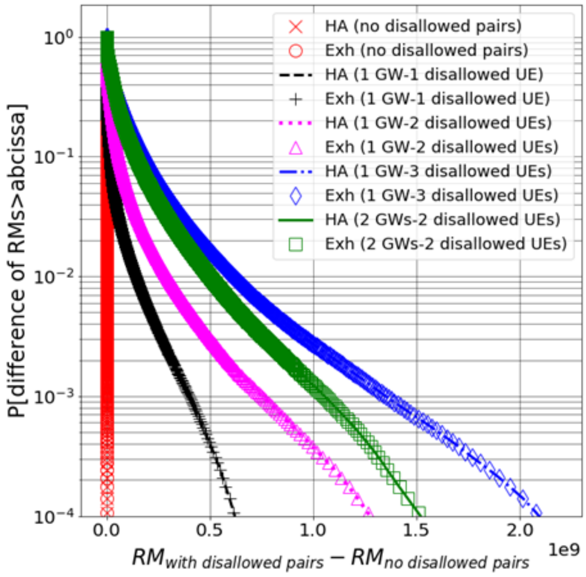
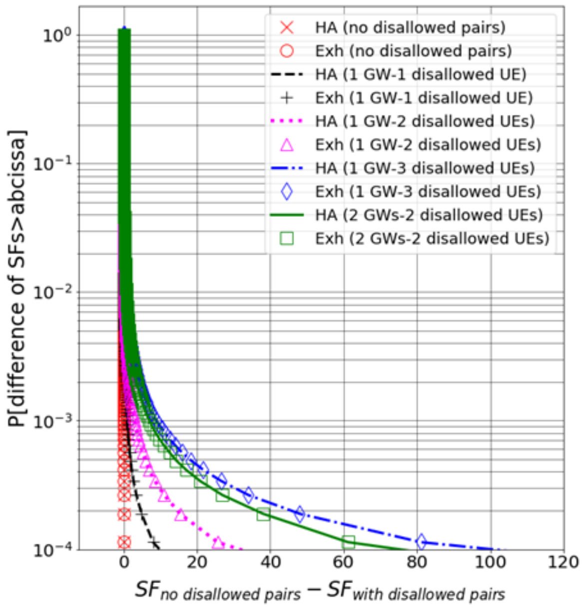


Figure 18: CCDF of (a) losses, (b) rate matching and (c) satisfaction ratio for Hungarian and Exhaustive mechanisms as the number of GWs decreases.





(b)



(c)

Figure 19: CCDF of difference of (a) losses, (b) rate matching and (c) satisfaction ratio for Hungarian and Exhaustive schemes assuming disallowed pairs.

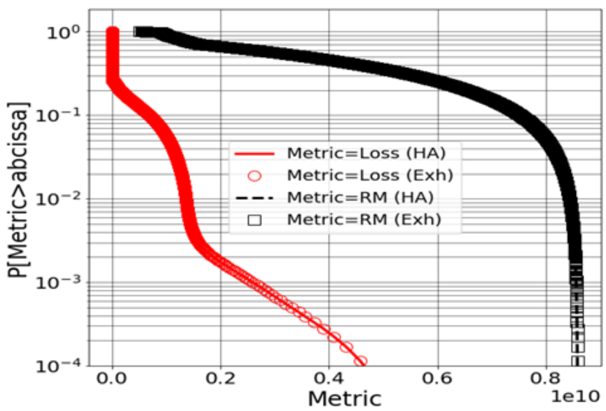


Figure 20: CCDF of losses and rate matching for Hungarian and Exhaustive mechanisms in O2M scenario.

4.3 Conclusion

In this Chapter optimal capacity allocation mechanisms with polynomial time complexity in multi-beam HTS systems have been proposed considering the offered and requested capacities of GWs and UE beams. The GWs' offered capacities are originated by a large-scale atmospheric attenuation model similar to Chapter 3 and UEs' requested capacities are uniformly distributed. The studied performance metrics are the minimization of system's losses and rate matching and the maximization of system's satisfaction ratio.

Optimal assignments are originated by the proposed scheme, based on Hungarian algorithm, in satellite networks scenarios where different UEs' links are considered, focusing on both different feeder links and downlinks. Moreover, equal and unequal number of GWs and UEs are examined, assuming the logical case that UEs are more than GWs. In latter case there are UEs that remain unserved. Furthermore in case of fewer GWs than UE beams, optimal pairings are also given considering that each GW can serve simultaneously multiple UEs in order that all UEs be served. In this case the number of simultaneously served UEs by each GW has been determined before the allocation process. Finally, optimal pairing is also achieved in scenarios with and without imposing payload or hardware constraints, i.e. the fact that each GW cannot serve every UE. This means that disallowed GW-UE pairings are possible due to adverse links' conditions.

Chapter 5

Suboptimal One-to-Many Allocation Schemes

In this Chapter same assumptions with the system model in Chapter 4 are considered. Specifically, the most important points for the definition and solution of current capacity allocation problems are repeated. A GEO HTS system is considered. There are *M* GWs that serve *N* UE beams with $\mathrm{M} \leq \mathrm{N}$ and $k_i>0$ UEs are served by each GW_i with *i=1,..,M*, called as $\forall \mathrm{i} \in M$ in problems below and $\sum_{i=1}^{M} \mathrm{k}_i = \mathrm{N}$. Hence, O2M pairings are assumed. Moreover, the requested capacity RC_j of each UE_j with *j=1,…,N*, called as $\forall j \in N$ in problems below, is served by exactly one GW. Finally, the offered capacity, OC_{ij}, among GW_i and UE_j is determined by Shannon formula and becomes $\mathrm{OC}_{ij}/\mathrm{k}_i$, due to the bandwidth allocation of GW_i, in order to serve simultaneously k_i UEs in the O2M case.

At this point we have to say that the crucial difference of the current Chapter with the previous ones is that while the number of served UEs by each GW is constant and predetermined in Chapter 3 and Chapter 4, here the served UEs' number is part of the optimization problems, making the latter scenario more complicated. This concept results in a two-step heuristic solution process: (a) the continuous step that includes the relaxation of binary allocation problems to continuous in [0, 1] and the application of iterative algorithms with approximations from fractional programming and sequential convex optimization (SCO) [Mark78] to result in a continuous solution and (b) the discrete step that includes the continuous to binary conversion of pairing solution from step (a). Especially in step (a), based on the approximations, appropriate convex/concave problems are solved in each iteration.

The concept of appropriate approximations of non-convex problems, in order to approach their solution by iterative algorithms that solve convex problems in each iteration, has been used in wireless networks. Especially, in [Li15] an iterative power allocation algorithm using sequential convex programming is presented, for the maximization of energy efficiency of the worst-case user in interference-limited wireless networks, while in [Efrem19] the SCO is applied in a multi-objective approach that takes into consideration both the total and minimum energy efficiency simultaneously, in device-to-device networks. Moreover, in [Huberman14] a sequential convex programming for full-duplex single-user multiple input-multiple output systems is shown and in [Tang17] the same theory is implemented in a scenario of user-centric joint admission control and resource allocation for 5G device-to-device extreme mobile broadband.

Furthermore, in [Efrem20] a dynamic energy-efficient power allocation in multi-beam satellite systems is described, to jointly minimize the system capacity and total radiated power using multi-objective optimization. To do that a successive convex approximation algorithm is applied that results in a stationary point with reasonable complexity, making it appropriate for on-board resource allocation. Finally, considering multi-UAV enabled wireless networks in [Wu18], the maximization of minimum throughput over all ground users in the downlink communication, by optimizing the multiuser communication scheduling and association jointly with the UAV's trajectory and power control is assumed, exploiting d successive convex optimization techniques.

5.1 Pairing Schemes for Satisfaction and Dissatisfaction Ratios

5.1.1 Capacity Allocation Problems

We target to find GWs-UEs assignments, i.e. $x_{ij} \in \{0,1\},\ \forall \mathrm{i,j}$ that are the elements of allocation matrix $X \in \{0,1\}^{MxN}$, for approaching the maximization of both minimum and total system's satisfaction ratios, called as max min SF and max SF problems respectively. By setting $c_{ij}=OC_{ij}/RC_j$ from the literature, the satisfaction ratio in O2M case is expressed in (1) and considering that the vectors $c_i=[c_{i1},c_{i2},...,c_{iN}]^T$ and $x_i=[\mathrm{x}_{i1},\mathrm{x}_{i2},...,\mathrm{x}_{iN}]^T$ have shape *N x 1* and correspond to GW_i and also e=[1,1,..,1]^T is a vector of same shape then the **max SF problem** takes after some transformations, the final form in (2). Moreover, its feasible set *S* is also given, where the inequality constraint declares that each GW serves at least one UE and the equality constraint that each UE is served by one GW.

$$c_{ij}^{SF}=\left[\sum_{y=1}^{N}x_{iy}\right]^{-1}\frac{OC_{ij}}{RC_j}=\left[\sum_{y=1}^{N}x_{iy}\right]^{-1}c_{ij}\,, \tag{1}$$

$$\max_{\mathbf{X}\in S}\sum_{i=1}^{M}\sum_{j=1}^{N}x_{ij}c_{ij}^{SF}=\max_{\mathbf{X}\in S}\sum_{i=1}^{M}\left[\left[\sum_{y=1}^{N}x_{iy}\right]^{-1}\sum_{j=1}^{N}x_{ij}c_{ij}\right]=\max_{\mathbf{X}\in S}\sum_{i=1}^{M}\frac{c_i^T x_i}{e^T x_i}\,, \tag{2}$$

where $S=\left\{1\le\sum_{j=1}^{N}x_{ij},\ \forall \mathrm{i}\in M,\ \sum_{i=1}^{M}x_{ij}=1,\ \forall j\in N \text{ and } \mathbf{X}\in\{0,1\}^{MxN}\right\}$.

Under a similar reformulation process the **max min SF problem**, i.e. the maximization of the satisfaction ratio of least satisfied UE, is presented in (3), with its feasible set $S_1=\left\{\sum_{i=1}^{M}\frac{x_{ij}c_{ij}}{e^T x_i}\ge t, \forall j\in N,\ \mathbf{X}\in \mathrm{S} \text{ and } \mathrm{t}\in \mathrm{R}\right\}$.

$$\max_{\mathbf{X}\in S}\ \min_{j=1,..,\mathrm{N}}\sum_{i=1}^{M}x_{ij}c_{ij}^{SF}=\max_{\mathbf{X}\in S}\ \min_{j=1,..,\mathrm{N}}\sum_{i=1}^{M}\frac{x_{ij}c_{ij}}{e^T x_i}=\max_{(\mathbf{X},t)\in S_1}t \tag{3}$$

Continuing the description of problems and based on the definition of satisfaction ratio we examine its multiplicative inverse given by $p_{ij}=RC_j/OC_{ij}$ as a possible alternative performance metric, called as dissatisfaction ratio. Thus the dissatisfaction ratio in O2M case is defined in (4) and the minimization of both total system's and maximum dissatisfaction ratios, called as min DSF and min max DSF problems, respectively, is investigated in (5) and (6).

$$c_{ij}^{DSF} = \frac{RC_j}{OC_{ij}} \sum_{y=1}^{N} x_{iy} = p_{ij} \sum_{y=1}^{N} x_{iy} \;, \tag{4}$$

$$\min_{\mathbf{X}\in S} \sum_{i=1}^{M}\sum_{j=1}^{N} x_{ij} c_{ij}^{DSF} = \min_{\mathbf{X}\in S} \sum_{i=1}^{M} \left[\left[\sum_{y=1}^{N} x_{iy} \right] \sum_{j=1}^{N} p_{ij} x_{ij} \right] = \min_{\mathbf{X}\in S} \sum_{i=1}^{M} x_i^T D_i x_i \;, \tag{5}$$

$$\min_{\mathbf{X}\in S} \max_{j=1,..,\mathrm{N}} \sum_{i=1}^{M} x_{ij} c_{ij}^{DSF} = \min_{\mathbf{X}\in S} \max_{j=1,..,\mathrm{N}} \sum_{i=1}^{M} \left[\left[\sum_{y=1}^{N} x_{iy} \right] p_{ij} x_{ij} \right] = \min_{\mathbf{X}\in S} \max_{j=1,..,\mathrm{N}} \sum_{i=1}^{M} x_i^T D_{ij} x_i = \min_{(\mathbf{X},t_1)\in S_2} t_1 \tag{6}$$

In case of minimization of total system's dissatisfaction ratio the reformulation of **min DSF** problem is defined in (5), where each j^{th} row of matrix $\boldsymbol{D_i}$, with shape *N x N*, is $r_j = [\mathrm{p}_{ij}, \mathrm{p}_{ij}, ..., \mathrm{p}_{ij}]$, $\forall j \in N$. Finally, for the **min max DSF** problem the appropriate reformulations and the final form are expressed in (6), where the matrix $\boldsymbol{D_{ij}}$ of shape *N x N* includes only zeros, except for the j^{th} row that is $\boldsymbol{r_j}$ as before. Moreover the feasible set of problem (6) is also described as $S_2 = \left\{ \sum_{i=1}^{M} x_i^T D_{ij} x_i \le t_1, \forall j \in N, \; \mathbf{X} \in \mathrm{S} \text{ and } \mathrm{t}_1 \in \mathrm{R} \right\}$.

5.1.2 Allocation Algorithms

The feasible sets *S*, S_1 and S_2 include the binary allocation matrix **X**, hence all the examined problems in (2), (3), (5) and (6) are binary optimization problems, which are hard to solve in polynomial time. To approximate these problems a heuristic two step approach is implemented. In the first step all the aforementioned problems are treated as continuous optimization problems with convex feasible S_3, that is equal to *S* with the relaxation of constraint $X \in \{0,1\}^{MxN}$ to $X \in [0,1]^{MxN}$. In what follows, an optimization problem is called *relaxed* when its binary constraints are replaced by continuous ones. This results in iterative solution approaches based on sequences of solutions of concave in (2), (3) and difference of convex problems in (5), (6). Then the continuous pairing solution from the first step is converted to a binary one and the corresponding objective is computed.

Assuming the continuous case, the max SF and max min SF problems belong to multiple ratio fractional programming (FP) problems and the concave approximation described in [Shen18] is applied. Specifically, due to the fact that $c_i^T x_i > 0$ in (2) based on inequality constraint of *S*, $x_{ij} c_{ij} \ge 0$ in (3) and $e^T x_i > 0$ in both problems, considering again the aforementioned inequality, then the assumptions of transformation in [Shen18, p.3] for non-negative numerator and strictly positive denominator are valid to our max SF and max min SF problems. Hence, problem (7) is equivalent to the relaxed problem (2), while problem (8) is equivalent to the relaxed problem (3). The solution of (7), (8), presented in Algorithm 1 of Figure 21, is based on the iterative approach

Algorithm 1: Concave Iteration Process for max SF (7) and max min SF (8) problems

1) Select $X^0 \in [0,1]^{MxN}$ to a feasible point based on S_3 and a tolerance $\varepsilon > 0$

2) Repeat

2a) Update $y_i\ \forall i \in M$ by $y_i^* = \begin{cases} \sqrt{c_i^T x_i^0}/(e^T x_i^0), \text{ for } (7) \\ \sqrt{x_{ij}^0 c_{ij}}/(e^T x_i^0), \text{ for } (8) \end{cases}$

2b) Update $\mathbf{X}$ by solving concave problems

$$\begin{cases} (7) \text{ over } \mathbf{X} \text{ with fixed } y_i \\ (8) \text{ over } \mathbf{X}, t \text{ with fixed } y_i \end{cases}$$

3) Until the values of objective in two sequential steps have relative error $\leq \varepsilon$

Figure 21: Continuous pairing process for max SF and max min SF problems.

in [Shen18], where sequential concave problems are solved.

$$\max_{\mathbf{X}\in S_3, \mathbf{y}\in R^M} \sum_{i=1}^{M} \left[2y_i \sqrt{c_i^T x_i} - y_i^2 (e^T x_i) \right], \tag{7}$$

$$\max_{(\mathbf{X},\mathbf{y},t)\in S_4} t, \tag{8}$$

where $S_4 = \left\{ \sum_{i=1}^{M} \left(2y_i \sqrt{x_{ij} c_{ij}} - y_i^2 (\mathrm{e}^T x_i) \right) \geq t, \forall j \in N,\ \mathbf{X} \in \mathrm{S}_3, (\mathbf{y}, \mathrm{t}) \in \mathrm{R}^{M+1} \right\}$. The solution of min DSF and min max DSF problems with the relaxation to continuous variables is based on the convex-concave procedure (CCP) [Lipp16], a heuristic iterative method that converges to a stationary point [Lanckriet09] of the relaxed problems (5) and (6). In order to apply the CCP mechanism the problems are retransformed appropriately based on the following result, whose proof is given in the Appendix 5.4.1.

Proposition 1 (*Quadratic to DC form*): Let ***D*** be a square (*N x N*) real matrix (not necessarily symmetric) and let ***x*** be a *N*-dimensional real column vector. Then, the quadratic form $x^T Dx = x^T D^{sym} x$, where $D^{sym} = (D + D^T)/2$ is a real symmetric matrix and *T* symbol declares the transpose operation. In addition, let $m \geq |\lambda_{\min}|$ be a (non-negative) real number, with $\lambda_{\min}$ being the minimum eigenvalue of D^{sym} (note that $\lambda_{\min}$ is a real number, because all the eigenvalues of a real symmetric matrix are real). Then $x^T D^{sym} x = x^T D^* x - x^T Ax$, where $D^* = D^{sym} + m\mathbf{I}$ and $A = m\mathbf{I}$ are symmetric positive semi-definite matrices (**I** is the *N x N* identity matrix). As a result, the initial quadratic form can be written as a difference of convex (DC) quadratic functions, i.e., $x^T Dx = x^T D^* x - x^T Ax$.

Algorithm 2: CCP Iterative Process for min DSF (9) and min max DSF (10) problems

1) Select $X^0 \in [0,1]^{MxN}$ to a feasible point based on S_3, set q=0 and a tolerance $\varepsilon > 0$

2) Repeat

2a) Set f for (9) and substitute A_i with A_{ij} in f for (10)

$$f = \sum_{i=1}^{M} x_i^{(q)T} A_i x_i^{(q)} + 2\sum_{i=1}^{M}\left[\left(\mathrm{A}_i x_i^{(q)}\right)^T \left(x_i - x_i^{(q)}\right)\right]$$

2b) Solve $\min_{\mathbf{X}\in S_3} \left[\sum_{i=1}^{M} x_i^T D_i^* x_i - f\right]$ for (9) and

$\min_{(\mathbf{X},t_1)\in S_6} t_1$ for (10) with convex feasible set S_6

$$S_6 = \left\{\sum_{i=1}^{M} x_i^T D_{ij}^* x_i - f \le t_1, \forall j \in N,\ \mathbf{X} \in \mathrm{S}_3, \mathrm{t}_1 \in \mathrm{R}\right\}$$

2c) Update iteration q:=q+1

2d) Set the value of $x_i^{(q)}$ to the solution of corresponding convex problems in (2b)

3) Until the values of objective in two sequential steps have relative error $\le \varepsilon$

Figure 22: Continuous pairing process for min DSF and min max DSF problems.

According to Proposition 1, the objective in (5) $\sum_{i=1}^{M} x_i^T D_i x_i$ is equal to $\sum_{i=1}^{M} x_i^T D_i^* x_i - \sum_{i=1}^{M} x_i^T A_i x_i$, while the constraint in (6) becomes $\sum_{i=1}^{M} x_i^T D_{ij}^* x_i - \sum_{i=1}^{M} x_i^T \mathrm{A}_{ij} x_i \le t_1$. As a result, we have the following problems:

$$\min_{\mathbf{X}\in S_3} \left[\sum_{i=1}^{M} x_i^T D_i^* x_i - \sum_{i=1}^{M} x_i^T A_i x_i\right], \tag{9}$$

$$\min_{(\mathbf{X},t_1)\in S_5} t_1, \tag{10}$$

where $S_5 = \left\{\sum_{i=1}^{M} x_i^T D_{ij}^* x_i - \sum_{i=1}^{M} x_i^T \mathrm{A}_{ij} x_i \le t_1, \forall j \in N,\ \mathbf{X} \in \mathrm{S}_3, \mathrm{t}_1 \in \mathrm{R}\right\}$.

The solution process of (9), (10), presented in Algorithm 2 of Figure 22, is based on the CCP iterative approach, where the linearization of subtrahend in the difference of convex functions results in the solution of a convex problem in each iteration.

After computing the continuous pairing solutions from (7)-(10) problems the conversion to a binary allocation matrix is made by the proposed heuristic Algorithm 3 of Figure 23. This algorithm is one of the possible processes for continuous to binary conversion and results in binary pairing solution based on *S* feasible set. Especially to explain the process of proposed

Algorithm 3: Continuous to Discrete Pairing Solution

1) Input: M, N and continuous pairing solution $X^C \in [0,1]^{MxN}$ from (7)-(10) problems
2) Compute $k_i = \sum_{j=1}^{N} x_{ij}^{C}$, $\forall i \in M$ and separate it in integer (int_i) and decimal (dec_i) parts.
3) Sort values of $\boldsymbol{X^C}$ in decreasing order and keep the corresponding indexes
4) Initialize the proposed $X^D \in \{0,1\}^{MxN}$ pairing matrix with zeros
5) Traverse X^D based on sorted indexes of (3) and if $(\sum_{j=1}^{N} x_{ij}^{D} < \text{int}_i \ \& \ \sum_{i=1}^{M} x_{ij}^{D} = 0)$ set $x_{ij}^{D} = 1$
6) Sort the M decimal parts in decreasing order and keep the corresponding indexes
7) Traverse the columns of X^D for which $\sum_{i=1}^{M} x_{ij}^{D} = 0$ and set $x_{ij}^{D} = 1$ to i^{th} row based on sorted indexes of (6).
8) Output: Feasible binary pairing matrix $\boldsymbol{X^D}$

Figure 23: Continuous to discrete allocation matrix conversion process.

algorithm, in the continuous pairing matrix the number of UEs served by each GW, in total *N* and at least equal to 1 due to the constraints, is separated in integer and decimal parts. Then we set appropriately 1 in the initially zeroed binary matrix based on each GW’s integer part and keeping the fact that each UE is served by one GW, described in steps 1-5 in Algorithm 3. After this point there are unserved UEs because the sum of integer parts are less than *N*. Finally, we set 1 to binary solution for the unserved UEs, given in steps 6, 7 of Algorithm 3. This process results in a feasible binary pairing matrix solution to initial problems (2), (3), (5) and (6).

5.2 Numerical Results

For the evaluation of the proposed methodologies, a framework in the PYTHON programming language has been developed and the CVXPY library has been used for the solution of convex/concave optimization problems [Diamond16].

We consider a GEO multi-beam HTS network with system’s parameters presented in Table 4 and simulation concept same with Section 4.2, but now the CNIR for the downlinks, $CNIR_{CS,dn,j}$, are uniformly distributed between *6* and *24 dB*. Moreover, the *RC*s for each UE are taken from a uniform distribution in the range (0, $B_C \log_2(1 + CNIR_{\mathrm{tot\_max,j}})$) bps, where $CNIR_{\mathrm{tot\_max,j}}^{-1} = CNIR_{CS,up}^{-1} + CNIR_{CS,dn,j}^{-1}$.

All graphs present statistical averages of examined metrics for 3500 independent simulation scenarios, in order to evaluate the performance of proposed schemes. In each scenario different sets of OCs and RCs are produced and the whole process described below is repeated for each scenario to obtain average results. Due to the fact that the solution of iterative processes in Algorithms 1 (Figure 21) and 2 (Figure 22) depends on the initial feasible point, in all figures the comparison between the constant, called as **Constant**, feasible point $(1/M)1_{MxN}$, where 1_{MxN} is the all-ones *M x N* matrix and a random process, called as **Random**, is shown. Particularly in random process 200 random initial feasible points are generated and that with the best value for (2), (3), (5) and (6) objectives, respectively, is chosen as starting point to Algorithms 1 and 2. Furthermore, for the Quadratic to DC conversion in Algorithm 2 we have set $m = \lceil |\lambda_{\min}| \rceil \geq |\lambda_{\min}|$ where $\lceil \cdot \rceil$ is the ceiling function and $\lambda_{\min}$ is the minimum eigenvalue of corresponding matrices. Moreover, the tolerance of these Algorithms is $\varepsilon=10^{-4}$. Finally, the **Exhaustive** mechanism, referred in simulations, is the optimization scheme that explores all the possible feasible combinations, in order to find the optimum objective value for each problem.

In Figure 24 the average relative error (%) between **Exhaustive** and **Proposed Allocation Schemes** is depicted for max SF, max min SF, min DSF and min max DSF problems. The factor of relative error in each simulation scenario, with the value of corresponding objective called as *obj*, is defined as $\left| obj_{Exhaustive} - obj_{\mathrm{Pr}oposed} \right| / obj_{Exhaustive}$. The performance of proposed methods has been studied for constant and random initial feasible points in HTS systems with *M=3, 4* and *N=[6-9]* GWs and UEs respectively.

The examination of two different starting points is presented because the mechanisms' performance depends on the initialization. Consequently a valuable performance indicator is the maximum of best achievable relative error, comparing the performance of both initializations in each system, across all systems. For example, in max SF graph this is higher than 0,15 % and belongs to the system with 3 GWs and 9 UEs, i.e. 3x9 case. Especially, in cases of max SF and min DSF problems this indicator is about 0,18 % in 3x9 case and 0,24 %, in 4x7 case, both in constant initialization, while for min max DSF and max min SF is about 3,8 % in 4x6 case, with constant initialization and 6,9 % in 3x9 case, with random initialization, respectively. The graphs show the importance of choosing appropriate starting feasible point. For example in the most systems in max min SF graph the constant feasible initial point results in average relative error higher than 15 %, but the same approach with a random starting feasible point has much better performance. Generally, the simulation results show that the proposed allocation schemes have very promising performance compared with the more complex optimal mechanism, even for random starting feasible points.

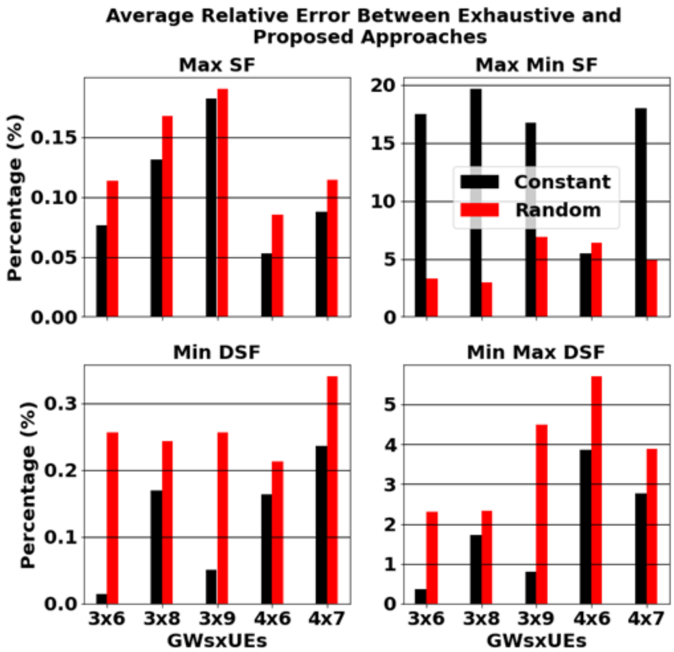


Figure 24: Average Percentage Relative Error between Exhaustive and Proposed Approaches, initializing the latter with Constant and Random feasible points, in HTS systems with various numbers of GWs and UEs for (a) max SF, (b) max min SF, (c) min DSF and (d) min max DSF problems.

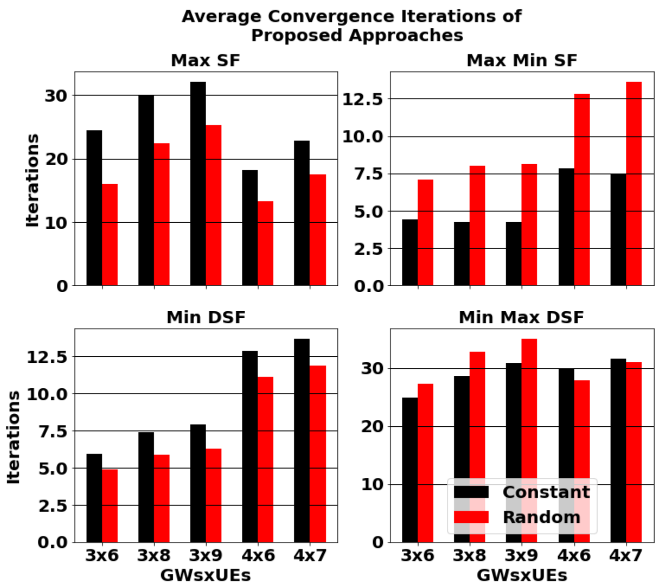


Figure 25: Average Convergence Iterations of Proposed Approaches, initializing the latter with Constant and Random feasible points, in HTS systems with various numbers of GWs and UEs for (a) max SF, (b) max min SF, (c) min DSF and (d) min max DSF problems.

Finally, in Figure 25 the average convergence iterations, with constant and random starting feasible points, to compute the continuous pairing solutions for max SF, max min SF, min DSF and min max DSF problems are presented. The iterations of Algorithm 1 are considered for max SF and max min SF problems and the iterations of Algorithm 2 for min DSF and min max DSF problems. It is obvious in the results, for all systems, that the iterative processes have fast convergence. They are terminated after a relatively small number of iterations. In case of HTS systems with larger number of GWs/UEs, where a pairing allocation decision has to be done in short time, it is practical to use an additional termination criterion with maximum number of iterations in Algorithms 1 and 2.

5.3 Pairing Schemes for Rate Matching

In this Section the intention is to find appropriate GWs-UEs pairing matrices $\mathrm{X} \in \{0,1\}^{\mathrm{MxN}}$ for approaching the minimization of n^{th} order rate matching (RM) [Kyrgiazos14]. We use the property that $|c|^n=|c^n|$ for any real *c* and *n* (*c* must be nonzero for negative *n*). Following a similar analysis with Section 5.1.1 the RM problem is presented in (11) where the offered capacity from GW_i to UE_j is expressed as $\frac{OC_{ij}}{\sum_{o=1}^{N} x_{io}}$ and models the O2M case. Moreover, we assume positive integer *n* in order the binomial formula to be converged [Graham94]. The feasible set S of constraints (C1), (C2) and (C3), given in (11), is the same as in Section 5.1.1.

$$\begin{aligned}
&\min_{\mathbf{X}} \sum_{i=1}^{M}\sum_{j=1}^{N} x_{ij}\left|RC_j - \frac{OC_{ij}}{\sum_{o=1}^{N} x_{io}}\right|^n = \min_{\mathbf{X}} \sum_{i=1}^{M}\sum_{j=1}^{N} x_{ij}\left|\left(RC_j - \frac{OC_{ij}}{\sum_{o=1}^{N} x_{io}}\right)^n\right| \\
&s.t.\ 1 \le \sum_{o=1}^{N} x_{io},\ \forall \mathrm{i}\ (C1) \\
&\quad \sum_{i=1}^{M} x_{ij} = 1,\ \forall j\ (\mathrm{C2}) \\
&\quad x_{ij} \in \{0,1\},\ \forall \mathrm{i,j}\ (\mathrm{C3})
\end{aligned} \tag{11}$$

Considering the binomial theorem [Graham94] with $\binom{n}{m} = \frac{n!}{m!(n-m)!}$ we conclude in (12).

$$\left(RC_j - \frac{OC_{ij}}{\sum_{o=1}^{N} x_{io}}\right)^n = \sum_{m=0}^{n}\left[(-1)^m \binom{n}{m}\left(RC_j\right)^{n-m}\left(\frac{OC_{ij}}{\sum_{o=1}^{N} x_{io}}\right)^m\right] \tag{12}$$

Problem in (11) is appropriately transformed in (13a)/(13b) for even/odd *n*, respectively, by adding $\mathrm{T} \in \mathrm{R}^{\mathrm{MxN}}$ auxiliary variables. Specifically for even *n* we have the property that $|c^n|=c^n$. Continuing the retransformation of problem in (13a)/(13b), we consider the matrix $\mathrm{Y} \in \mathrm{R}^{\mathrm{Mx2N}}$, given in (14), where $\mathrm{y_i} = [\mathrm{x_{i1}},\mathrm{x_{i2}},\ldots,\mathrm{x_{iN}},\mathrm{t_{i1}},\mathrm{t_{i2}},\ldots,\mathrm{t_{iN}}]^{\mathrm{T}}$ is a *2N x 1* vector related with the i^{th} GW.

$$\begin{aligned}
&\min_{\mathbf{X},\mathbf{T}} \sum_{i=1}^{M}\sum_{j=1}^{N} x_{ij}\, \mathrm{t}_{ij} \\
&s.t.\ 1 \le \sum_{o=1}^{N} x_{io},\ \forall \mathrm{i}\ (C1) \\
&\quad \sum_{i=1}^{M} x_{ij} = 1,\ \forall j\ (\mathrm{C2}) \\
&\quad x_{ij} \in \{0,1\},\ \forall \mathrm{i,j}\ (\mathrm{C3}) \\
&\quad \mathrm{t}_{ij} \ge \left(RC_j - \frac{OC_{ij}}{\sum_{o=1}^{N} x_{io}} \right)^n \Rightarrow \\
&\quad \Rightarrow \sum_{o=1}^{N} x_{io}\, \mathrm{t}_{ij} \ge \sum_{m=0}^{n}\left[(-1)^m \binom{n}{m} RC_j^{\,n-m} OC_{ij}^m \left(\sum_{o=1}^{N} x_{io}\right)^{1-m} \right],\ \forall \mathrm{i,j}\ (\mathrm{C4})
\end{aligned} \tag{13a}$$

$$\begin{aligned}
&\min_{\mathbf{X},\mathbf{T}} \sum_{i=1}^{M}\sum_{j=1}^{N} x_{ij}\, \mathrm{t}_{ij} \\
&s.t.\ 1 \le \sum_{o=1}^{N} x_{io},\ \forall \mathrm{i}\ (C1) \\
&\quad \sum_{i=1}^{M} x_{ij} = 1,\ \forall j\ (\mathrm{C2}) \\
&\quad x_{ij} \in \{0,1\},\ \forall \mathrm{i,j}\ (\mathrm{C3}) \\
&\quad \mathrm{t}_{ij} \ge \left(RC_j - \frac{OC_{ij}}{\sum_{o=1}^{N} x_{io}} \right)^n \Rightarrow \\
&\quad \Rightarrow \sum_{o=1}^{N} x_{io}\, \mathrm{t}_{ij} \ge \sum_{m=0}^{n}\left[(-1)^m \binom{n}{m} RC_j^{\,n-m} OC_{ij}^m \left(\sum_{o=1}^{N} x_{io}\right)^{1-m} \right],\ \forall \mathrm{i,j}\ (\mathrm{C4}) \\
&\quad \mathrm{t}_{ij} \ge -\left(RC_j - \frac{OC_{ij}}{\sum_{o=1}^{N} x_{io}} \right)^n \Rightarrow \\
&\quad \Rightarrow \sum_{o=1}^{N} x_{io}\, \mathrm{t}_{ij} \ge \sum_{m=0}^{n}\left[(-1)^{m+1} \binom{n}{m} RC_j^{\,n-m} OC_{ij}^m \left(\sum_{o=1}^{N} x_{io}\right)^{1-m} \right],\ \forall \mathrm{i,j}\ (\mathrm{C5})
\end{aligned} \tag{13b}$$

$$Y = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1N} & t_{11} & t_{12} & \dots & t_{1N} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ x_{M1} & x_{M2} & \dots & x_{MN} & t_{M1} & t_{M2} & \dots & t_{MN} \end{bmatrix} \tag{14}$$

Furthermore, we set $\mathrm{D}=\begin{bmatrix} 0_{\mathrm{NxN}} & 0_{\mathrm{NxN}} \\ \mathrm{I}_{\mathrm{NxN}} & 0_{\mathrm{NxN}} \end{bmatrix}$, where 0_{NxN} is the zero matrix and **I** is the identity main diagonal matrix both of shape *N x N*, and $\mathbf{A}_\mathbf{j}$ is a zero *2N x 2N* matrix with 1 in row *N+j* till the first *N* columns, namely $A_j = \begin{bmatrix} 0_{NxN} & 0_{NxN} \\ 0_{NxN} \text{ with } 1_{N+j,1:N} & 0_{NxN} \end{bmatrix}$. Moreover assuming that $e = [1_{1:N}, 0_{N+1:2N}]^T$ is a *2N x 1* vector, with 1 in the first N positions and 0 in the rest and relaxing the binary constraint (C3) as in Section 5.1.2 the problems in (13a)/(13b) take the form in (15a)/(15b).

$$
\begin{aligned}
&\min_{\mathbf{Y}} \sum_{i=1}^{M} y_i^T D y_i \\
&s.t.\ 1 \le \sum_{o=1}^{N} y_{io},\ \forall \mathrm{i}\ \ (C1) \\
&\quad \sum_{i=1}^{M} y_{ij} = 1,\ \forall j \le N\ \text{(C2)} \\
&\quad 0 \le \mathrm{y}_{ij} \le 1,\ \forall \mathrm{i}, \forall j \le N\ \ \text{(C3)} \\
&-y_i^T A_j y_i + RC_j^{\ n}\left(e^T y_i\right) - nRC_j^{\ n-1} OC_{ij} + \\
&+\sum_{m=2}^{n}\left[\left(-1\right)^m \binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \le 0, \forall \mathrm{i}, \forall \mathrm{j} \le \mathrm{N}\ \text{(C4)}
\end{aligned}
\tag{15a}
$$

$$
\begin{aligned}
&\min_{\mathbf{Y}} \sum_{i=1}^{M} y_i^T D y_i \\
&s.t.\ 1 \le \sum_{o=1}^{N} y_{io},\ \forall \mathrm{i}\ \ (C1) \\
&\quad \sum_{i=1}^{M} y_{ij} = 1,\ \forall j \le N\ \text{(C2)} \\
&\quad 0 \le \mathrm{y}_{ij} \le 1,\ \forall \mathrm{i}, \forall j \le N\ \ \text{(C3)} \\
&-y_i^T A_j y_i + RC_j^{\ n}\left(e^T y_i\right) - nRC_j^{\ n-1} OC_{ij} + \\
&+\sum_{m=2}^{n}\left[\left(-1\right)^m \binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \le 0, \forall \mathrm{i}, \forall \mathrm{j} \le \mathrm{N}\ \text{(C4)} \\
&-y_i^T A_j y_i - RC_j^{\ n}\left(e^T y_i\right) + nRC_j^{\ n-1} OC_{ij} + \\
&+\sum_{m=2}^{n}\left[\left(-1\right)^{m+1} \binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \le 0, \forall \mathrm{i}, \forall \mathrm{j} \le \mathrm{N}\ \text{(C5)}
\end{aligned}
\tag{15b}
$$

Continuing the analysis and following the process described in Section 5.1.2 in Proposition 1 about the conversion of quadratic to DC form, we treat appropriately the quadratic forms in objective and (C4), (C5) and the problems become:

$$
\begin{aligned}
&\min_{\mathbf{Y}} \sum_{i=1}^{M} y_i^T D^* y_i - \sum_{i=1}^{M} y_i^T P y_i \\
&s.t.\ 1 \le \sum_{o=1}^{N} y_{io},\ \forall \mathrm{i}\ \ (C1) \\
&\quad \sum_{i=1}^{M} y_{ij} = 1,\ \forall j \le N\ \text{(C2)} \\
&\quad 0 \le \mathrm{y}_{ij} \le 1,\ \forall \mathrm{i}, \forall j \le N\ \ \text{(C3)} \\
&y_i^T P_j y_i - y_i^T A_j^* y_i + RC_j^{\ n}\left(e^T y_i\right) - nRC_j^{\ n-1} OC_{ij} + \\
&+\sum_{m=2}^{n}\left[\left(-1\right)^m \binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \le 0, \forall \mathrm{i}, \forall \mathrm{j} \le \mathrm{N}\ \text{(C4)}
\end{aligned}
\tag{16a}
$$

$$\begin{aligned}
&\min_{\mathbf{Y}} \ \sum_{i=1}^{M} y_i^T D^* y_i - \sum_{i=1}^{M} y_i^T P y_i \\
&s.t.\ 1 \le \sum_{o=1}^{N} y_{io},\ \forall \text{i}\ \ (C1) \\
&\quad \sum_{i=1}^{M} y_{ij} = 1,\ \forall j \le N\ \text{(C2)} \\
&\quad 0 \le \text{y}_{ij} \le 1,\ \forall \text{i}, \forall j \le N\ \ \text{(C3)} \\
&y_i^T P_j y_i - y_i^T A_j^* y_i + RC_j^{\ n}\left(e^T y_i\right) - nRC_j^{\ n-1} OC_{ij} + \\
&+ \sum_{m=2}^{n}\left[\left(-1\right)^m \binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \le 0, \forall \text{i}, \forall \text{j} \le \text{N (C4)} \\
&y_i^T P_j y_i - y_i^T A_j^* y_i - RC_j^{\ n}\left(e^T y_i\right) + nRC_j^{\ n-1} OC_{ij} + \\
&+ \sum_{m=2}^{n}\left[\left(-1\right)^{m+1} \binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \le 0, \forall \text{i}, \forall \text{j} \le \text{N (C5)}
\end{aligned} \tag{16b}$$

where $D^* = D^{sym} + rI$, $A_j^* = A_j^{sym} + r_j I$, **P**=r**I** and $\mathbf{P}_j$=r_j**I** with **I** the 2*N x 2N* identity matrix and r, r_j are originated appropriately by the eigenvalues of D^{sym} and A_j^{sym}, respectively as described in Proposition 1 of Section 5.1.2.

Furthermore, we prove in Appendix 5.4.2 that the term $\left(-1\right)^m \left(e^T y_i\right)^{1-m}$ inside the summation of (C4) is convex for even *m* and concave for odd *m*. Thus, in (C5) the term $\left(-1\right)^{m+1} \left(e^T y_i\right)^{1-m}$ is convex for odd *m* and concave for even *m*. Hence the application of CCP method is straightforward. Specifically, considering (C4), for implementing the CCP algorithm the part that remains the same is defined in f_1 and the 'convexified' part in f_2, while for (C5) these are expressed in f_3 , f_4.

$$\text{f}_1 = y_i^T P_j y_i + RC_j^n\left(e^T y_i\right) - nRC_j^{n-1} OC_{ij} + \sum_{m=2,4,6,\dots}^{n}\left[\binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \tag{17}$$

$$\text{f}_2 = y_i^T A_j^* y_i + \sum_{m=3,5,7,\dots}^{n}\left[\binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \tag{18}$$

$$\text{f}_3 = y_i^T P_j y_i - RC_j^n\left(e^T y_i\right) + nRC_j^{n-1} OC_{ij} + \sum_{m=3,5,7,\dots}^{n}\left[\binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \tag{19}$$

$$\text{f}_4 = y_i^T A_j^* y_i + \sum_{m=2,4,6,\dots}^{n}\left[\binom{n}{m} RC_j^{\ n-m} OC_{ij}^m \left(e^T y_i\right)^{1-m}\right] \tag{20}$$

The convexification of f_2/f_4 are shown in (21)/(22) where $y_i^{(q)}$ is the solution of the problem in *q^th^* iteration of the process and the general algorithm is the same as in Figure 22, where the convex problems in (23a)/(23b) are solved in each iteration.

$$h = y_i^{(q)\mathrm{T}} A_j^* y_i^{(q)} + \sum_{m=3,5,7,...}^{n} \left[\binom{n}{m} RC_j^{\,n-m} OC_{ij}^m \left(e^T y_i^{(q)} \right)^{1-m} \right] + \left[2\left(A_j^* y_i^{(q)} \right)^T + \left(\sum_{m=3,5,7,...}^{n} \left[\binom{n}{m} RC_j^{\,n-m} OC_{ij}^m (1-m) \left(e^T y_i^{(q)} \right)^{-m} \right] \right) e^T \right] \left(y_i - y_i^{(q)} \right) \tag{21}$$

$$h_1 = y_i^{(q)\mathrm{T}} A_j^* y_i^{(q)} + \sum_{m=2,4,6,...}^{n} \left[\binom{n}{m} RC_j^{\,n-m} OC_{ij}^m \left(e^T y_i^{(q)} \right)^{1-m} \right] + \left[2\left(A_j^* y_i^{(q)} \right)^T + \left(\sum_{m=2,4,6,...}^{n} \left[\binom{n}{m} RC_j^{\,n-m} OC_{ij}^m (1-m) \left(e^T y_i^{(q)} \right)^{-m} \right] \right) e^T \right] \left(y_i - y_i^{(q)} \right) \tag{22}$$

$$\begin{aligned} \min_{\mathbf{Y}} \ & \sum_{i=1}^{M} y_i^T D^* y_i - \sum_{i=1}^{M} y_i^{(q)\mathrm{T}} P y_i^{(q)} - 2\sum_{i=1}^{M} \left[\left(\mathrm{P}\, y_i^{(q)} \right)^T \left(y_i - y_i^{(q)} \right) \right] \\ s.t.\ & 1 \le \sum_{o=1}^{N} y_{io},\ \forall \mathrm{i}\ (C1) \\ & \sum_{i=1}^{M} y_{ij} = 1,\ \forall j \le N\ (\mathrm{C2}) \\ & 0 \le \mathrm{y}_{ij} \le 1,\ \forall \mathrm{i}, \forall j \le N\ (\mathrm{C3}) \\ & f_1 - h \le 0, \forall \mathrm{i}, \forall j \le N\ (\mathrm{C4}) \end{aligned} \tag{23a}$$

$$\begin{aligned} \min_{\mathbf{Y}} \ & \sum_{i=1}^{M} y_i^T D^* y_i - \sum_{i=1}^{M} y_i^{(q)\mathrm{T}} P y_i^{(q)} - 2\sum_{i=1}^{M} \left[\left(\mathrm{P}\, y_i^{(q)} \right)^T \left(y_i - y_i^{(q)} \right) \right] \\ s.t.\ & 1 \le \sum_{o=1}^{N} y_{io},\ \forall \mathrm{i}\ (C1) \\ & \sum_{i=1}^{M} y_{ij} = 1,\ \forall j \le N\ (\mathrm{C2}) \\ & 0 \le \mathrm{y}_{ij} \le 1,\ \forall \mathrm{i}, \forall j \le N\ (\mathrm{C3}) \\ & f_1 - h \le 0, \forall \mathrm{i}, \forall j \le N\ (\mathrm{C4}) \\ & f_3 - h_1 \le 0, \forall \mathrm{i}, \forall j \le N\ (\mathrm{C5}) \end{aligned} \tag{23b}$$

Therefore, we see that the CCP method can be applied in order to find a continuous solution to approximate the minimization of positive integer n^{th} order rate matching function.

5.4 Appendix

5.4.1 Proof of Proposition 1

Firstly, the proof about the zero quadratic form of an anti-symmetric matrix is given. It is known that any square matrix can be written as the sum of a symmetric and an anti-symmetric matrix. Therefore, $D = D^{sym} + D^{antisym}$, where $D^{sym} = (D + D^T)/2$ and $D^{antisym} = (D - D^T)/2$. Notice that $(D^{sym})^T = D^{sym}$ and $(D^{antisym})^T = -D^{antisym}$. Finally, because the scalar

$x^T D^{antisym} x = (x^T D^{antisym} x)^T \Rightarrow x^T D^{antisym} x = x^T (D^{antisym})^T x \Rightarrow x^T D^{antisym} x = 0$. Hence $x^T Dx = x^T D^{sym} x + x^T D^{antisym} x = x^T D^{sym} x$.

Secondly, it remains to show that the square matrices D^* and A are symmetric and positive semi-definite. Obviously, both matrices are symmetric due to their construction. Now, $A = m\mathbf{I}$ is a positive semi-definite matrix since all its eigenvalues are equal to the non-negative number $m \geq 0$ (because $m \geq |\lambda_{\min}| \geq 0$). Let us suppose that λ is a real eigenvalue of D^{sym}, i.e., $D^{sym} u = \lambda u$, where ***u*** is a non-zero *N*-dimensional column vector. Then $D^* u = (D^{sym} + m\mathbf{I})u = \lambda u + mu = (\lambda + m)u$ where $\lambda + m$ is a real eigenvalue of D^*. Due to the fact that $m \geq |\lambda_{\min}| \Rightarrow -m \leq \lambda_{\min} \leq m \Rightarrow \lambda + m \geq \lambda_{\min} + m \geq 0$, all the eigenvalues of D^* are real and non-negative, so D^* is a positive semi-definite matrix. To conclude, both the square matrices D^* and A are symmetric and positive semi-definite.

5.4.2 Derivatives of Fractional Terms in Rate Matching

In the summation of (C4) in (16) all the terms are constant and positive except from the fractional term that includes the variables. In order to prove that the fractional terms are convex or concave we apply the rule about the composition with an affine mapping [Boyd04]. This rule states that for scalar functions *g*, *f* and affine function **Ax**+**b** then g(**x**)=f(**Ax**+**b**) is convex if *f* is convex and concave if *f* is concave.

In our case we set $f(z) = (-1)^m z^{1-m}$ and the fractional terms have the form

$$g(y_i) = (-1)^m \left(e^T y_i\right)^{1-m} = f(e^T y_i) \tag{21}$$

In order to check the convexity of *f(z)* we study its second derivative given in (22).

$$\frac{d^2 f}{dz^2} = (-1)^m (1-m)(-m) z^{-1-m} \tag{22}$$

The sign of $\frac{d^2 f}{dz^2}$ depends only on term $(-1)^m$, due to the fact that $m \geq 2$ and $z \geq 1$ (resulting by $e^T y_i \geq 1$ given in (C1)). Thus $\frac{d^2 f}{dz^2}$ is positive for even *m* and negative for odd *m*. To conclude from the rule about the composition with an affine mapping, *f* and consequently *g*, namely the fractional terms in the binomial formula are convex for even *m* and concave for odd *m*.

5.5 Conclusion

In this Chapter suboptimal one-to-many pairing scenarios are examined in HTS system for various numbers of gateways and UE beams, where different UEs' links are considered. The number of simultaneous served UEs in the studied O2M cases is part of the optimization problems and not predetermined. Especially, the complex problems of maximization of both minimum and total system's satisfaction ratios and minimization of both maximum and total system's dissatisfaction ratios are examined. A two-step heuristic approach with fast convergence based on simulations is proposed, containing the relaxation to continuous case of aforementioned allocation problems and the continuous to discrete conversion of pairing solution. For the satisfaction problems the proposed mechanism is based on fractional programing theory, while for the dissatisfaction problems the difference of convex programming theory is implemented.

Furthermore, considering the case of dissatisfaction ratios, we have shown a general method to solve quadratic optimization problems that are non-convex, by applying the convex-concave procedure. Especially, we process appropriately the eigenvalues of problem's matrix and form convex and concave functions, written as difference of a concave function from a convex one. Hence the problem can be solved by the convex-concave procedure that results in a stationary point.

Moreover, all the presented solution processes depend on the starting feasible point thus different initial points, constant and random, are studied. In conclusion, the simulation results for the proposed mechanisms are very promising, showing cases with small relative error in all presented systems, compared with the optimal performance of the exhaustive algorithm that checks all the possible feasible pairings.

Finally, we present a theoretical analysis to approach the minimization of n^{th} order rate matching, for positive integer *n*, by applying the convex-concave procedure. To do that we exploit appropriately the quadratic forms and the convexity or concavity of terms inside the binomial formula.

Chapter 6

Thesis Summary and Future Work

In this Chapter the main contributions of this PhD thesis are given and a few points for future work are stated. We must have in mind that this research is just a small part in the general scientific concept of radio resource management in satellite networks, while the presented mathematical theories can also be applied in other wireless networks.

6.1 General Conclusions

In Chapter 3 we focus on the feeder links and the different pairing theories, i.e. Gale-Shapley algorithm and Monge arrays are applied in performance metrics that include minimization of system’s capacity losses and rate matching and maximization of total and minimum satisfaction ratio.

Specifically, from the Section 3.1 the main contributions are given below:

- A flexible resource allocation algorithm for HTS communication systems based on principles of matching theory is proposed and the Gale-Shapley algorithm is used. Its objective is to minimize the system’s capacity losses in multi-beam HTS system, considering different scenarios, where one GW can serve one or more UE beams simultaneously. The second case is examined to study the performance of the HTS system assuming that GWs are fewer than UE beams, which consists of a realistic scenario for satellite networks.

- This algorithm considers realistic propagation attenuation channel conditions for the feeder links, through a reliable large scale total atmospheric channel model. Consequently, the connection among the GWs and UE beams changes periodically depending on the dynamic atmospheric channel conditions of feeder links and the UE beams’ traffic demands. Hence, our procedure is ideal for satellite systems with highly dynamic conditions.

- To provide a more robust system’s performance analysis, we make comparisons with other RRM mechanisms, namely the more complicated exhaustive one, the fairness one, a less complicated fixed one and finally a naive random mechanism. Specifically in both aforementioned investigated scenarios the proposed matching mechanism has identical performance with the exhaustive mechanism, which means that our process results to the minimization of system’s losses. Additionally, in the former scenario where one GW serves one UE beam, our RRM algorithm achieves better performance, compared with the fairness mechanism, the less complicated fixed mechanism and the random pairing process.

- Consequently, the promising results of matching theory combined with its simplicity and low complexity make it a possible ally for solution of problems in the RRM field in future HTS networks.

In terms of Section 3.2 the same general scenario is also used and the most important points are:

- A very low complexity optimal scalable dynamic resource allocation mechanism between the GWs and UEs, considering the minimization of two different performance metrics, i.e. the system's capacity losses and the rate matching is presented. The optimality of the proposed resource allocation scheme is theoretically originated by the fact that both performance metrics constitute Monge arrays.

- Moreover, low complexity optimal capacity allocation schemes are proposed for the fairness method, targeting to the maximization of minimum satisfaction ratio considering the system's pairs and the maximization of system's total satisfaction ratio. Specifically, both objectives, i.e. the fairness method and total satisfaction ratio, both after some transformation, constitute problems with bottleneck Monge and Monge arrays.

- The application of Monge arrays results in appropriate sorting of GWs' offered and UEs' requested capacities, in order to solve optimally the aforementioned problems. Finally an important theoretical tradeoff results: the optimal pairing scheme for fairness method causes the minimization of system's total satisfaction ratio and the inverse happens in terms of the optimal pairing of latter objective.

The main contributions of the topic in Chapter 4 are:

- Optimal assignments are originated by the proposed scheme in satellite networks scenarios, where different UEs' links are considered, focusing on both different feeder links and downlinks. The Hungarian or Kuhn-Munkres algorithm is exploited resulting in a theoretically optimal result in polynomial time complexity.

- Optimal assignments are achieved with equal and unequal number of GWs. In that case there are UEs that remain unserved. In the case of fewer GWs than UE beams, optimal pairings are also given in case that each GW can serve simultaneously multiple UEs, in order not to have unserved UEs.

- The optimal pairing is also achieved in scenarios with payload or hardware constraints, i.e. the fact that UEs cannot be served by all GWs. This means that disallowed GW-UE pairings are possible due to adverse links' conditions.

- The presented outcomes in all different studied optimization problems show that the existence of constraints in the system, i.e. disallowed GW-UE pairings, result in optimal system's performance worse than the corresponding optimal performance, when there are no disallowed assignments, i.e. when each user beam can be served by each gateway.

Finally, Chapter 5 is an extension of Chapter 4 and suboptimal assignments are presented. While in previous Chapters constant predetermined simultaneous served UEs for each GW are assumed, in current Chapter the number of GW's simultaneously served UEs is part of optimization problems, making the latter more complicated and heuristic solution methods are examined. Specifically, the main contributions are:

- Except from the metric of satisfaction ratio, already defined in literature, a new proposed metric is defined as the multiplicative inverse of satisfaction ratio and is called dissatisfaction ratio. This new metric is examined analytically and provides a possible alternative performance figure of merit in resource allocation problems.

- Suboptimal one-to-many assignments for the considered metrics of satisfaction and dissatisfaction ratios are originated by the proposed allocation schemes in HTS networks scenarios, where UEs with different links' conditions are considered, focusing on both different feeder links and downlinks.

- The proposed two-step pairing process, for approximating the aforementioned binary optimization problems, includes the relaxation of binary pairing to a continuous counterpart in [0, 1], the application of appropriate non-convex optimization theories and the continuous to binary conversion of pairing solution. Especially, the continuous pairing solution is based on fractional programing theory for the satisfaction problems and the difference of convex programming theory for the dissatisfaction problems. Moreover, the final outcome of this two-step approach depends on the initial feasible point of first step algorithms.

- Furthermore, there is an important remark for the solution of the dissatisfaction ratio optimization problem. In the solution of this problem, we have presented a simple straightforward general method for approaching the optimization problems that contain quadratic forms, that are non-convex, either in objective or/and in the constraints. The quadratic form can be written, with an appropriate simple transformation, as a difference of convex functions and the problem can be solved by the convex-concave procedure, that guarantees convergence to a stationary point.

- Based on the extended simulations, the proposed allocation mechanisms result in suboptimal one-to-many assignments with fast convergence. Finally, the presented results, for different starting feasible points in all different studied optimization problems, depict the very promising performance of the proposed pairing algorithms, compared with the corresponding performance of optimal mechanism.

- To conclude, we have also presented the theoretical formulation of the minimization of the n^{th} order rate matching, where *n* is positive integer. It has been approximated by the difference of convex optimization theory. Specifically, the problem has quadratic forms that are processed as described above and the terms inside the binomial formula are also convex or concave. Hence the convex (concave) parts from the quadratic forms are grouped together with the convex (concave) terms from the binomial formula and then the algorithm of difference of convex functions is directly applied.

6.2 Future Work

Based on the assumptions of the models developed under this thesis, there are points that can be considered for further research in the future, in the concept of RRM in satellite networks [Kuang17], [Kisseleff21].

To begin with, the performance of the method described for the minimization of n^{th} (positive integer) order rate matching in Section 5.3 has to be evaluated and compared with the exhaustive mechanism through simulations. The relative error and the iterations until the convergence of algorithm have to be examined.

Moreover, we have a uniform distribution for UEs' requested capacity. Even though the presented mathematical analysis can be directly applied for different formulas of offered and requested capacities, it is valuable more realistic distributions for requested capacities [Al-Hraishawi20], [Ortiz-Gomez21]. Furthermore, real satellite communication data are of utmost importance and instead of using statistical models and distributions, the OCs and RCs can be originated by them and make a study, e.g. about the system’s losses based on real data. Additionally, except from the O2O and O2M cases, appropriate scenarios can be considered where each GW can serve many UEs and each UE can be served by multiple GWs.

A direct extension of the system model in Chapter 5 is the assumption of payload constraints, i.e. the case that a GW cannot serve all UEs. This is important and has to be considered appropriately in the pairing allocation processes assuming also the UEs’ links and a not predetermined number of the UEs that are served by each GW.

Finally, the study of joint resource allocation problems is crucial and of vital importance in next generation satellite networks where there is need to use all the possible resources. As scenarios become more complicated by considering more parameters, the employment of artificial intelligence techniques is a possible ally to face up with these problems. In the latter case, the training process is time consuming and can be made offline. Afterwards, the trained model provides rapid solutions for the online operation. Even though AI models can capture complex relations and are able to solve in an acceptable level many problems, in a wide range of scientific fields, there are not theoretical guarantees about their performance, due to the formulation of the functions that need effort to be approached and always there is a percentage of failure.

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