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BEAMFORMING AND NON-ORTHOGONAL MULTIPLE ACCESS FOR RATE AND SECRECY ENHANCEMENT OF FIFTH GENERATION COMMUNICATION SYSTEM

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DEDICATION

Traveller there is no path,
The path forms itself as you walk it.
Antonio Machado

This thesis is dedicated

To the memories of my parents,
who always supported me, whatever path I took.

To my paths companion, who has always been there for me,
I am what I am because of your support, sacrifices, and encouragement,
my wife Rola.

To my angle, to the cause, and the destiny of each path I take,
you have made me stronger, better and more fulfilled than I could have ever imagined,
my daughter Perla.

To my wounded country, I hope that our paths will cross again,
my Syria.

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ABSTRACT

The fifth-generation (5G) communication systems have many anticipated functionalities and requirements such as high data rate, massive connectivity, wide coverage area, low latency and enhanced secrecy performance. In order to meet these criteria, communication schemes that combine 5G key enabling technologies need to be investigated. In this thesis, a novel communication system that merges non-orthogonal multiple access (NOMA), energy harvesting, beamforming, and full-duplex (FD) techniques in order to enhance both capacity and secrecy of 5G system is introduced. In the capacity improving scheme, NOMA is first combined with beamforming to serve more than one user in each beamforming vector. Next, simultaneous wireless information and power transfer (SWIPT) technique is exploited to encourage the strong user (user with better channel condition) to relay the information messages of the weak user (user with poor channel condition) in FD manner. The total sum rate maximisation problem is formulated and solved by means of convex-concave procedure. The system performance is also analysed by deriving the outage probability of both users. Additionally, the model is extended to a more general case wherein the users are moving, and the outage probability of this dynamic topology is provided by means of the stochastic geometry framework. Novel secure schemes are also introduced to safeguard legitimate users' information from internal and external eavesdroppers. In the internal eavesdropper's case, artificial signal concept is adopted to protect NOMA's weak user's information from being intercepted by the strong user. The secrecy outage probability of the weak user is derived and validated. In addition, game theory discipline is exploited to provide an efficient eavesdropping avoidance algorithm. Null-steering beamforming is adopted in the external eavesdropper's case in two different schemes namely self and nonself-cooperative jamming. In self-cooperative strategy, the base station applies the null-steering jamming to impair the eavesdropper channel, while sending the information-bearing signals to the intended legitimate users. Whereas in the nonself-cooperative jamming scheme, the base station provides the helpers with the required information and power by means of SWIPT technique in the first phase. The helpers deploy null-steering beamforming to jam the eavesdropper during the information exchange between the base station and the intended users in the second phase. The secrecy outage probability of the legitimate users is derived in both jamming schemes. Game theory is also introduced to the nonself-cooperative jamming scheme for further improvements on the secrecy outage behaviour and the economic revenue of the system. The proposed capacity enhancing scheme demonstrates about 200% higher sum rate when compared with the non-cooperative and half-duplex cooperative NOMA systems. In addition, the novel secure scheme in the internal eavesdropper case is proven to enhance the information security of the weak user without compromising the functionalities of the strong user or NOMA superiority over orthogonal multiple access systems. Null-steering based jamming system also illustrates improved secrecy performance in the external eavesdropper case when compared to the conventional jamming schemes. Numerical simulations are carried out in order to validate the derived closed-form expressions and to illustrate the performance enhancement achieved by the proposed schemes where the rate is increased by 200% and the secrecy outage probability is decreased by 33% when compared to the baseline systems.

ABSTRAK

Sistem komunikasi generasi kelima (5G) mempunyai banyak jangkaan fungsi dan keperluan seperti kadar data yang tinggi, sambungan besar-besaran, kawasan liputan yang luas, kependaman rendah dan prestasi kerahsiaan yang dipertingkatkan. Untuk mencapai kriteria ini, skim-skim komunikasi yang menggabungkan teknologi pemboleh utama 5G perlu dikaji. Dalam tesis ini, satu sistem komunikasi novel yang menyatukan capaian berbilang tak ortogonal (NOMA), penuaian tenaga, pembentuk alur, dan dupleks penuh (FD) untuk meningkatkan kedua-dua kapasiti dan kerahsiaan sistem 5G diperkenalkan. Dalam skim peningkatan kapasiti, NOMA digabungkan terlebih dahulu dengan pembentuk alur untuk melayan lebih daripada satu pengguna dalam setiap vektor pembentuk alur. Kemudian, teknik maklumat wayarles dan pemindahan kuasa secara serentak (SWIPT) telah dieksploitasi untuk menggalakkan pengguna kuat (pengguna dengan keadaan saluran lebih baik) untuk menyampaikan mesej maklumat pengguna lemah (pengguna dengan keadaan saluran yang lebih lemah) secara FD. Masalah pemaksimuman kadar jumlah keseluruhan dirumus dan diselesaikan melalui prosedur cembung-cekung. Prestasi sistem juga dianalisis dengan menerbitkan kebarangkalian gangguan kedua-dua pengguna. Selain itu, model ini dilanjutkan kepada kes yang lebih umum di mana pengguna-pengguna sedang bergerak, dan kebarangkalian gangguan topologi dinamik ini telah disediakan melalui kerangka geometri stokastik. Di samping itu, skim-skim keselamatan novel diperkenalkan untuk melindungi maklumat pengguna yang sah dari pemasang telinga dalaman dan luaran. Dalam kes pemasang telinga dalaman, konsep isyarat buatan diamalkan untuk melindungi maklumat pengguna NOMA yang lemah dari dipintas oleh pengguna kuat. Kebarangkalian gangguan kerahsiaan pengguna lemah diterbitkan dan disahkan. Di samping itu, disiplin teori permainan dieksploitasi untuk menyediakan algoritma mengelak pemasangan telinga yang berkesan. Pembentuk alur stereng-nol digunakan dalam kes pemasang telinga luaran dalam dua skim berbeza yang dinamakan penyesakan koperatif kendiri dan tak kendiri. Dalam strategi koperatif kendiri, stesen pangkalan menggunakan penyesakan stereng-nol untuk menjejaskan saluran pemasang telinga, sambil menghantar isyarat mengandungi maklumat kepada pengguna sah yang dimaksudkan. Manakala dalam skim penyesakan koperatif tak kendiri, stesen pangkalan menyediakan pembantu dengan maklumat dan kuasa yang diperlukan melalui teknik SWIPT dalam fasa pertama. Pembantu ini menggunakan pembentuk alur stereng-nol untuk menyesak pemasang telinga semasa pertukaran maklumat di antara stesen pangkalan dan pengguna yang dimaksudkan dalam fasa kedua. Kebarangkalian gangguan kerahsiaan pengguna yang sah diterbitkan dalam kedua-dua skim penyesakan. Teori permainan juga diperkenalkan kepada skim penyesakan koperatif tak kendiri untuk penambahbaikan lanjut prestasi dalam tingkah laku gangguan kerahsiaan dan pendapatan ekonomi sistem. Skim peningkatan kapasiti yang dicadangkan menunjukkan kadar jumlah sekitar 200% lebih tinggi berbanding dengan sistem NOMA tak koperatif dan separuh dupleks. Di samping itu, skim keselamatan novel dalam kes pemasangan telinga dalaman terbukti meningkatkan keselamatan maklumat pengguna yang lemah tanpa menjejaskan fungsi pengguna yang kuat atau keunggulan NOMA daripada sistem capaian berbilang ortogonal. Sistem penyesakan berasaskan stereng-nol juga menunjukkan prestasi kerahsiaan yang lebih baik dalam kes pemasang telinga luaran jika dibandingkan dengan skim penyesakan konvensional. Simulasi berangka dilakukan untuk mengesahkan ungkapan tertutup yang diterbitkan dan untuk menunjukkan peningkatan prestasi yang dicapai oleh skim yang dicadangkan di mana kadarnya meningkat sebanyak 200% dan kebarangkalian gangguan kerahsiaan menurun sebanyak 33% daripada sistem dasar.

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LIST OF ABBREVIATIONS

5G	-	Fifth-generation
AS	-	Artificial signal
AN	-	Artificial noise
AWGN	-	Additive white Gaussian noise
CCP	-	Convex-concave programming
CDF	-	Cumulative distribution function
CDMA	-	Code division multiple access
CSI	-	Channel state information
EH	-	Energy harvesting
FD	-	Full-duplex
HD	-	Half-duplex
HJ	-	Harvest-and-jam
ID	-	Information decoding
i.i.d	-	Independent identically distributed
IoT	-	Internet of things
JBPS	-	Joint beamforming and power splitting
MIMO	-	Multiple-input multiple-output
MISO	-	Multiple-input single-output
MRT	-	Maximum ratio combining
NE	-	Nash equilibrium
NOMA	-	Non-orthogonal multiple access
OFDMA	-	Orthogonal frequency division multiple access
OMA	-	Orthogonal multiple access
PDF	-	Probability density function
PHY	-	Physical layer
PS	-	Power splitting
QoS	-	Quality of service

RF	-	Radio frequency
SC	-	Superposition coding
SDR	-	Semi-definite relaxation
SIC	-	Successive interference cancellation
SINR	-	Signal to noise plus interference ratio
SNR	-	Signal to noise ratio
SOCP	-	Second order cone programming
SWIPT	-	Simultaneous wireless information and power transfer
TS	-	Time switching
WPCN	-	Wireless powered communication networks
WPT	-	Wireless power transfer

LIST OF SYMBOLS

a_k	-	NOMA power coefficient of user k
N	-	Number of base station antenna
L	-	Number of helpers in jamming schemes
K	-	Total number of users
P_T	-	Total transmit power
P_S	-	Information transmission power
α	-	Path loss exponent
P_A	-	Artificial signal transmission power
β	-	Information to artificial noise power splitting ratio
s_k	-	Information-bearing signals for the user k
h_k	-	Channel gain between the base station and the user k
ρ	-	Energy harvesting power splitting ratio
η	-	Energy conversion efficiency
R_k	-	Target rate of user k
x	-	Denotes scalars
$\mathbf{x}$	-	Boldface lower case letters denote vectors
$\mathbf{X}$	-	Boldface upper case letters denote matrices
$\|.\|$	-	Euclidean Norm
$[x]^+$	-	Max (x or 0)
$(.)^T$	-	Transpose operation
$(.)^H$	-	Hermitian transpose operation
$(.)^\dagger$	-	Conjugate transpose operation
$\mathcal{CN}(\mu, \sigma^2)$	-	Circular symmetric Gaussian random variable with mean μ and variance σ^2

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The fifth-generation (5G) communication systems will not be an incremental version of the previous generations, as in addition to the ultra-high data rate (1 Gbps (100 times the user-experienced data rate in 4G)), ultra-large number of connected devices, ultra-low latency and ultra-wide radio coverage, 5G has many anticipated new services and functionalities such as internet-of-things (IoT) and cloud-based applications [1]. These envisioned services pose challenging requirements like massive connectivity, spectral and power efficiency (the Joules per bit will need to fall by at least 100 times) and low latency (1 millisecond end-to-end round-trip delay). In order to meet up with these requirements, a variety of novel technologies are involved such as new multiple access techniques, novel network architectures, new spectrum and power utilization methods, multi-antenna techniques and full-duplexing. Moreover, the future communication systems should combine these different techniques to introduce further enhancement and to boost the system performance [2].

In order to meet the increased number of connected devices, high data rate and low-latency requirements, novel multiple access schemes are needed to be adopted. Being an answer to the future 5G communication system's essentials, non-orthogonal multiple access (NOMA) has been recognised as the potential multiple-access scheme for the future communication systems, for its appealing features of spectral efficiency, low latency and user fairness [3]. Unlike previous multiple access schemes, NOMA differentiates users according to their channel condition to transmit the information message at the same time, frequency and code but with different levels of power. User with better channel condition (strong user) is allocated with less power than that of the user with poor channel gain (weak user). Downlink NOMA system deployment involves two main techniques. Firstly, superposition coding (SC) at the base station side to build the information message of the paired NOMA users. Secondly, successive interference cancellation (SIC) at the strong users' terminals. Where based on side-information provided by the base station, NOMA strong user decodes the information message of the week user, subtracts it from the superimposed message and decodes his own [2]. NOMA weak user decodes his information message directly by considering the strong user signal as interference since he is allocated with higher power level [4]. The knowledge of weaker users' information messages feature can be exploited by encouraging strong users to relay weaker users' messages to enhance the reliability of the system, in what is referred to as cooperative NOMA scheme [5]. On the other hand, from an information security perspective, this feature highly threatens the system data secrecy if the strong user is a malicious node.

To meet the ultra-wide radio coverage requirement, future 5G communication systems consider deploying relays as an efficient technique for capacity enhancement, improved reliability and coverage extension [6]. To avoid interference, the conventional half-duplex (HD) relays operate either in different time slots or separate frequency bands. As a result, HD scheme suffers from 50 percent loss in resource efficiency [7]. Full-duplex (FD) relaying scheme has been proposed to overcome the spectral inefficiency of HD system. In favour of the ability of transmitting and receiving signals simultaneously at the same frequency/time, FD can double the date rate of the system for a given bandwidth/time slot. However, the real implementation of FD has been considered as impractical due to the self-interference (SI) signal resulting from the signal leakage from the terminal's output to the input, which can be billions of times greater than the desired receive signal [8]. Recent advances in signal processing allow SI suppressing to within tolerable limits through a combination of passive and active cancellation in both analogue, and digital domains [9]. Passive cancellation involves antenna-based isolation techniques that depend on the separation distance between antennas, orientation and polarisation [10]. Active cancellation approaches are carried out via digital processing techniques at the baseband with the aid of accurate knowledge of the channel's status after passive cancellation processes [11]. Recently, a new superimposed signalling-based scheme is proposed to overcome the SI burden where no channel condition estimation is required [12].

Inter-user cooperation and information relaying is bounded by the energy limitation and finite battery-powered devices, as users are selfish and prefer to maintain their power for the own functionalities. Energy harvesting (EH) technique has gained lately a lot of attention in both academia and industry, as it provides a promising solution for prolonging the lifetime of the future communication networks [13, 14]. Many types of EH schemes according to the energy source have been considered, such as solar, piezoelectric, wind, hydroelectric, and radio frequency (RF) signals [15]. The stability and the availability of wireless signals (TV broadcasting, mobile base stations), and the dependence of natural energy on location, climate and time, nominate RF-EH (the ability of transforming the wireless RF signals into DC voltage to charge the device battery) as the optimal EH scheme. Yet, this emerging technology requires a shift in the system architecture and its power-information resource allocation strategies to meet its new demands [16]. Unlike information decoding circuits, the sensitivity of the EH process is quite low ($-10dBm \ - 30dBm$) [17]. The need for higher signal energy levels makes the EH process highly sensitive to signal decay due to propagation distance, reflection, scattering, and fading (which is high in the case in omnidirectional transmission by single antenna) motivates the use of multi-antenna techniques like beamforming in EH enabled communication networks, for its appealing feature of increasing the wireless power and information transfer efficiency [18].

On the other hand, wireless communications are vulnerable to security breaches which is more common in the future 5G systems due to the ultra-number of connected devices and wider radio coverage area [19]. This pivotal issue necessitates taking measurements to guarantee data confidentiality, such as orthogonal code division technique, frequency hopping, and data encryption. Yet, fully secure communications can be only achieved by exploiting physical layer (PHY) security [20, 21]. Beamforming and EH techniques can be exploited in PHY security by transmitting the energy signals waveform as a Gaussian pseudo-random sequence, that is known a priori to all legitimate receivers. This technique can provide secure communication, as this sequence can serve as interference to illegitimate eavesdroppers, while can be cancelled easily at legitimate users terminals by means of beamforming technology [22]. In addition, secure communication can be guaranteed by letting nearby nodes transmit jamming signals to impair the potential eavesdroppers' channels. The processes of generating and broadcasting these signals drain the terminal battery, that can be compensated by wireless charging provided by the EH approach. Furthermore, in order to locate and deliver a sufficient energy amount to helper nodes, multi-antenna techniques like beamforming are important [23]. Secrecy threats can be divided according to the source of the threat into internal and external threats. In the internal case, the threat is provoked by a legitimate user of the wireless network who is trying to intercept other legitimate users' information. While in the external scenario, the communications are carried out under malicious attempts of non-legitimate (external) user to intercept the legitimate users' data.

Game theory is a formal discipline with a set of mathematical tools to analyse the complex interactions among competing independent rational users or players. For more than half a century, this framework has led revolutionary changes in the economical field, in addition to politics, psychology, and transportation. During the last period, there has been a surge in research activities that deploy game theory in modelling, analysing and optimizing wireless communication systems. The need to apply game theory in the modern 5G communication systems become more urgent as it involves large scale, heterogeneous and distributed communication schemes, in addition to the need for robust implementations against telecommunication systems uncertainties [24].

1.2 Problem Statement

In order to meet up with envisioned requirements of the 5G communication systems and its anticipated services and functionalities, novel communication schemes are needed to be adopted. The enormous number of connected users (individuals and things), ultra-high data rate and low-latency requirements make adopting new multiple access scheme as one of the revolutionary aspects of the upcoming wireless communications. Due to its performance superiority over the conventional orthogonal multiple access (OMA), NOMA has been nominated as the potential multiple access scheme for 5G communication systems. In addition, future communication scheme should adopt FD relaying to fulfil the ultra-wide coverage requirement and enhance the spectral efficiency and communications reliability. However, relaying and inter-user cooperation is highly threatened due to power-limitation in the wireless network, as each user prefers to utilize his power for the own functionalities. Hence, novel systems should consider wireless EH techniques to overcome the energy scariness issue in wireless networks and further encourage the inter-user cooperation. Furthermore, multi-antenna techniques need to be exploited in the proposed communication to enhance both wireless information and power transfer efficiency and to increase the system's degrees of freedom. Introducing 5G potential technologies such as beamforming, energy harvesting and FD communications to NOMA in order to improve the full system performance has drawn considerable attention of late. In some literature, NOMA is combined with multiple-antenna techniques like beamforming to exploit both power and spatial domains to enhance the signal to noise plus interference ratio (SINR) [25], or to increase the spatial multiplexing gain [26] by serving more than one user per each beamforming vector but no inter-user cooperation is considered. On the other hand, NOMA and energy harvesting techniques are merged in a few literature to enhance both energy and spectral efficiency and overcome energy and spectrum scarcity in the system. The authors in [27, 28] introduce simultaneous wireless information and power transfer (SWIPT) to NOMA system to encourage strong users to relay weak users' information messages as this collaboration will not drain their batteries. Strong users in [29], use the harvested energy in the first time slot, to relay weak users' messages in the second time slot using beamforming in half-duplex (HD) manner. Of course, cooperation in HD scheme is not optimal as the resources are divided between receiving and transmitting processes. Therefore, novel FD cooperative EH-enabled NOMA communication schemes are needed to be proposed, optimized and analysed.

The feature that NOMA strong user can decode weak user's information messages is exploited in cooperative NOMA schemes to increase the reliability of the communication system. On the other hand, from an information security perspective, this feature highly threatens data confidentiality in the system, if the strong user is a potential eavesdropper. Exploiting PHY security in NOMA systems has gained a lot of attention lately. Yet, NOMA internal or legitimate eavesdropper case has only been investigated in [30], where the cell-edge (weak) user is considered as a potential eavesdropper who is trying to decode the cell-centre (strong) user's message in a beamforming NOMA system. However, eavesdroppers are usually users with good channel condition located near to the base station, as the attack will be more energy efficient and more destructive to the network [31]. Therefore, secure communication schemes that protect weak user's data against strong user malicious attempts without compromising the system functionalities are needed to be investigated.

Moreover, information secrecy and data confidentiality are expected to be highly compromised in the 5G systems due to the enormous number of connected users and the ultra-wide radio coverage provided by future communication schemes. These desired features in terms of system data rate performance increase the probability of external malicious nodes existence. Some literature on enhancing the information confidentiality by means of PHY security in NOMA systems has appeared lately. The authors in [32] derive the secrecy outage probability in downlink NOMA system for several antenna selection schemes. In [33], the secrecy sum rate is maximised in a downlink NOMA system consisting of base station, multiple legitimate receivers and an external eavesdropper. Both [34, 35] investigate enhancing the secrecy performance of large-scale NOMA networks with external eavesdropper scenario. PHY security is enhanced in the aforementioned system model in [34] by introducing the concept of protected zone around the source node. While AN technique is exploited in [35] to enhance the secrecy outage probability of multiple-antenna transmission scenario. In secure AN-aided NOMA technique, the noise signal is broadcast in the orthogonal directions of the intended NOMA user, resulting in not only the degradation of the base station-eavesdropper link but also the link between the base station and the other NOMA legitimate users. The AN signal of the NOMA weak user adds extra interference to the strong user yielding incorrect SIC execution and imperfect decoding of the own message. In addition, strong user AN signal degrades the SINR at the weak user and his ability to decode his message. Hence, secrecy paradigms that exploit the physical medium characteristics of the communications and reap the benefits provided by the disruptive techniques to 5G are needed to be investigated. The proposed secure schemes need to enhance information privacy under external threats without affecting the legitimate users' quality of service (QoS).

Resources and power allocation and optimization strategies play a crucial role in wireless communications system performance and involve high computational complexity tasks. Resource allocation, system modelling and optimization are expected to be even more challenging in information secrecy of the 5G communication schemes, as these systems involve higher data rate, enormous number of served users and multiple interleaved techniques. One of the sophisticated mathematical tools that has been adopted in resource allocation and modelling of the PHY security of the conventional communication system is the game theory. Game theory has been exploited in the literature for enhancing the information secrecy of different networks models such as cognitive radio [36, 37], D2D communication [38] and the cooperative OMA communication systems [39]. However, introducing this mathematical framework to enhance the secrecy performance of NOMA communication scheme has not been considered yet, and secure paradigms that exploit this discipline are needed to be studied and introduced for enhanced secrecy performance.

1.3 Research Objectives

The problem statement leads us to the following research objectives:

1. To propose, optimize and analyse a communication scheme that combines NOMA, EH, beamforming and FD techniques in order to enhance the rate of future communication systems.
2. To design a secure paradigm to impair NOMA strong user's capabilities of intercepting weaker users' information messages.
3. To exploit the 5G techniques to propose a secrecy scheme to protect legitimate users' information from being intercepted by an external eavesdropper.

1.4 Scope of Work

The study is aimed to design a communication scheme that combines NOMA, EH, Beamforming, and FD techniques. The performance of the proposed scheme is optimized by introducing power allocation strategies and NOMA user clustering algorithms. The system performance is analysed by deriving the outage probability of both weak and strong users. In addition, in order to capture the dynamic nature of wireless networks, the framework of stochastic geometry is adopted, and the outage probability of the system is derived and provided in a closed-form formula. Furthermore, two secrecy schemes are proposed to enhance the system security under the malicious attacks of internal and external eavesdroppers. The secrecy outage probability performance metric of both schemes is derived, analysed and compared with the corresponding baseline schemes. The mathematical framework provided by game theory is then exploited to introduce further enhancement over the secrecy behaviour of the proposed schemes. Numerical simulations are carried out by using Matlab software to validate the derived results by means of Monte Carlo simulations and to compare the performance of the proposed schemes with its corresponding baseline systems.

The study is carried out under the availability of perfect channel state information (CSI) at the base station assumption and limited to power-domain NOMA only. Slow-fading Rayleigh channel model is the channel model adopted in this work. In addition, the research investigates downlink NOMA communication systems, wherein system performance optimization with respect to power allocation strategies and clustering algorithms is examined. Furthermore, the PHY security will be investigated in two different scenarios, internal and external eavesdropper. In internal eavesdropper case, the strong user is considered as the potential malicious user who is trying to intercept the weak user's data. The study considers outage probability and secrecy outage probability as performance metrics of capacity and PHY security enhancing schemes respectively.

1.5 Limitation of the Work

The work does not analyse partial or imperfect CSI availability scenarios. In addition, the research does not consider uplink NOMA communication systems or code-domain NOMA scheme. Furthermore, no hardware implementation is investigated during the study.

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