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Hybrid Satellite Terrestrial Relay Networks

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ABSTRACT

With the ever-increasing satellite and terrestrial communication demands in our 5G era, integrating cooperative transmission into satellite networks is seen as a viable technique for increasing satellite communications' energy efficiency and coverage. The high data rate terminals with the demand for ubiquitous connectivity makes the simultaneous use of satellite and terrestrial infrastructures a necessity and with the emerging cooperative relaying techniques satellite communications systems can provide seamless connectivity and broadband access for mobile users. The subject of this thesis is a satellite system, specifically a hybrid satellite-terrestrial relay system (HSTRS). The advantages and problems that arise in HSTRS will be identified and explored, as well as key system characteristics. Parallel to this, we cover a variety of strategies that have been or will be used with HSTRS, as well as the advantages of non-orthogonal multiple access (NOMA) schemes. The application of Power-domain NOMA to various satellite architectures has demonstrated considerable system gains in terms of coverage, availability, efficiency, and other 5G target requirements. The main knowledge of the relay systems is also covered using the DF and AF models. Finally, the thesis concludes with a discussion on future HSTRS research.

SUBJECT AREA: Hybrid Satellite-Terrestrial Relay Systems

KEYWORDS: HSTRS, 5G, Satellite Communications, Relay Systems, NOMA

ΠΕΡΙΛΗΨΗ

Με τις συνεχώς αυξανόμενες απαιτήσεις δορυφορικών και επίγειων επικοινωνιών στην εποχή του 5G, η ενσωμάτωση της συνεργατικής μετάδοσης σε δορυφορικά δίκτυα θεωρείται μια βιώσιμη τεχνική για την αύξηση της ενεργειακής απόδοσης και κάλυψης των δορυφορικών επικοινωνιών. Τα τερματικά υψηλής ταχύτητας δεδομένων με τη ζήτηση για πανταχού παρούσα συνδεσιμότητα καθιστούν την ταυτόχρονη χρήση δορυφορικών και επίγειων υποδομών απαραίτητη και με τις αναδυόμενες συνεργατικές τεχνικές αναμετάδοσης τα συστήματα δορυφορικών επικοινωνιών μπορούν να παρέχουν απρόσκοπτη συνδεσιμότητα και ευρυζωνική πρόσβαση σε κινητούς χρήστες. Αντικείμενο της παρούσας διπλωματικής εργασίας είναι ένα δορυφορικό σύστημα και συγκεκριμένα ένα υβριδικό δορυφορικό-επίγειο σύστημα αναμετάδοσης (HSTRS). Τα πλεονεκτήματα και τα προβλήματα που προκύπτουν στο HSTRS θα εντοπιστούν και θα διερευνηθούν, καθώς και τα βασικά χαρακτηριστικά του συστήματος. Παράλληλα με αυτό, καλύπτουμε μια ποικιλία από στρατηγικές που έχουν χρησιμοποιηθεί ή θα χρησιμοποιηθούν με το HSTRS, καθώς και τα πλεονεκτήματα των σχημάτων μη ορθογώνιας πολλαπλής πρόσβασης (NOMA). Η εφαρμογή του Power-domain NOMA σε διάφορες δορυφορικές αρχιτεκτονικές έχει επιδείξει σημαντικά κέρδη συστήματος όσον αφορά την κάλυψη, τη διαθεσιμότητα, την αποτελεσματικότητα και άλλες απαιτήσεις-στόχους 5G. Η βασική γνώση των συστημάτων αναμετάδοσης καλύπτεται επίσης χρησιμοποιώντας τα μοντέλα DF και AF. Τέλος, η διατριβή ολοκληρώνεται με μια συζήτηση για μελλοντική έρευνα πάνω στο HSTRS.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Υβριδικό Δορυφορικό-Επίγειο Σύστημα Αναμετάδοσης

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: HSTRS, 5G, Δορυφορικές Επικοινωνίες, Συστήματα Αναμετάδοσης, Μη Ορθογώνια Πολλαπλή Πρόσβαση (NOMA)

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1. INTRODUCTION

To support a slew of connected devices and new services spawned by paradigms like the Internet of Things, the fifth-generation (5G) of wireless networks will need to meet stringent requirements, such as extremely high data throughput, very low latency, and a highly efficient use of energy and spectrum resources.

To begin, it is important to highlight that the evolution of telecommunication networks is impacted by three interconnected elements. The first is technological advancement, the second is the development of new services, and the third is traffic increase [1].

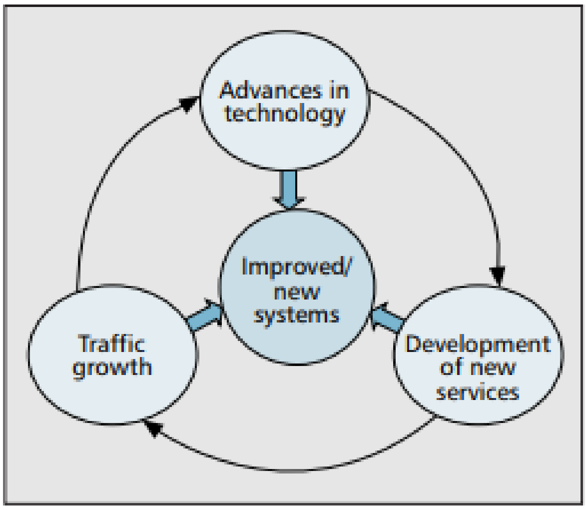

Figure 1.1: Three interconnected elements impacting Telecommunication Networks.

Satellites could no longer afford to focus on a certain sort of service as they once could due to the dominance of Internet-based multimedia applications and the resulting shift in client trends, as well as differentiated shifting market and business models (CISCO). From a technical standpoint, delivery can be divided into two categories: fixed and mobile. Both service categories rely on the number of pieces of user equipment receiving the same multimedia information from the same source at the same time, so those two types of delivery mechanisms, unicast and broadcast/multicast, are relevant.

Satellite systems can currently provide dependable and cost-effective services in a variety of domains, particularly in light of the upcoming fifth-generation (5G) era in fields such as disaster recovery [2], smart grid, Internet-of-Things (IoT), wireless sensor networks, space-based clouds, enhanced Mobile BroadBand (eMBB) [3], vehicular ad-hoc networks, and wireless backhaul. In mobile scenarios, the simultaneous usage of terrestrial and satellite infrastructures is required due to the high data rate of terminals and the desire for anywhere-anytime user connectivity. There are significant technical hurdles in implementing multipath communication protocols and robust recovery mechanisms to cope with signal degradation due to the impacts of the mobile fading channel in order to provide a reliable and timely delivery of data.

The integration of satellite and terrestrial systems was foreseen, and it posed issues in both systems' functioning, but particularly in the first. One of the key concerns is that excessive shadowing or deep fading would substantially damage satellite systems, especially if the line-of-sight (LOS) link between the satellite and terrestrial components could not be maintained due to barriers.

Because terrestrial infrastructures have the capability to give low-cost coverage that is used in populated/urban areas while keeping non-line-of-sight (NLoS) connections, an integrated architecture known as hybrid satellite-terrestrial relay network may be the answer to those issues.

By maintaining those non-line-of-sight (NLoS) connections, terrestrial infrastructure has the potential to provide cheap coverage in both residential and urban areas. The hybrid satellite-terrestrial relay network (HSTRN) is an integrated architecture system that concerns both satellite and terrestrial systems used as an extension/complement to each other and is considered a very promising architecture that can achieve better transmission rate and more reliable service [4].

1.1 Hybrid Satellite Terrestrial Relay Networks (HSTRN)

One of the most reliable wireless communications forms is considered to be satellite communication. There are many advantages of networks of satellite communication including communication of long-distance, enormous coverage area, and adaptable environments of communication compared to conventional ones [5]. Therefore, the role of satellite communication in applications related to emergencies is spreading over the years. For instance, situations of large-scale disasters are related to the destroyed infrastructure of communication, while the possible congestion and overload of the network because of increased demand are the common issues [6]. Therefore, disaster relief operations are more feasible by applying satellite communication networks [7].

HSTRN is a relaying technique that is adopted in order for the benefit of spatial diversity to be achieved and it is proposed as being an effective means of mitigating the masking effect and improving the satellites' communication reliability [8]. There have been multiple efforts that have been devoted to investigating the key performance measures of HSTRNs, for example, outage probability (OP), ergodic capacity, and bit error rate (BER) [9].

Even though Hybrid Satellite-Terrestrial Relay Networks are considered revolutionary driving forces on what concerns satellite communications in the modern era and they share unique features they tend to show a slower evolution than terrestrial wireless networks. It is evident that there is increased importance in using these networks for the seamless integration of terrestrial cellular and satellite communications as well [10].

1.2 Advantages of using HSTRN

Long-distance communication, customizable communication contexts, and a broad coverage area are just a few of the advantages that satellite communication networks have over traditional wireless communications [5]. As a result, they play a vital part in the ever-increasing number of emergency applications. This is especially crucial in the aftermath of large-scale disasters that disrupt communication infrastructure [6]. In terms of disaster relief activities, satellite communication is becoming more viable and important [7].

Years ago, during the early stages of 5G systems, HSTNs were proposed as a way to improve the performance of 5G networks. Several papers have highlighted the benefits of satellite-terrestrial systems, such as higher performance, improved QoS, expanded coverage, and increased diversity, for example. Synergies of different wireless communication systems and various access mechanisms have been established and proposed by many

HSTN implementations to increase QoS, coverage, and energy efficiency, for example.

Although mobile satellite networks are critical for disaster and risk management, the expenses of their operation and transmission capacity must not be overlooked. As a result, in disaster management zones, it is critical to construct a communication network that is robust, adaptable, and broadband [11]. Furthermore, when the user does not stand outdoors or the satellite elevation angles are low, conventional mobile satellite networks suffer from severe performance deterioration. As a result of this, several relaying methods are used to improve network coverage and dependability. The hybrid satellite-terrestrial relay network (HSTRN) is a form of network that eliminates the masking effect significantly [12].

The cooperation of different wireless systems and multi-interface access enable design and runtime optimizations that account for quality of service requirements, signal quality (coverage), and network conditions, making integrated satellite and terrestrial networks another key research topic for 5G. Satellite networks are viewed as a vital component of 5G networks due to their extensive coverage, energy efficiency, mobility support, backhauling capability, and central optimization capability. For 5G deployments, satellite networks will function in tandem with other emerging technologies like as device-to-device (D2D) communications, millimeter-wave (mm-wave) connectivity, and edge caching. To achieve the severe 5G criteria, these technologies will complement and exploit one another. As a result, hybrid satellite networks are seen as a cost-effective and efficient way to meet 5G needs.

HSTRNs combine the benefits of conventional satellite and terrestrial broadband networks. Extended transmission coverage, high data speeds without environmental limits, decreased cost, connectivity variety, rapid implementation, and easy network and bandwidth flexibility management are just a few of the benefits. It improves indoor coverage and maintains service availability, especially in heavily shadowed areas such as shopping malls, tunnels, and other places where users are unable to communicate with the satellite due to the masking effect. HSTRNs also deliver multimedia services, ensuring the quality of service criteria for mobile consumers via the standard cross-layer design of ITU-R S.2222 [13]. As a result, the establishment of HSTRNs helps to ensure public safety in disaster situations.

1.3 Challenges of using satellites in combination with terrestrial systems

Although satellite communications can provide our networks with a wide range of connectivity options, ubiquitous coverage, support and reliability for mobile users, lower costs and faster deployment, and other benefits, combining them with terrestrial systems can have significant drawbacks and problems. The mix of satellite and terrestrial systems creates a heterogeneous environment that necessitates network flexibility to meet QoE demands, signal quality (coverage), and network conditions. Combining satellite and terrestrial links necessitates multipath communication solutions capable of effectively distributing information across diverse links. However, providing multipath capabilities is insufficient to provide efficient content delivery to mobile consumers, as channel fading causes significant signal deterioration and corresponding packet losses.

Energy Management Satellite infrastructures as well as some IoT sensors cannot be connected to a power station, in contrast to devices on the ground that can be charged or connected to the power at any time. Solar and battery are the potential power sources of the current satellites (solar cells to absorb and convert solar energy, batteries to use saved energy when moving to dark areas). Because the entire time of a complete charge of battery cells is limited, increasing energy efficiency can extend the life and use time of satellites. As a result, energy management is a crucial and difficult problem for HSTN.

Network Control The amount of traffic created by various items linked to the network is exponentially expanding on current ground networks. The control approach of the HSTN is one of the most important factors that directly affect the network performance. Distributed management can considerably reduce reaction time and the likelihood of a bottleneck, yet cooperative device operation can increase network complexity. The centralized control method, on the other hand, can simplify the network structure, but the response delay will have an impact on the network's performance. Moreover, since the HSTN consists of heterogeneous networks, network integration has a substantial impact on QoE. The management of the HSTN is extremely tough and faces many difficulties due to the inherent heterogeneity as well as the great mobility.

Spectrum Management The quality of wireless communication is influenced by the propagation medium, as we all know (transmission medium is a system that can mediate the propagation of signals). Because the HSTN's propagation medium is distinct and far more diversified than from that of well-studied terrestrial communication systems, and because the high variation leads to rapid changes, spectrum management in the HSTN requires additional work. Moreover, despite the abundance of studies on this topic for ground networks, channel resource allocation remains one of the most critical aspects affecting network performance. Because the frequency bands are already congested, it is required to enhance spectrum efficiency in order to collect all satellites for packet transmissions. Internet service providers (ISPs) have considered sharing the same frequency bands for many different types of communications. However, the HSTN's intrinsic heterogeneity and rapid mobility make the problem more difficult, necessitating the use of more efficient solutions than those used in terrestrial networks.

Routing and Handover Management First, the main challenge as we have seen and before is the high mobility of the HSTN, which leads to uncertainties in the locations of the mobile users. This high mobility, in terms of all the heterogeneous components that consist a HSTN, results in frequent handovers and the implicit need of different handover schemes, to ensure seamless transmission and more. It's also worth noting the numerous obstacles that network security faces. Frequent handover makes secure routing more difficult to achieve, and the network becomes subject to jamming, which is difficult to remedy due to the broad coverage areas. HSTN has the difficulty of multipaths in addition to high mobility. There are various paths from the source to the destination since we have a multi-layer network. On the one hand, this can be exploited to meet a variety of service requirements, but on the other hand, many channels complicate routing techniques because each path must be evaluated in terms of packet loss rate, end-to-end delay, and so on.

It is also worth noticing that many studies and works have assumed the knowledge of perfect channel state information (CSI) to facilitate the user selection process. In practice, the CSI for user selection may be outdated due to various reasons such as feedback delay, mobility, etc. Further, with dense frequency reuse in wireless networks, the HSTRN is prone to co-channel interference (CCI).

2. RELATED WORKS

The growing applications for satellite communication networks have gotten a lot of interest from the research community. Because terrestrial mobile devices have a greater transmitting reach, these networks can be used in a variety of sectors, including navigation and broadcasting [14]. There are other challenges, including as connecting satellites to terrestrial users and transmitting over a limited line of sight (LOS). As a result, the main point of failure for these systems is the masking effect.

The investigation of the HSTRN is extensive. For instance, according to the studies of [15], [16] the performance of HSTRN is enhanced by using the amplify-and-forward (AF) relaying. In contrast, in studied of [17], the HSTRN is in relaying mode by applying the decode-and-forward (DF). In the study of [18], the combination of AF transmission mode and beamforming method in a model system for HSTRN was examined. [18] described the effect of the application of a network combining a cognitive hybrid satellite-terrestrial system permitting the operation of a pair between a primary satellite source and a receiver as well as a secondary pair of a transmitter and a receiver under the effect of useful hardware impairments (HIs). Scenarios of networks between satellite and terrestrial systems including the DF-based relaying 3D mobile unmanned aerial vehicle (UAV) were studied by [19]. For instance, the secrecy outage probability (SOP) and the probability of non-zero secrecy capacity (PNZSC) are described. The improvement of the HSTRN outage performance can be achieved by using a multi-relay selection (MRS) scheme [20].

Currently, the HSTRS is frequently used for the creation of integrated approaches by merging HSTRS with existing systems. For example, [21], [22] amplify-and-forward (AF) algorithms whose primary goal is to improve HSTRS performance. HSTRS has also investigated its performance when used in conjunction with the decode-and-forward (DF) relaying mode [4], [23].

Characteristic is the research that studied the impact of hardware imperfections on HSTRS, in which a geosynchronous earth orbit (GEO) satellite provides its extracted data to its destination on earth being assisted by DF-aided terrestrial relays. Those data derived the expressions of the outage performance. [24] investigates a HSTRS's delay-limited throughput in hybrid automatic repeat request (HARQ) mode. In the system model they described, in the event of an AF terrestrial relay, a satellite can connect with a user. They demonstrated the mathematical analysis for two situations, namely fixed gain AF relaying and channel state information (CSI)-assisted protocols [25]. [26] investigated a HSTRS in which a satellite is assisted by several DF three-dimensional (3-D) mobile unmanned aerial vehicle (UAV) relays in providing information to ground user equipment (UE). Furthermore, in a hybrid satellite and free-space optical (FSO) cooperative system, the security performance at the physical layer is studied in [27]. For both AF and DF relaying, this study presented explicit analytical formulas as well as asymptotic analysis for average secrecy capacity and secrecy outage probability (SOP). Nonetheless, the studies conducted by [4], [23], and [28] only considered hybrid terrestrial-satellite networks used in classic cellular networks. It should be remembered that such systems are intrinsically inefficient due to the inefficient use of massive connections and higher coverage areas.

To surpass the difficulties referred, the non-orthogonal multiple access (NOMA) techniques have recently been proposed and implemented to HSTRS [29], [30] [31]). To begin, NOMA systems were investigated [29], [30] in order to allow different users to access the same source, such as the frequency, time, space, or code domain. The vast connectivity, great spectrum efficiency, and low delay appear to be the other advantages of NOMA.

Consider the desirable attributes of NOMA, such as fairness and spectrum efficiency, which can be met through cognitive radio transmission[29]. The security and reliability of ambient backscatter (AmBC) NOMA systems, where the base station can deliver information to two NOMA users while an eavesdropper still hears the main signal, are explored in [32]. The advantages of unmanned aerial vehicles (UAVs) have been discovered in UAV-NOMA [31]. To be more specific, many terrestrial users have as a goal in multi-way relaying NOMA networks to transmit their mutual signals by enabling AF-aided UAV relay. [31] also took into account the real-world scenario of residual hardware impairments (RHIs) at the transceivers. Later in the thesis, NOMA's extended works are discussed.

3. NOMA NETWORK SYSTEMS

Simultaneously, non-orthogonal multiple access (NOMA) technologies are used to increase the spectral efficiency of wireless networks [33]. Combining cognitive radio and NOMA approaches, for example, improves spectrum efficiency [34]. Despite the fact that NOMA approaches have not been fully explored in HSTRNs, NOMA-enabled HSTRNs can achieve significant improvements. NOMA also improves user fairness by allowing diverse users to experience services of similar quality. One important advantage of NOMA methods is the use of the architecture of the existing network without critical modifications [35]. Because of the benefits of NOMA-enabled HSTRNs, researchers are able to test the network's limits and find performance variances under various conditions.

[36] was the first to investigate the possibilities of NOMA in a 5G network, and the authors determined that NOMA is superior to orthogonal multiple access (OMA) in terms of transmission capacity and user fairness. In 5G networks, NOMA approaches improve the effectiveness of the communication spectrum [37]. The basic approach of NOMA techniques is the possibility of transmission of data in the identical frequency band and at the same time slot by users, and the distinction of data sent to various users through particular levels of transmission power. The power domain multiplexing NOMA offers more advantages since it allows multiple users to experience the resources of the spectrum and the application of successive interference cancelation (SIC) method to detect multi-user. Although the receiver's complexity is increased, NOMA's usage of the communication system's frequency spectrum is substantially better than OMA's.

The base station sends two superimposed user signals, as seen in Figure 3.1. Device 2 in a NOMA communication system has a link gain that is larger than that of device 1. Through downlink NOMA, users with poor link gain or good link gain tolerate higher or lower transmit power, respectively. According to the successive interference cancellation (SIC) technique, the user's signal with the highest transmitting power is decoded first, followed by the next most effective signal, and so on until all of the user's signals have been divided. The research on NOMA techniques related to various application scenarios is extended in [39].

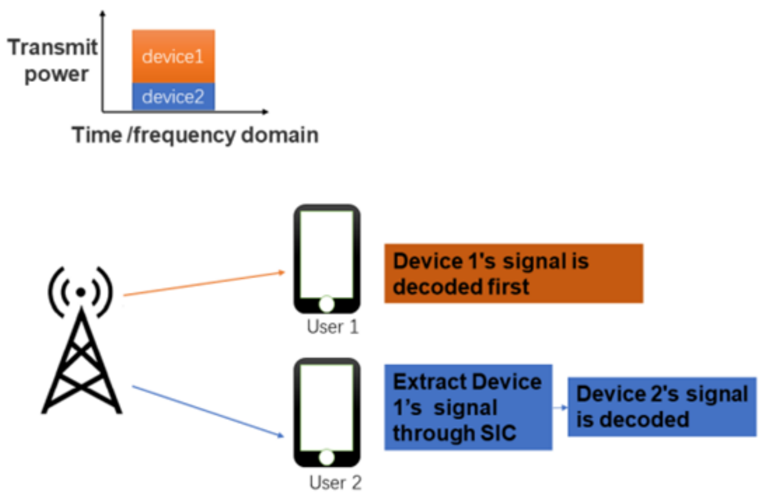

Figure 3.1: Procedure of network of a downlink NOMA associated with two users [39].

3.1 NOMA-based network system

In the fifth-generation (5G) wireless system, the efficiency of spectrum has recently been improved by introducing NOMA for multiple access applications. NOMA is viewed as a significant candidate technology for future fifth generation and beyond (5G) standards due to its appealing spectral efficiency gains and enhanced connectivity. Furthermore, NOMA promises to reduce latency, which is a fundamental goal of future networks, thanks to simultaneous spectrum access. One of the most common ways to implement NOMA is through power domain NOMA, in which users are separated inside the power domain by the transmitters' strategic power allocation in order to manage user interference.

Multiple users can be served by identical resources at the same time and through the same power domain or frequency thanks to NOMA. The transmitter, in particular, is subjected to the superpositioning signal from numerous users, while successive interference cancellation (SIC) is used at the receivers, which is required to divide the mixed signals in the domain of power [38]. [30] investigated the coupling of NOMA and a cooperative network architecture, resulting in C-NOMA, a NOMA scheme that is promoted in NOMA-based cellular networks with many users. The main notion is that in this network, users with poor channel conditions are aided by relays, while users with good ones perform as such relays.

Let's take a step back and take it one at a time. Because of the inherent benefits of cooperative relaying schemes in terms of coverage extension and dependability, the usage of NOMA in cooperative 5G deployment scenarios has recently gotten a lot of attention. A relay node in a cooperative relaying network aids communication between a source and a destination by exploiting spatial diversity to improve transmission range or reliability. Two main protocols are widely known in terms of relay behavior: decode-and-forward (DF), in which the relay decodes and re-encodes the information signal before forwarding it; and amplify-and-forward (AF), in which the relay simply amplifies the received signal from the source and forwards it to the destination [40].

Because the terrestrial and satellite networks would interfere with one another, the capacity performance of the terrestrial and satellite networks is evaluated independently in HSTN, which can be decomposed into the designing of beamforming vectors and the power allocation schemes. While terrestrial networks offer high bandwidth at a low cost, satellite networks offer the finest and most extensive coverage for those who are not covered by BSs. With multiple antennas, beamforming will be executed among groups and among satellite users. The optimization problem for system capacity performance is then broken into three sections based on the framework: the paring scheme, the terrestrial resource allocation scheme, and the satellite resource allocation scheme. NOMA integrations are extremely beneficial in any satellite-terrestrial system because of these three components.

The combined use of NOMA and cooperative communications, whose contributions can be classified into two categories: (i) cooperative NOMA, in which NOMA users with good channel conditions, referred to as near or strong users, act as relays to assist NOMA users with poor channel conditions, referred to as far or weak users; and (ii) relay-aided NOMA transmission, in which one or more dedicated relays assist NOMA users in communicating with one another.. Based on the aforementioned three main concerns when integrating a satellite-terrestrial system, researchers have made quite the leaps in the NOMA-based HSTRS integrations.

In [41], the authors used a user with a better channel condition as a relay node, which sends signals to other users, reducing the masking impact of users with poor channel conditions in heavy shadowing. The authors introduced NOMA to cognitive radio-based HSTRNs in [42] and [43], which allows spectrum sharing in the underlay mode. Spectrum sharing (particularly in the form of cognitive radios, which allow equipment to dynamically access the spectrum by adopting agile and adaptive medium access) has been a major research focus for next-generation wireless networks in order to deal with spectrum scarcity (or underutilization). There have been proposals for a coordinated transmission strategy for deployment scenarios with a base station having a direct link to one user while simultaneously communicating with another user through a relay, both in half-duplex and full-duplex mode, where NOMA was used to enable receivers to acquire other user's information for interference cancellation [44][45]. The performance of an underlay cognitive hybrid satellite-terrestrial network with a primary satellite transmitter and a corresponding terrestrial receiver was evaluated by the authors in [19], while the secondary transmitter (ST) communicated with its paired users on the ground. Users are sorted depending on their quality of service (QoS) requirements using two-stage DF and AF relaying techniques. The DF protocol is used to evaluate two optimal relay selection techniques for cooperative NOMA with fixed and adjustable power allocations at the relay nodes [46]. Because FD relaying has been thoroughly addressed in OMA-based cooperative networks, and just a few works have dealt FD in cooperative relaying networks based on NOMA, many works focused on HD-based relaying scenarios. Many scenarios for combining NOMA and cooperative communications based on FD relaying techniques have yet to be investigated. [48] shows a detailed performance analysis of NOMA-enabled HSTRNs that use energy harvesting relays in both the AF and DF models.

The common assumptions in NOMA-based networks researches consider the channel status information (CSI) to be completely known. However, practically the CSI of communication system is hard to be known. The channel estimation error has an impact on the system's performance. As a result, determining the optimal parameters of NOMA-based network systems with inadequate CSI is crucial. [59] suggested that the power for the transmission signals is increased than the one for the collection of data by IoT devices. The minimization of the power consumption of IoT devices is attributed to the fact that mobiles used their battery for power during data transmission prolonging the device life cycle.

The study in [47] is another important work on HSTRN in combination with NOMA. An HSTN comprising of a low earth orbit (LEO) satellite belonging to a LEO constellation, a terrestrial base station (BS), and numerous terrestrial mobile terminals is shown and integrated with a combined NOMA-NC (NNC) scheme (MTs). HST-NNC (Hybrid satellite terrestrial-NNC) is a proposed technique that allows pairs of users to be serviced simultaneously through NOMA via the terrestrial BS link and the satellite link. Furthermore, within the general framework of systematic network coding (SNC), the satellite uses random linear network coding (RLNC) to improve the reception of the MTs when errors occur. In comparison to standalone NOMA, the proposed HST-NNC requires no additional channel state information (CSI) overheads because the satellite only need the indices of user pairs to perform RLNC.

4. DF & AF MODELS

In wireless communications, cooperative diversity has emerged as a viable strategy to prevent fading [49][50]. It is based on the wireless medium's broadcast nature and allows single-antenna users to "enjoy" space diversity benefits by sharing their physical resources via a virtual transmit and/or receive antenna array. In order to improve communication between the source and the destination, the basic relay channel model consists of three terminals: a source that transmits information, a destination that receives information, and a relay that both receives and transmits information. Models with many relays, which can be thought of as an extension of this fundamental structure, have also been investigated [51], [52], [53], [54]. A number of relaying protocols have been developed in the literature [55], [56], [51] since the work of [49],[50], which established the concept of cooperative diversity. Decode-and-Forward (DF) and Amplify-and-Forward (AF) schemes are the two most common types (there is also the compress-and-forward strategy which allows the relay station to compress the received signal from the source node and forward it to the destination without decoding the signal where Wyner-Ziv coding can be used for optimal compression, which method is not used for our purposes).

The relay decodes the received source message, re-encodes it, and sends the resultant signal to the destination in the DF schemes. In AF schemes, on the other hand, the relays simply amplify and transmit the received signal without any further signal processing in the analogue domain. Amplification can be thought of as multiplication with an amplification factor that normalizes the received power. Because it does not require a decoding procedure at the relays, AF appears to be a low-complexity solution for practical ad-hoc networks with crucial power constraints. In addition to the benefits of complexity, [55], [57] have shown that AF asymptotically approaches the DF scheme in terms of diversity performance. Furthermore, in some cases avoiding decoding the signal at the relay nodes actually prevents propagation of decoding errors at the relay [54].

Transparent satellites are well-known in satellite mobile communication systems for using AF relaying. Transparent satellites are often employed in practice due to their simple circuitry, whereas decode-and-forward (DF) relaying-based satellites or on-board processing satellites require complex circuitry. When compared to AF-based satellites, DF-based satellites are significantly heavier. Because DF-based satellites require more processing at the satellite terminal, they may require more power, resulting in a heavier and more expensive satellite system than AF-based satellites. Many early studies on HSTRN's with amplify-and-forward (AF) [21],[22],[28] and decode-and-forward (DF) relaying modes [4],[28], have their corresponding performance evaluations and more current studies chose the relaying technique based on the technology they are pairing it with and not those performances. For example, in [58], writers looked into the effects of HIs on HSTRS, a system in which GEO delivers data to a DF relay. The delay-limited throughput of a HSTRS in HARQ mode is evaluated in [24] with the help of an AF terrestrial relay. All of these studies, however, used HSTS in a standard cellular network, which has poor performance due to inefficient use of enormous connections and a larger coverage area. These are the types of issues that the deployment of NOMA with HSTRS addresses.

5. THE FUTURE POTENTIAL USE OF HSTRN

The extant research has only looked at scenarios with fixed or constant transmission power schemes. In recent years, software-defined networking (SDN) and network virtualization (NV) have gained popularity as prospective applications for improving the manageability and adaptability of future 5G-6G and satellite integration. This leads to a paradigm shift by introducing flexible onboard processing. The network can supply resources that can be assigned adaptively / flexibly to changing channel circumstances, resulting in efficient resource configuration and management. New hardware with more capable architectures, material advances, complex microelectromechanical systems, and signal processing/physical layer (PHY) algorithms for adaptive operation is opening new possibilities for spectrum sharing and content-driven services. The joint design of spectrum sharing and content-centric operations is crucial because it can boost content delivery and spectral efficiency.

Therefore, there are some critical decisions to make if networks and radios are to provide efficiency. These range from the most basic, such as determining a channel's occupancy, to the more advanced and complex traffic analysis for utilizing the spatial peculiarities of spectrum occupancy and content availability. Cooperation through intersatellite links for transferring spectrum-occupancy information, stored data, and metadata caching can help enhance system performance. In addition, better environmental awareness is essential in the terrestrial sector, necessitating collaboration across terrestrial infrastructures.

D2D communications is another study area that satellites can help with on a large scale (beam level) and a small scale (cell level). Beam adaptation mechanisms for the position, size, and transmission parameters are still in progress, but they can undoubtedly improve satellite terminal SINR, spectrum interference detection, and many D2D mechanisms. Finally, various efforts on caching in 5G hybrid satellite networks exist, such as hierarchical caching substrates and cooperative cache management. Caching close to the user can improve the delivery of popular material (for example, by reducing delivery time) while also reducing network resource requirements (for example, bandwidth and server load).

HSTRN is expected to support a flexible and customizable adaptive transmission with power and speed adjustment for machine-type mass communication (mMTC) and high-quality multimedia requests. With the aforementioned features always present, wider global coverage, higher capacity, and lower capacity energy consumption are the results. However, no previous research on the performance of adaptive transmissions on HSTRN has been done.

6. CONCLUSIONS

Hybrid Satellite Terrestrial Relay Systems were examined in this thesis. It has been demonstrated that integrating satellite segments into terrestrial wireless networks makes it easier to provide large connectivity to coexisting users and devices. We've explored the advantages and problems of integrating HSTRS in our era of continually demanding requirements since the early adaptations of HSTS, and we've detailed the various benefits of integrated power domain NOMA in this type of system. In terms of wireless resource usage, efficient non-orthogonal multiple access can provide fairness and system capacity, as well as expanded coverage and spectrum efficiency. In order to comprehend the essential core of relay systems, this thesis also discusses both AF and DF models. The use of NOMA schemes, which have the potential to deliver ”anytime-anywhere” connectivity in very efficient ways with enhanced spectral efficiency, system capacity, and coverage, provides a fruitful research field for Integrated Satellite-Terrestrial Relay Networks.

APPENDIX A. FURTHER RESEARCH ON NOMA TECHNIQUES

Due to the rapidly increasing demand for higher data rates, more connected users and devices, and diversity of deployments, Non-orthogonal multiple access (NOMA) is one of the promising radio access techniques for performance enhancement in current-and-next generation (5G-6G) cellular communications.

The NOMA scheme allows the simultaneous serving of all users by using the entire system bandwidth (BW) to transmit data. There are different types of NOMA techniques, including power-domain and code-domain but we focus on power-domain NOMA (PD-NOMA). PD-NOMA is a technique in which multiple users' signals are multiplexed in a single sub-carrier using superposition coding (SC) at the transmitter side and further at the receiver side Successive Interference Cancellation (SIC) is carried out to retrieve the individual users' signals.

In Superposition coding, each of the users is allocated a power level based on the distance from the transmitter, by allocating a fraction a_i of the total power to each U_i, the power allocated for the i_{th} user is $P_i = a_i \cdot P$ (and so on for each User). Superposition coding is a fancy term for power domain multiplexing. To superpose means to add. Let's say that we have two Users, U_1 and U_2. Let x_1 be the user's 1 data and x_2 be the user's 2 data accordingly. For simplicity, we assume BPSK (Binary phase-shift keying) modulation for both Users, so x_1 and x_2 have peak amplitude at ± 1. We know that $amplitude^2 = power$ and we get that they both have $P = 1W$. So for superposition, we just have to add x_1 and x_2. But before the addition, we have to multiply each signal with their power level. We assume a fixed power allocation scheme where the factor $a_1 = 0.8$ and $a_2 = 0.2$ $(a_1 + a_2 = 1)$ has these fixed values. We will later present another power allocation scheme where we optimize a_1 and a_2 dynamically. As a_1 is bigger than a_2, we understand that U_1 is further from the Base Station than U_2, so we have to allocate more power to him (hence $a_1 > a_2$ and an example of user fairness in NOMA). We multiply x_1 with $\sqrt{a_1}$ and x_2 with $\sqrt{a_2}$ respectively and so we get the scaled data of $U_1 : x_1 \cdot \sqrt{a_1}$ and $U_2 : x_2 \cdot \sqrt{a_2}$. We add them and the resulting signal is the superposition coded signal:

$$x = x_1 \cdot \sqrt{a_1} + x_2 \cdot \sqrt{a_2} \tag{A.1}$$

x is a linear combination of x_1 and x_2 and the superposition coded NOMA signal that is transmitted into the channel.

On the receiver side, SIC decodes each of the users' signals separately by detecting the strongest signal first and considering all the other signals as noise (U_i can decode the signals for each U_m with $m < i$). The signals for weaker users are then subtracted from the received signal to decode the signal of user U_i, itself treating the signals of the stronger users (U_m, with $m > i$) as interference, termed as "intra-cell interference" or "intra-cluster interference". To explain it better, we are going to continue with our previous example. We have x, the linear combination of x_1 and x_2 received by U_1 and U_2. First, we decode x by directly performing BPSK demodulation on it. That way we detect the strongest signal (that which has been allocated with higher power-weight) x_1. We get the BPSK modulated version of x_1, multiply it with $\sqrt{a_1}$ and subtract it from the received signal. Now we decode the remaining $x_2 \cdot \sqrt{a_2}$, itself treating the signal of stronger users as interference (we have none here), by directly performing BPSK demodulation as before. We arrive at a demodulated signal which is x_2. This concludes our process of multiplexing two separate data in the power domain and successfully recovering them under the assumption of Perfect SIC and no channel noise effects. These conditions are practically impossible to meet, but they help with the example. By imperfect SIC, we mean that a residue of the x_1 component is still present in x_2 after SIC and that residue can affect the achievable rate of NOMA. Imperfect SIC is measured by term SIC error and as SIC error increases, the achievable rate degrades.

To continue our work on NOMA though, we mustn't work on an ideal channel case scenario. As known, wireless channels are prone to multipath propagation and fading. Several channel models are available to capture the effects of fading. One such model is the Rayleigh fading model. Rayleigh fading model can be used when there is no line of sight (LOS) path between the transmitter and the receiver. In other words, all multipath components have undergone small-scale fading effects like reflection, scattering, diffraction, shadowing, etc. For our work, we assume that every bit undergoes a different attenuation and phase shift due to multipath transmission, so the Rayleigh fading coefficient (h) is constantly changing. Furthermore, we also must consider the noise parameter in our signals, produced by a basic and generally accepted noise model, AWGN. Additive white Gaussian noise (AWGN) is a noise model used in information theory to mimic the effect of many random processes that occur in nature. With these in mind let's continue to our system model and our simulation's results and findings.

SYSTEM MODEL

We consider a cellular downlink transmission scenario, in which the base station is located at the center of a disc, denoted by B, with radius R_d, and N users (U_i, with $i \in \mathrm{N} = \{1, \ldots, N\}$), uniformly distributed within the disc. All terminals are equipped with a single antenna. The base station has always data to transmit for each user and its total available transmitted power is equal to P_t. All wireless links exhibit independent and identically distributed (i.i.d.) block Rayleigh fading and additive white Gaussian noise (AWGN). This means that the fading coefficient h_i (for the $B \to U_i$ link) remain constant during one slot, but change independently from one slot to another according to a complex Gaussian distribution with zero mean ($\mu = 0$) and variance σ_h^2, the variance captures path-loss and shadowing effects. Without loss of generality, the channels are sorted as $0 < |h_1|^2 \leq |h_2|^2 \leq \cdots \leq |h_{th}|^2 \leq \cdots \leq |h_N|^2$, the -th user always holds the -th weakest instantaneous channel. The AWGN is assumed to be normalized with zero mean ($\mu = 0$) and variance σ_n^2. Our model is in Figure **A.1** (center-dot is the BS, green-dot is a user).

According to the NOMA protocol, the base station will send

$$\sum_{i=1}^{N} \sqrt{a_i P_t} x_i \tag{A.2}$$

where x_i is the message for the i_{th} user, P_t is the available transmit power and a_i is the power allocation coefficient of the i_{th} user. The received signal at user U_i can be represented as

$$\begin{aligned} y_i &= h_i x + n_i \\ y_i &= h_i \sum_{m=1}^{N} \sqrt{a_m P_t} x_m + n_i \end{aligned} \tag{A.3}$$

If signal superposition at the BS, and SIC at U_i, is carried out perfectly, the achievable data rate for user U_i for $1Hz$ system BW is given by :

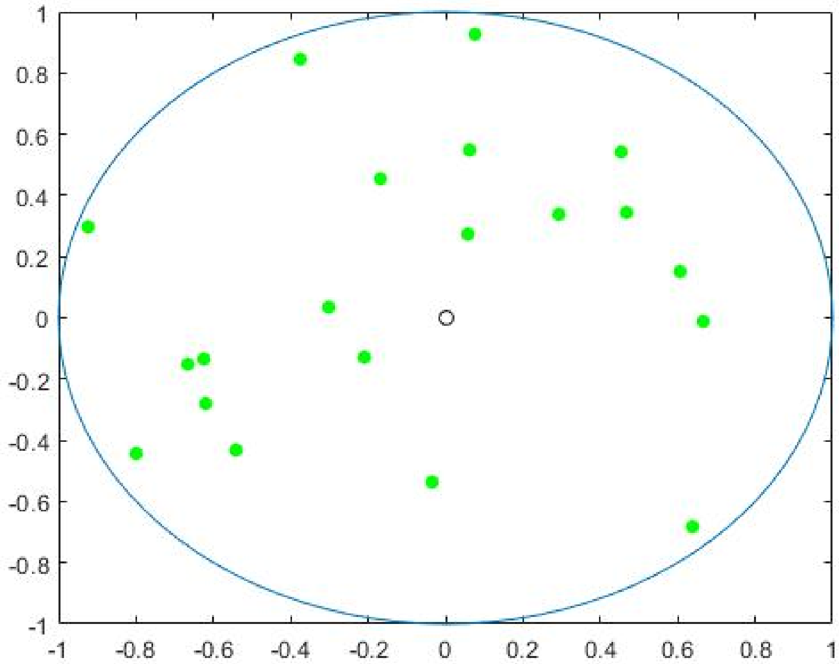

Figure A.1: A visual presentation of our model with N = 20 users.

$$R_i = \log_2\left(1 + \frac{a_i P_t |h_i|^2}{P_t |h_i|^2 \sum_{m=i+1}^{N} a_m + \sigma_n^2}\right) \tag{A.4}$$

With **A.4** and the achievable rate for the i_{th} OMA user [$R_i = \frac{1}{N}\log_2(1 + \frac{P_t|h_i|^2}{\sigma^2})$] we observe that the boundary of achievable rate pairs with NOMA is outside the OMA capacity region and so NOMA can outperform OMA by offering high capacity, as shown in A.2.

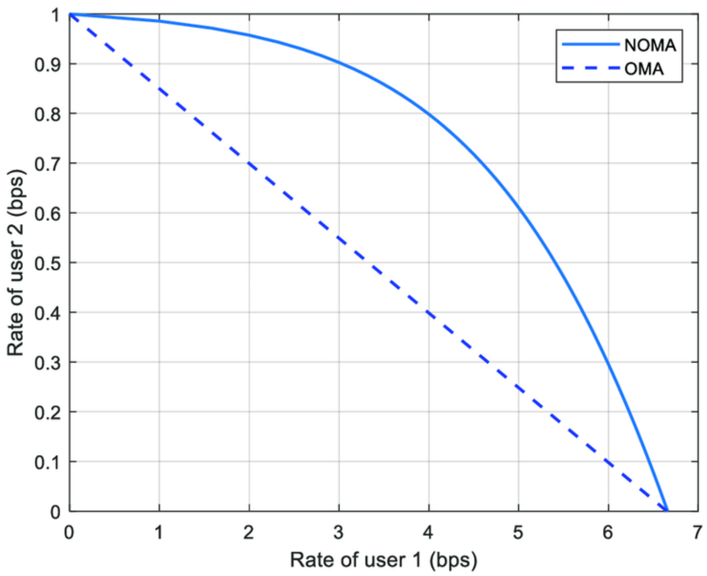

Figure A.2: Data rate comparison between OMA and NOMA.

OMA schemes like TDMA, FDMA, CDMA, OFDMA, separate the users in time, frequency, code, and subcarrier domains respectively. No two or more users are allowed to share the same resources simultaneously, as interference would occur and the users would lose data. This is the limitation and the condition that NOMA breaks by allowing simultaneous transmission of multiple users in the same frequency carrier while dealing with the interference with SIC. Let's think of our N users. The channels are sorted as $0 < |h_1|^2 \leq |h_2|^2 \leq \cdots \leq |h_{th}|^2 \leq \cdots \leq |h_N|^2$ as previously said. At the receiver side the weakest user, U_1, will perform direct decoding. In U_2's signal, as U_1 is dominating, U_2 has to perform SIC to estimate U_1's data and subtract it from the signal received. Then U_2 can perform direct decoding. In U_3's signal, U_3 must perform SIC to remove U_1 and U_2 data before decoding its own signal. U_4 must do the same for U_3, U_2, U_1. U_5 for $U_4, \ldots, U_1$ etc. So for our N users in the same carrier, as the interference between the users increases, the N_{th} user must perform SIC, $N-1$ times to retrieve the signal, leading to high processing delay. Other than processing delay, due to the high complexity of the many users in the same carrier, our system becomes more vulnerable to SIC error propagation because if any of the user's data is decoded in error then the whole SIC process goes wrong. As we examine it further, SIC is a technique needed to subtract any interference but as we use it for more and more users we introduce to our system other difficulties that may decrease our system performance.

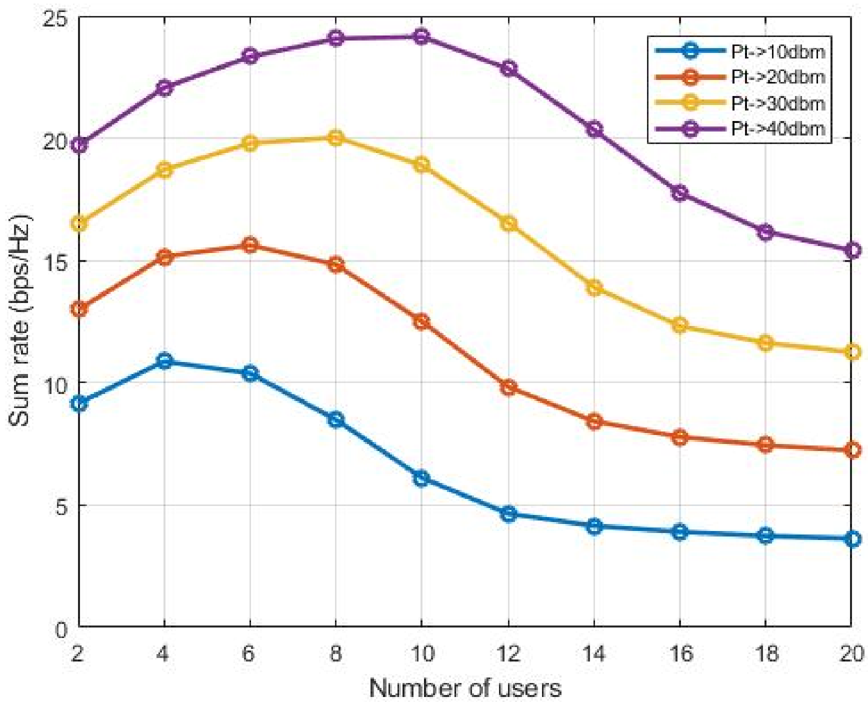

Figure A.3: Sum rate in terms of different number of users in the same carrier.

In Figure **A.3** we have plotted the achievable data rates of a single carrier NOMA network by varying the number of multiplexed users in the carrier. Just by looking at it, we observe that in all 4 variations there is a drop-off point beyond which the capacity falls. These drop-off points give us the maximum number of users we can multiplex in the same carrier, regarding the transmit power, without degrading the system performance. The number of users we can multiplex without degradation is increasing as the transmit power is also increasing. Thus, to accommodate more users without performance degradation, we must increase the transmit power. But more transmit power won't help us that much because SIC complexity and error propagation still harass our system performance the more users we multiplex. To avoid such limitations in the number of users in the same carrier, we can go for techniques like hybrid NOMA. Hybrid NOMA is a combination of NOMA and any OMA technique. A very typical implementation of Hybrid NOMA is NOMA with TDMA characteristics, which by dividing each available orthogonal resource and assigning each divided part of the resource to a pair of NOMA users, we manage to serve all users and reduce complexity compared to using Single Carrier NOMA or TDMA. For the pairing of NOMA users, we are using the N-F pairing technique, where we pair a near and a far user. The nearest one is paired with the farthest, the next nearest user is paired with the next farthest one, and so on. The achievable rates of its pair is determined by:

$$R_{nearuser} = \frac{2}{N} \log_2 \left(1 + \frac{P_t a_{near} |h_{near}|^2}{\sigma^2}\right) \tag{A.5}$$

$$R_{faruser} = \frac{2}{N} \log_2 \left(1 + \frac{P_t a_{far} |h_{far}|^2}{P_t a_{near} |h_{far}|^2 + \sigma^2}\right) \tag{A.6}$$

The whole sum (achievable rate) of the N-F user pairing scheme will be this :

$$R_{near-far} = \sum_{1}^{N} R_i \tag{A.7}$$

The near-far technique is genuinely better than any other pairing technique as it is based on the fact that NOMA performs better the more distinct the channel conditions between the two users are. We can also see that in the case of SC-NOMA as we already have discussed, its performance is pretty good, but the users' overloading in the same carrier creates a lot of interference issues (for 20 users and this distances, SC-NOMA can hardly do any good to our system perfomance). In Figure **A.4** and **A.5** we can see plotted all the aforementioned findings and see the much larger achievable sum rate we get with the N-F user pairing Hybrid NOMA technique. I present the same plot for different scales in the distances. We either have $R_d = 1000m$ or $R_d = 10000m$. The difference in NOMA's performance is obvious, as the channel conditions are more distinct the bigger the R_d is.

A very important factor to the overall performance of NOMA and its techniques is the fair use of power allocation. Up until now, we have only used fixed power allocation to simulate our prementioned techniques, and certainly, this is something that may not be seen at once but a dynamic power allocation technique should have shown us even better results in terms of sum rate, outage probability, etc. Although we need no knowledge of CSI and it is not computationally complex to use fixed power allocation it is not the optimum way to allocate power between users. In our system model, we should take advantage of the perfect CSI and so based on that we can dynamically optimize the values of the power allocation factor α. Another thing to consider is that as we increase N, the number of total users, the far user's target data rate is even more difficult to be met. So, we propose a fair power allocation technique that derives the power allocation coefficients (α_i) driven by the target data rate of the far users. That's why we call it fair power allocation technique (modified version of technique shown in "The impact of power allocation on cooperative non-orthogonal multiple access with SWIPT", Z. Yang, Z. Ding, P. Fan and N. Al-Dhahir, IEEE transactions on wireless communications, vol.6, no.7, July 2017).

From equations **A.5** and **A.6** we can see that a_{near} and a_{far}, if set to the right values, they can achieve the desired data rates of the far user and of course, same goes and for the

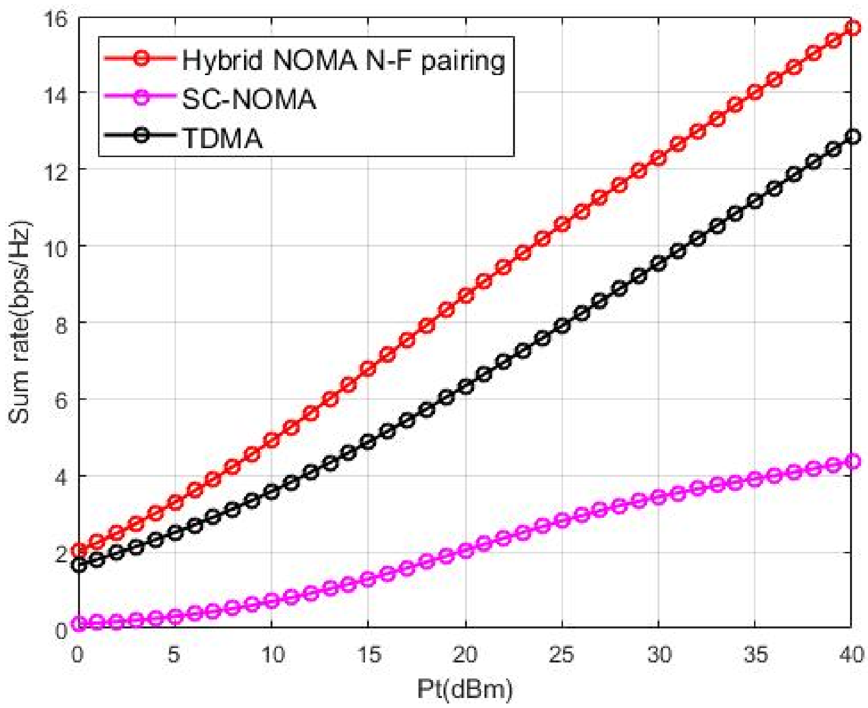

Figure A.4: Sum rate in terms of different P_t with $R_d = 1000m$ (NF technique).

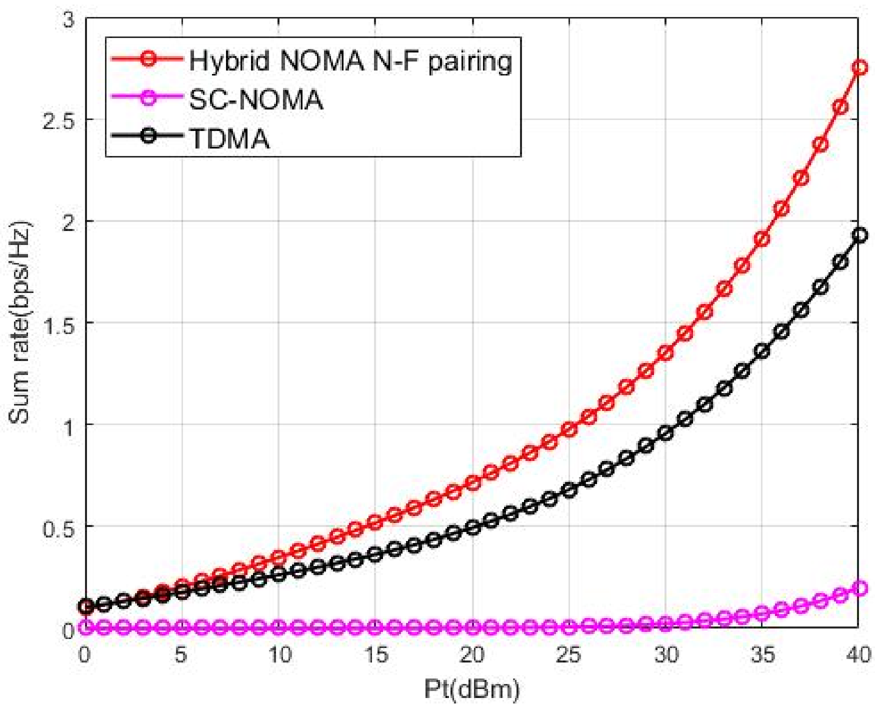

Figure A.5: Sum rate in terms of different P_t with $R_d = 10000m$ (NF technique).

near user. Our main goal is that we meet the target rate of the far user and after meeting that data rate, we can freely allocate the whole power to the near user (will explain later). Let's denote R^* the far user's data rate. As R^* increases so do the outage probability of the far user, and that is something expected to happen as the higher the target data rate the lower the possibility of achieving the desired data rate. By setting R^* = R_{far} we are concluding to the following:

$$a_{far} = (2^{R^*} - 1)\left(\frac{|h_{far}|^2 P_t + \sigma^2)}{|h_{far}|^2 P_t 2^{R^*}}\right) \tag{A.8}$$

If a_{far} exceeds 1 we just set its value to 1 because as well known a_{near} + $a_{far} = 1$. But thinking of it again, we see that if a_{far} is equal to 1 then a_{near} will be 0. This will lead to something unwanted because the near user will be in outage while we allocate the whole power to the far user in order not to go in outage. To avoid this scenario we just have to add an if statement to our whole procedure. If a_{far} goes beyond the value of 1 we set it back to 0 and allocate all the power to our near user (a_{near} = 1). If a_{far} exceeds 1 we can't bring him out of outage so we don't have to allocate any power to him anymore and that's why we allocate our whole transmit power to the near user. This exact finding is visible by simulating the outage probability by varying the different far & near user's data rate (we have to set the R^*_{near} and R^*_{far} to the same values in order to simulate the outage probability). The same goes for the value of the transmit power P_t. All the aforementioned are in figure **A.6**.

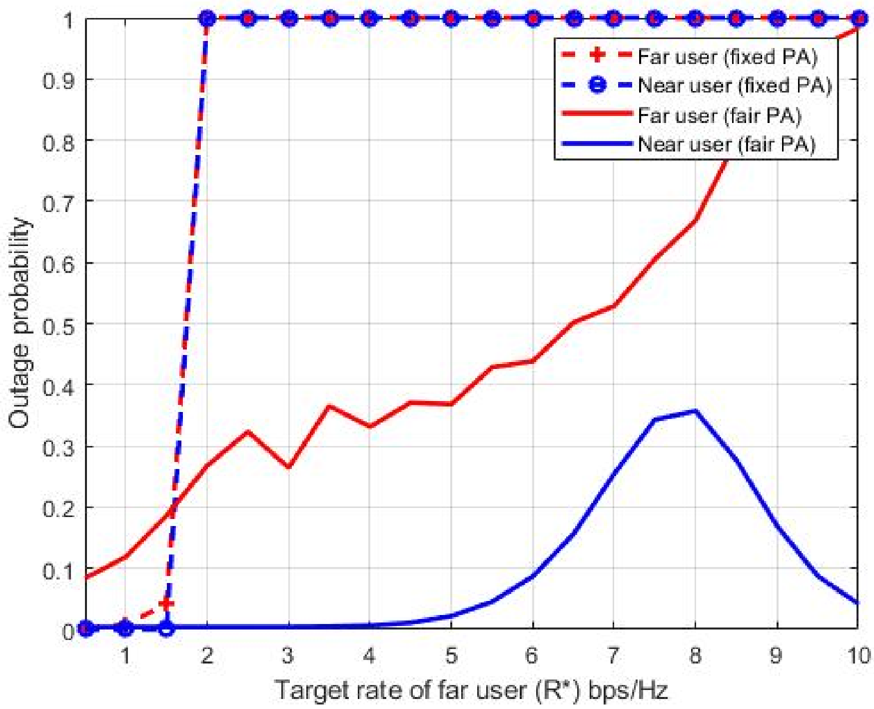

Figure A.6: Outage Probability in terms of the far user's target data rate.

As clearly, we see the moment where a_{far} goes beyond 1. It is where the outage probability of the near user goes from increasing to decreasing. It is the moment where we understand that is inevitable for the far user to reach outage and we want to “save” the near user by allocating him full transmit power.

It is a fact that wireless channels are dynamic, and fixed power allocation goes against this nature. What-ever the CSI, a_{far} and a_{near} remain constant. That's why dynamic power allocation and more specific our fair model can achieve lower outage and significantly higher achievable rate than fixed power allocation schemes. Simulations about the difference in achievable rate are also made and are being demonstrated below. For this, we also have 2 different plots to show as we change the scale of the distances. As $R_d = 1000m$, in figure **A.7** we observe that fair PA and fixed PA are having a very similar behavior as we increase the transmit power. If we make $R_d = 10000m$, in figure **A.8** we observe that with dynamic power allocation we achieve higher rates than fixed power allocation but we will need more P_t, to achieve the same sum rate.

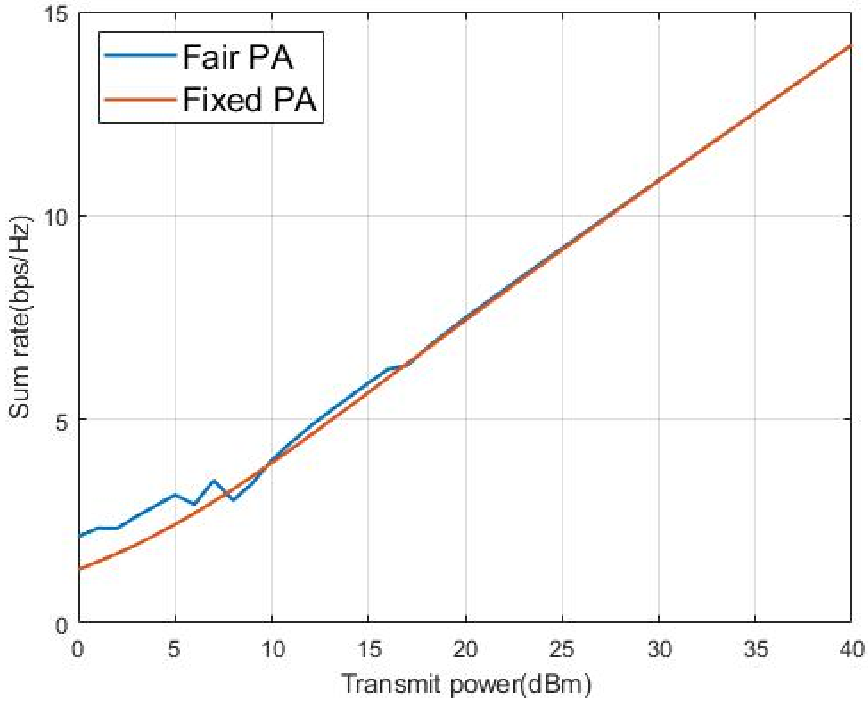

Figure A.7: Sum Rate in terms of P_t . Fair PA vs Fixed PA with $R_d = 1000m$.

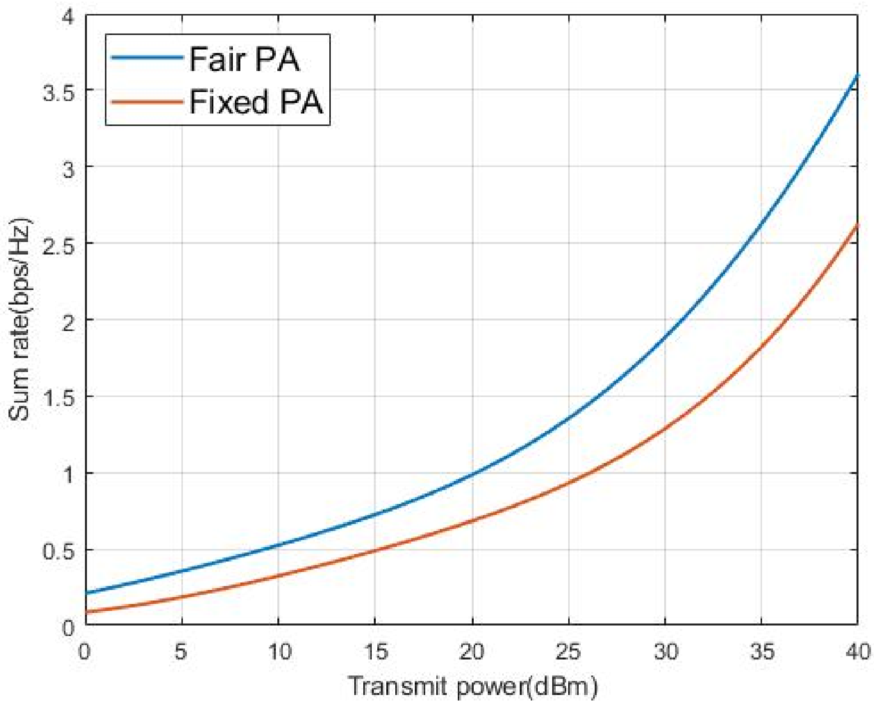

Figure A.8: Sum Rate in terms of P_t . Fair PA vs Fixed PA with $R_d = 10000m$.

To be more clear of the advantages of our Fair Power Allocation technique, we have also these two Figures. In Figure **A.9** we can't see that improvement, but in Figure **A.10** the implementation of Fair PA with N-F pairing achieves even higher rates than all the other techniques (the more distant the better).

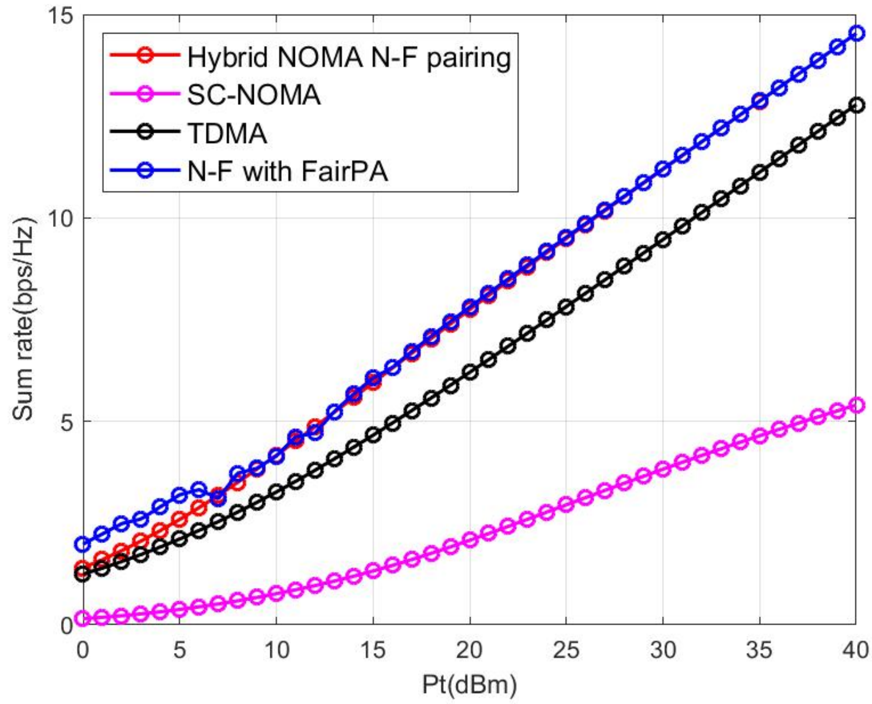

Figure A.9: Sum rate in terms of P_t with $R_d = 1000m$ (NF technique with Fair PA).

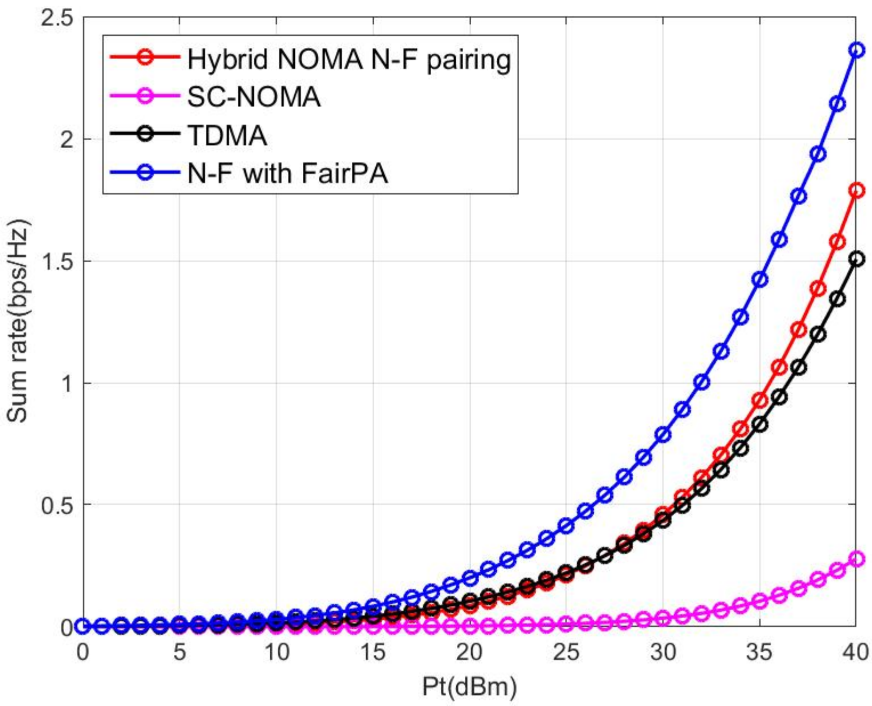

Figure A.10: Sum rate in terms of P_t with $R_d = 10000m$ (NF technique with Fair PA).

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