PERFORMANCE IMPROVEMENT OF UNDERLAY COOPERATIVE COGNITIVE NETWORKS BANDWIDTH EFFICIENCY UNDER INTERFERENCE LIMITATION

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PERFORMANCE IMPROVEMENT OF UNDERLAY COOPERATIVE COGNITIVE NETWORKS BANDWIDTH EFFICIENCY UNDER INTERFERENCE LIMITATION

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ABSTRACT

PERFORMANCE IMPROVEMENT OF UNDERLAY COOPERATIVE COGNITIVE NETWORKS BANDWIDTH EFFICIENCY UNDER INTERFERENCE LIMITATION

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Diversity techniques are known to provide an efficient way of combating fading in wireless communication environments. Time, frequency, and spatial diversity are the three main forms of these diversity techniques. Cooperative diversity could achieve better performance compare to the MIMO system. In cooperative communications, multiple nodes in a wireless network work together to form a *virtual antenna array*. Using cooperation, it is possible to exploit the spatial diversity of the traditional MIMO techniques, without each node necessarily having multiple antennas. In this work studied with cooperative diversity, cognitive cooperative.

The definition of the bandwidth efficiency (BE) of cognitive cooperative network (CCN) is the ratio between a number of the licensed slot(s) or sub-channel(s) used by the unlicensed users to transmit a single data packet from the unlicensed transmitter to unlicensed destination, and from unlicensed relay(s) to unlicensed destination. This paper analyzes and improves the BE in the underlay CCN with a new reactive relay selection under interference and power constraints. In other words, this paper studies how unlicensed cooperative users use the licensed network slot(s) or sub-channel(s) efficiently. To this end, a reactive relay selection method named as Relay Automatic Repeat Request (RARQ) is proposed and utilized with a CCN under interference and power constraints. It is shown that the BE of CCN is higher than that of cooperative transmission (CT) due to the interference and power constraint. Furthermore, the BE of CCN is affected by the distance of the interference links which are between the unlicensed transmitter to the licensed destination and unlicensed relay to the licensed destination. In addition, the BE for multiple relays selection over a CCN under interference and power constraints is also analyzed and studied, and it is shown that the BE of CCN decreases as the number of relays increases.

Keywords*:* Bandwidth efficiency, Reactive relay selection, Cooperative transmission, Cognitive cooperative network.

ÖZ

PARAZIT ALTINDAKI IŞBIRLIĞINE DAYALI BILIŞSEL AĞLARIN BANT GENIŞLIĞI VERIMLILIĞININ PERFORMANS GELIŞTIRILMESI

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Nisan 2019, 79 sayfa

Çeşitlilik tekniklerinin, kablosuz iletişim ortamlarında solma ile mücadelede etkili bir yol sağladığı bilinmektedir. Zaman, frekans ve mekansal çeşitlilik, bu çeşitlilik tekniklerinin üç ana şeklidir. Kooperatif çeşitliliği, MIMO sisteminden daha iyi performans sağlayabilir. İşbirlikli iletişimde, bir kablosuz ağdaki birden çok düğüm bir sanal anten dizisi oluşturmak için birlikte çalışır. İşbirliğini kullanarak, geleneksel MIMO tekniklerinin mekansal çeşitliliğini, birden fazla antene sahip olmak zorunda olmadan kullanmak mümkündür.

Bilişsel kooperatif ağının (CCN) bant genişliği verimliliğinin (BE) tanımı, lisanssız kanal (lar) veya lisanssız kullanıcılar tarafından lisanssız alanlardan tek bir veri paketini iletmek için kullanılan alt kanal (lar) arasındaki orandır. lisanssız varış yeri ve ruhsatsız varış yerine lisanssız varış yerine rölesi. Bu çalışma, girişim ve güç kısıtlamaları altında yeni bir reaktif röle seçimi ile aşağı akım CCN'de BE'yi analiz etmekte ve geliştirmektedir. Başka bir deyişle, bu çalışma lisanssız işbirlikçi kullanıcıların lisanslı ağ soketlerini veya alt kanallarını nasıl verimli bir şekilde kullanabileceklerini incelemektedir. Bu amaçla

Röle Otomatik Tekrar İsteği (RARQ) olarak adlandırılan bir reaktif röle seçim yöntemi önerilmiştir ve girişim ve güç kısıtlamaları altında bir CCN ile birlikte kullanılır. CCN'nin girişim ve güç kısıtlaması nedeniyle kooperatif iletimden (CT) daha yüksek olduğu gösterilmiştir. Ek olarak, CCN'nin BE lisanslı gönderen ile lisanslı varış yeri arasındaki lisans bağlantılarının lisanssız varış yerine lisanssız varış yerine olan mesafesinden etkilenir. Ek olarak, BE bir müdahale ve güç kısıtlamaları altında bir CCN üzerinden çoklu röle seçimi için analiz edilir ve incelenir ve CCN'nin BE sayısının, röle sayısı arttıkça azaldığı gösterilmiştir.

Anahtar Kelimeler: Bant genişliği verimliliği, Reaktif röle seçimi, Kooperatif iletim, Bilişsel kooperatif ağı.

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To my examining committee members, I give them thanks.

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LIST OF ABBREVIATIONS

CN	Cognitive Network
PU	Primary User
CSI	Channel State Information
WBAN	Wireless Body Area Network
BSN	Body Sensor Network
BCU	Body Control Unit
MAC	Medium Access Control
DF	Decode And Forward
AF	Amplify and Forward
MRC	Maximum Ratio Combining
SC	Selection Combining
OC	Optimal Combining
SNR	Signal-to-Noise Ratio
SIR	Signal Interference Ratio
CSI	Channel State Information
BER	Bit Error Rate
CRN	Cognitive Relay Network
UCCN	Underlay Cooperative Cognitive Network
VDS	Virtual Doctor Server
HMS	Health Monitoring System
CRBAN	Cognitive Radio Body Area Network

HSH	Health Smart Home
PDR	Packet Delivery Ratio
QoS	Quality of Service
MIoT	Medical Internet of Things
HBC	Human Body Communication
BE	Bandwidth Efficiency
CCN	Cooperative Cognitive Network
RARQ	Relay Automatic Repeat Request
CT	Cooperative Transmission
MIMO	Multi-Input-Multi-Output
JNRS	Joint Next-hop node and Relay Selection
FD	Full Duplex
CR	Cognitive Radio
SEP	Symbol Error Probability
LU	Licensed User
LT	Licensed Transmission
LD	Licensed Destination
UT	Unlicensed Transmission
UD	Unlicensed Destination
UR	Unlicensed Relay
ACK	Acknowledgment
NACK	Negative Acknowledgment
DT	Direct Transmission
CT	Cooperative Transmission

CDF	Cumulative Distribution Function
DTM	Direct Transmission Mode
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
e2e	End-to-end
TCC	Traditional Cooperative Communication
ICC	Incremental Cooperative Communication
EE	Energy Efficiency
PL	Path loss
RF	Radio Frequency
ORS	Opportunistic Relay Selection

CHAPTER 1

INTRODUCTION

1.1. Introduction

1.1.1. Cognitive cooperative communication

With the fast deployment of wireless services over the last decade, the radio spectrum has become a valued and scarce resource. Furthermore, the Federal Communications Commission has reported that most of the licensed spectrum is severely underutilized [1]. As a promising technique a cognitive network (CN) is proposed to address the dilemma between spectrum scarcity and spectrum underutilization. CN allows unlicensed users to access licensed slots or sub-channels while taking into account the effect of interference on the licensed users, so it should not exceed the tolerable interference threshold [2], If we examine part of the spectrum may be found the following results (1) most of the time the bandwidth is not fully exploited, (2) The frequency band is sometimes partially exploited (3) remaining frequency bands are significantly used. Due to lack of use spectrum leads to the concept of the holes in the spectrum. As shown in Fig. 1. A spectrum hole is a band that is assigned to a primary user (PU), however, at certain time and geographic location, the band is not used by that PU [3].

To accommodate the growing demand for wireless service and use spectrum hole efficiently, technology introduced such as cognitive radio by Joseph Mitola III, the following definition of the cognitive radio [4].

“Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world). Uses the methodology of understanding by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind”:

1. Reliable communications when and where necessary.
2. Radio spectrum utilization efficiency.

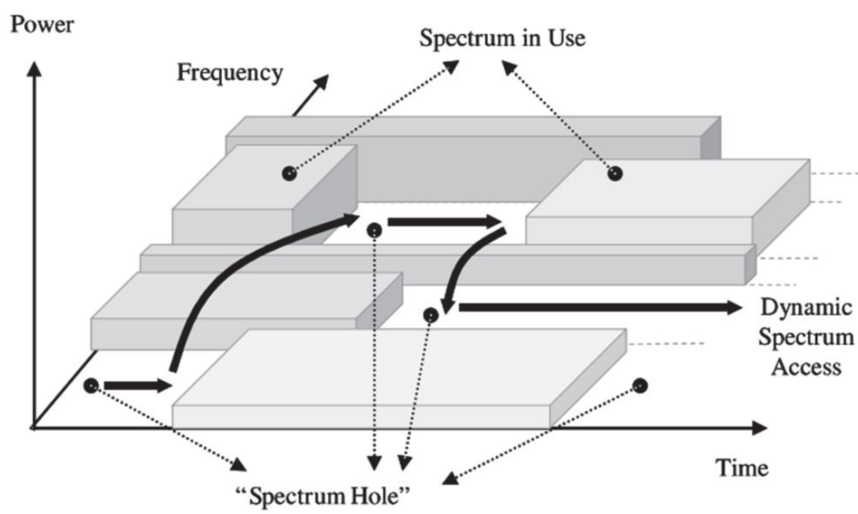

Fig. 1. Spectrum of Cognitive Radio [4].

Fig. 1. Displays the main functions in CR including: (1) Analysis of the radio scene which includes the estimation of the interference temperature and detection of spectrum holes; (2) channel determination, which includes channel status information (CSI) estimation and channel capacity; (3) control of transmit-power and dynamic spectrum management.

Summarize cycling step of cognitive as follow: (1) spectrum sensing, which is used to detect spectrum holes for spectrum use without product interference to the PU; (2) spectrum analysis, which is the identification of the characteristics of the holes spectrum detected; (3) spectrum decision, determined by cognitive radio for the data rate, the transmission mode, and transmission bandwidth.

1.1.2. The use of cognitive radio in medical issues

In last years WBANs have gained considerable attention in many areas of health care [5], [6], like medical [7] telemetry and patient monitoring [8], [9]. Availableness of bio-medical sensors which can be implanted in the body or worn [9]. Biomedical sensors used in the human body can assess, monitor, process and communicate the patient’s condition and symptoms to the expert and provide real-time feedback to the user and medical staff without the uncomforting with intermediate wires [10]. Body sensor network (BSN) is the sensors assembly to the human body and there is a device receives data from the sensors and operates according to the requirement is called the actuator node. A Body Control Unit (BCU) is a device that collects information from the sensors to inform the user particularly in a patient monitoring system [9].

Convert BSN into a WBAN is a challenge. The wireless communication technology make the sensors cultivable easily and user can moving without hesitation about communication between sensors and actuator node. Biomedical sensors are placed inside or outside the body, communicate with a short range covering, transmitting or receiving information related the human body [11]. Unlike healthcare, WBAN applications extend from sport training to safety in the workplace, as well as secure authentication of consumer electronics and the protection of unskilled employees [11].

Communication suffers weak signal propagation and attenuation in WBAN because the biomedical sensors inside body, where the presence of blood and tissues inside human body. The sensors inside human body required to keep it functional for a long period of time. They lead to heating the tissues due to energy absorption, therefore, emissions should be low power to prevent excessive tissues heating and subsequent cell death [12]. Energy absorption and thus heating within the human body are directly related to the frequency of the process. A WBAN nodes can operate at different frequencies. Medical Implantable Communication Service (MICS), ultrasonic, and Ultra-Wide Band are suitable for implantable applications [13]. Regardless of operating frequency, there are other requirements that must be taken into account during WBAN network design.

WBAN is a special case of WSN [9], but differs from other networks such as wireless personal area networks (WPAN) because of their own requirements. WBAN requirements are:

1. **Transducer size:** The smaller size of adapter makes it easy to implantable and comfortable to wear. The size of the adapter depends on the frequency of operation. Highest the frequency is the smallest adapter size and smaller is the antenna.
2. **Interference:** Interference occurs in the case of WBAN, that is, when two persons are connected to WBAN in each other’s environment. Interference between systems occurs due to the presence of other electromagnetic devices such as a microwave oven. Interference is usually lower at higher frequencies where a greater frequency range is

available. Regardless the transmission power, interference depends on multiple access system and resource allocation.

3. **Attenuation and SAR:** Choosing a playback frequency is the one of the key parameters. When the frequencies are higher lead to more heat dissipation within the human body [14] it is harmful to tissues. As well as the energy absorbed by the body known as the Specific Absorption Rate (SAR), expressed in watts per kilogram W/kg should be lower.
4. **Data rate:** Some application required high data rate such as endoscopy such as endoscopy [15], EEG [16] and improved decision for real time applications. The bandwidth availability and playback frequency is directly affected the amount of data rate, applications with higher data rate requirements can then choose a larger bandwidth such as UWB.
5. **Delay:** Delay is very important for remote control of insulin, heartbeat rate and blood pressure where remedial must be taken immediately. The delay can occur because of propagation or because of lack of resources. The propagation delay depends on the frequency of the device and its location, while the lack of resources may cause delays or delays due to collisions.
6. **Multipath:** This is a design consideration, which relies entirely on the medium. High multipath and more delay spread is the overlap symbols (ISI). Design receiver should be considered on multipath.
7. **Transmit Power:** Device sending power should be lower as possible [17], when compared to other networks should be main requirement. High frequency radio have lower transmission power.

8. **Battery:** The devices must have a rechargeable battery or no battery. The number of Battery transmissions can be reduced using harvesting techniques, which must be considered based on applications.
9. **Network lifetime:** the WBAN Network life time should be for a longer period, especially for transplanted devices. This parameter is based on multiple access systems, power consumption and routing algorithms. Wastage of power can be reduced through the effective design of the MAC and network layer protocols.

1.2. **Outlines**

- The second chapter was presented a literature review of **Taxonomy of cooperative communication methods** a classification must first be identified and must compared different methods for analysis with shared properties within groups, related work of **Cognitive network,** where a series of previous research and techniques used were reviewed, and The use of cognitive radio in medical issues there are many studies in Wireless Body Area Networks (WBAN) that have been done in many of the categories that relate to WBAN issues.
- In the third chapter we discuss the **Improvement of Underlay Cooperative Cognitive Networks Bandwidth Efficiency Under Interference Limitation by use of Reactive Relay Selection,** where Relay Automatic Repeat Request (RARQ) is suggested and used with cognitive cooperative network, then Bandwidth is analyzed and improved, and the simulation and numerical results presented here.
- Fourth chapter show the conclusion and future work.

CHAPTER 2
LITERATURE REVIEW

2.1. Taxonomy of cooperative communication methods

To evaluate modern cooperative transport methods, a classification must first be identified and must compared different methods for analysis with shared properties within groups. In this work, cooperative communication methods categorized on the basis of three key characteristics: **1) traditional cooperative communication, 2) multi-source, multi relay and multi destination cooperative communication, 3) incremental cooperative communication, 4) cooperative communication with relay selection, and 5) Two-Way cooperative communication**.

2.1.1. Traditional Cooperative Communication Methods.

The traditional cooperative communication is simplified form of cooperation technique, it is described as follow: in the first phase, the source broadcast the data to the relay node(s), and at the second phase the relay(s) transmits what was received from the source to the destination. There are four methods used to describe cooperative communication as follow, 1) dual-hop cooperative communication method, 2) cooperative communication with combining method, and 3) cooperative communication with relay selection.

2.1.1.1. Dual-Hop and Multi-hop Cooperative Communication Method.

Dual hop technique is used through a cooperating relay nodes. In such a case, the source and destination shares does not the same transmission range, therefore, direct transmission cannot be possible. The source transfer the data directly to relay nodes, then relays send what was received to the destination. In fact, relays have several operations that can be done by either processing the data (i.e. estimation, decoding and coding, and amplify and forward) or retransmit to the destination without any operation on it. The (DF) is Decode-and-Forward, (AF) is Amplify-and-Forward they are analyzed in [18]. The relay position effects on using of the performance technology. If the relay node is near to transmitter the DF will outperforms AF, and if the relay node is near to destination, therefore, AF outperformance DF [18]. In practice, it is still debatable, the easiest to implement. DF may be further complicated by the decryption requirements in the relay node. On the other hand, storing data in analog format may be a problem in AF [19].

2.1.1.2. Cooperative Communication with Combining Method

In order to, combine signals in the method of cooperative communication, along with the path, each receiver node can use techniques that combine traditional diversity such as Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Combining (SC) [20]. In MRC, signals received from all cooperators are evaluated and combine to increase the signal-to-noise ratio (SNR). It is well known that MRC is optimized and maximizes the total SNR in limited noise links with Gaussian noise. However, the full knowledge about channel status information is the main disadvantage of MRC technique [21]. EGC is a streamlined optimization technique, where the destination is combined among the received copies of the signal by adding them coherently. Therefore, the desired channel information in the receiver node is reduced to path information. SC is simpler than that and simply selects the signal with greater SNR. Although SC removes the load to estimate the channel status information, its performance eventually deteriorates compared with MRC and EGC [21]. In addition to the previous combination techniques, it is suggested that the Optimal Combining (OC) of the link is limited interference in the literature [22], [23].

With Optimal Combination at the receiver node, the signals will be received from source and relay and evaluated to maximize the Signal Interference Ratio (SIR). However, OC requires the real-time CSI of all interfaces factors be known in the future at the receiver, and therefore, requires significant system complication [24].

2.1.2. Incremental Cooperative Communication Method

To send the data by using fixed relaying techniques from the source to destination, multiply the time when compared with direct transmission. Thus, the fixed relaying throughput is reduced compared to a direct transmission. Additionally, when the destination node can decode packet of data sent from source in the first slot correctly, the channel resource wasted for the second slot that is exploited by the relay node. To solve these problems, it suggests incremental or adaptive relaying methods that use channel resources effectively [25].

There are two methods of incremental cooperative communication; the first one, called reactive incremental cooperative, is an automatic repeat request, if the destination does not receive the data from the source correctly, the relay node(s) re-send what was received from the source to the destination, otherwise, the destination node sends a positive acknowledgment and relay(s) remain silent. the second one is called proactive incremental cooperative and follow the work description: in the first phase, the source decides to use the direct transmission or use cooperative communication based on a channel available between source - relay, relay - destination, and source – destination [26].

2.1.3. Cooperative Communication with Relay(s) Selection

It is important to assess the performance cooperative communication in terms differentiation of the diversity-multiplexing. In [27] analysis of diversity-multiplexing and outage capacity rates achieved through different protocol. Using relay selection is one way of resisting the loss. Rather than retransmitting the information from all the relays, just few relays can be chosen dependent on the quality of their channel to the source and the destination. The choice of relays in cooperative is classified as follow: 1) Best relay selection, 2) Nearest neighbor selection, 3) Best worse channel selection, 4) Best harmonic mean selection, and 5) Multiple relay selection schemes.

1. **Best relay selection:** select a relay that has a path with maximum SNR. This is clearly the ideal single relay determination conspire, where rounding is used in the cumulative density function to receive SNR.
2. **Nearest neighbor selection:** The most terrible channel choice is utilized, in which the channel relay is worse, min$\{|f_i|, |g_i|\}$, is the best is chosen.The diversity examination depends on the outage probability. To consolidate distinctive constraints of

relay power, we change the choice function to be min*{P|fi|*2*, Pi|gi|*2*}*. We take a shot at the blunder rate and demonstrate that the best choice for worse channel accomplishes full diversity.

3. **Best worse channel selection:** There are two channels for each relay in dual-hop, first one, from source to relay, second, from the relay to the destination. The best more awful channel choice is utilized, in which the channel relay is worse, min{|fi|, |gi|}, is the best is chosen, where the diversity analysis depends on the outage probability. To join different constrain of relay power, we change the determination capacity to be min{P|fi|2, Pi|gi|2}. We take a shot at the blunder rate and demonstrate that the best more awful channel determination accomplishes full diversity.

4. **Best harmonic mean selection:** It suggest the best choice of harmonic mean, the relay selection function is selected as a harmonic mean to measure the two channels: The relay with the biggest harmonic mean |*fi*|-2 + |*gi*|-2-1 participates. Nonetheless, the derivation is not strict since the upper limit is utilized on the received SNR. In this paper, first, the choice function is changed to be *P* |*f*12 + *Pi*|*gi*|2 *i*|-1 to integrate the various relay powers, at that point give a strict upper limit to the symbol error.

5. **Multiple relay selection schemes:** In this segment, we take a shot at the various relay choice issue in (3). Because of the relay coupling, the SNR work is a nonlinear function of αi. Along these lines, our concern is a general nonlinear 0-1 programming. Straight whole number writing computer programs is known to be NP-finished. Nonlinear number writing computer programs is positively harder than linear.

Each relay has two options, where R relays there, there are 2R - 1 potential outcomes (it is clear that the situation in which the relay does not cooperative is not ideal). The receiver can always find the perfect solution through a comprehensive search due to it knowns all channels. But exponential in R describes the arithmetic complexity of this comprehensive scheme, the amount of feedback bits required is R since one bit data is needed for each relay. Undesirable number of feedback bits in the network size with a substantial number of relays. The genuine challenge of this issue is the discovery of many selections relays schemes with low intricacies (for instance, linear in R), great execution, and, in the meantime, a small number of feedback bits.

2.1.4. Multi-Source, Multi Relay and Multi Destination Cooperative Communication.

In the customary cooperative communication, there is a single source, single/multiple relay (s) and a single destination However, there is a possibility of different scenarios and their description as follows: 1) multi-source with multiple relay(s) and a single destination, and 2) multi-source with multiple relays and multiple destination. In [28] authors proposed two transmitters and two relays with a single destination The general transmission is split-up two pairs of hops. Transport between source and relays in the first hop and second hop relays to destination. Assume that multiple sources communicate at the same time with relays, i.e., non-symmetrical that the different sources all the while speak with the transfers, i.e., non-orthogonal transmission for the source-to-relay links. Network analysis with outage probability.

However, in [29] the researcher analyzed cooperative multi-source, multi-relays, multi-destination communication in a period of energy efficiency. Authors proposed two sources, two destinations, and three relay (s). In addition, they proposed the elimination of interference, thus improving capacity performance.

2.1.5. Two-Way Relaying Cooperative Communication

The two-way relay connection has recently attracted considerable attention, and the transmission schemes were analyzed and compared in two-way relay network. To create a reliable two-way communication, one or several relays are used between the two transceivers. Three ways to achieve a two-way migration schema: The four-step method including two single way relaying, the three-step time division broadcast (TDBC), and multiple access broadcast (MABC) two step approach. The MABC requires dual-time slots to exchange dual symbols among the transceivers, and thus, bandwidth is more efficient compared to the other two [30].

2.2. Cognitive network

In [2] proposed surveys the fundamental capacity limits and various wireless network design models for transmission techniques that rely on this promising technology These models are standardized by defining cognitive radio as an intelligent wireless adapter which use information around their environment to improve spectrum using. This information usually includes knowledge about activity, channels, codebooks, and/or other nodes messages that share the cognitive node in the spectrum.

In [31], the authors analyzed the performance of BER for underlay DF cognitive networks with the best selection of the proposed relay scheme, which is proved to be optimal capacity. The maximum transmit power restricted and interference power restricted was taken into the analysis. In [32], the innovation spectrum aware multi-channel MAC and energy-efficient for cognitive radio network. The researcher designed asynchronous work cycle of spectrum aware that meet both WSNs and CR requirements. The suggest MAC protocol performance was assessed out of both analytical and simulation methods, the proposed process is superior the WSNs multi-channel system

performance of outage probability studied of the DF dual-hop system of cognitive in Nakagami-m fading channel, taking into account the temperature of the interference, and the effect of various main system parameters, like fading gravity and interference temperature, are inspected in [33].

In[3], the outage probability is assessed for a cognitive relay network with regards cooperation among secondary users based underlay process, while taking into account the restricted interference on the primary user, a relay selection standard is provided, appropriate for cognitive networks.

Analyze the outage performance of the CRN with the underestimated channel knowledge estimates. If the channel status information (CSI) is not accurate, estimate of the interconnect between primary and secondary systems, particularly links from the secondary sender and secondary relays to the primary users, is suggest in [34].

In [35], which dealt with the effects between the licensed and unlicensed framework in terms of error estimation of the channel and reciprocal on the performance of the outage for reactive relay chosen in the unlicensed framework unlicensed systems through independent non-identical (i.n.i) channels of Rayleigh fading and down the constraint of maximum transmit power and outage constraint of primary.

Inspected the effect of operating conditions such as lack of channel information, independent mismatch fading distributions, stringent power restrictions, and primary interference on the performance of outage of opportunistic relay selection (ORS) in underlay cognitive cooperative networks (UCCNs) the secondary sender power is created for the first time to meet strict power restriction and primary interference account and CII, in [36].

In [37], In cognitive networks analysis of the performance of the proactive relay selection under process outline that heading direct channel, Asymmetric fading channels, and correlation between SNR received. Maximum ratio combining (MRC) is used at the destination to merge the signals from the relay and source, which can be expected to perform better among signal collection techniques.

In [38], authors examined first adjusts the traditional incomplete relay determination in cooperative cognitive networks to avert error spread and then suggests correct and asymptotic outage analysis for the altered partial relay choice under actual task conditions, like channel estimation errors (CEEs) on every wireless channel, free and non- identical fading allocation, interference power limitation, and extreme transmit power restriction. In addition, so as to quantitatively assess the execution gain of using the direct channel between the source and the destination in transferring communications.

The authors researched the cognitive relay network (CRN) in terms of the physical layer security with various antennas within the sight of numerous eavesdroppers. orthogonal space-time block code (OSTBC) transmission and spectrum sharing scenario, and inferred both the exact and asymptotic articulations of mystery outage probability over channels of rayleigh fading and give the unwavering quality security tradeoff investigation, and demonstrated that the loss of the mystery outage execution caused by an increase of eavesdropper's number can be thoroughly overwhelmed by numerous antenna diversity. It's showed that expanding the quantity of antennas can likewise enhance both the reliability and security of the framework, in [39].

2.3. Use of cognitive cooperative mechanism in medical issues

There are many studies in WBAN networks that have been done in many of the categories that relate to WBAN issues. We will see a general idea about the current study/survey contemplates on the WBAN, which can be classified as application, difficulties and issues; Medium access control (MAC) convention; Security; Antennas design; Interference; and IoT for application of health.

2.3.1. Application, challenges and issues

Enthusiasm for Wireless Body Area Networks (WBANs) has expanded altogether in last years. This will modify the fate of medicinal services benefits by empowering pervasive monitoring of patients. For example, For example, the paper [12] reviews pioneer WBAN investigate projects and empowering innovations. It investigates application situations, sensor/actuator instruments, radio frameworks, and linkage of WBANs to give point of view on the trade-offs between information rate, network coverage, and power utilization. During overview on the current study on the physical layer, existing MAC and system conventions, the fundamental instruments of WBAN with together engineering and topology is given [10],[40],[41], [42],[43],[44],[45], [46]. In addition to this, the quality of service and cross-layer is talked about. In the [47], the authors give an expansive outline of the most difficult angles in the plan of a WBAN. They try to give valuable insights about the best approach to handle these difficulties. Furtherly, writers provide some novel numerical outcomes, with specific reference to the IEEE 802.15.6. Additionally, they give concurrence researches, chiefly determined through experimentation. In the [48] propose a plan idea for a virtual doctor server (VDS) so as to help different patient medicinal services administrations. VDS will keep the chronicled information about the patient, provide the everyday tips and guidance for him/her, call the specialist or crisis squad if required and can give medical aid help directions on patient or any of his/her nearby relative's PDA's.

In the [49] authors provide a study on the current research that examines the state of the craft of the in vivo correspondence. It additionally concentrates describing and displaying the in vivo remote channel and compared this channel for the other commonplace channels.

In the [50] authors the essential commitment of this paper is not just research and contrast the current low-power communication technologies on-body, yet additionally to consider the wearable technologies have challenges and requirement such as low-power and their interaction with the environment surrounding the home.

Table 1: WBAN survey

Sl.no.	Survey (ref. no.)	Description
1.	Application, challenges and issues [[12]-[43]]	This survey study the issues that affect the performance of WBAN network, WBAN applications, WBAN terminology, and comparison with other existing short-range technology.
2.	Medium access control (MAC) protocol [[12]-[43]]	This survey study different MAC protocol, energy-efficient MAC, power allocation with MAC, MAC protocol challenges, MAC protocol for cognitive radio network, superframe structure, and adaptive traffic MAC protocol.
3.	Routing protocol [[12]-[43]]	Present a comprehensive review of the existing recent routing protocols/algorithms is discussed, energy-aware routing protocols, a priority based routing protocol, thermal-aware routing protocols, and QoS-based routing.
4.	Security [[12]-[42]]	Study Security technology, challenges and its design methodology issue, authentication methods, securing internal communication in WBAN and securing communication between WBAN and external users
5.	Interference [12]	Focuses on a comparative study of mitigation techniques of inter-network interference and discusses the open issues in WBAN.
6.	Mobility [12]	Present state-of-the-art approaches and discuss the important features of related to mobility in WBAN. We give an overview of mobility model

		and categorize the models as individual and group.
7.	Antennas design [12]	Study key points for the design and development of textile antennas for WBAN.
8.	IoT [12]	Present advances in IoT-based health care technologies and reviews the state-of-the-art network architectures/platforms, applications, and industrial trends in IoT-based health care solutions

In the [51] authors introduced a complete investigation of setting context-aware registering in healthcare of elder people. In this manner, elderly individuals can stay away from, for whatever length of time that conceivable, any communication with human services organizations like nursing homes and clinics, which Reducing momentum due to the ongoing review of health institutions. The goal is to feature the current technologies, and additionally necessities and the difficulties in the structure of Health Monitoring Systems (HMS) in the Health Smart Home (HSH).

In the [52] authors investigate plenty of WBAN applications and system architecture in detail utilized for information gathering, data transmission and investigation that form sensor expert framework in the domain of Internet of Things**.**.

2.3.2. Medium Access Control (MAC) protocol in WBAN

MAC protocol performs a formatting operation to access the wireless node with the shared wireless medium, One of the important features is the use of low-energy techniques of sensor points, which increases the operational life of the network, Determining energy consumption is important in WBAN networks where MAC protocols plays an important role in this determination. Current MAC protocols can't oblige communication prerequisites in WBANs. There is a need to create novel, adaptable and reliable MAC protocols that must have the capacity to address every one of these prerequisites in a dependable manner.

For example, in [53], [54], [55], [56], [57] The authors studied WBANs where they conducted a comprehensive study of current MAC protocol. In [58] The authors conducted a study of a MAC protocol for cognitive radio body area network (CRBAN). The MAC layer plays an important and primary role in the cognitive functions that effect, like spectrum mobility, spectrum sharing, and resource allocation. At that point, distinctive MAC protocols with each other and examine testing open issues in the pertinent research.

In the [59] authors made a plenty contemplate on the MAC protocols for WBAN. Firstly, MAC protocol structures are checked for super 802.15.4 and 802.15.6 based on design objectives. Secondly, various access techniques like CSMA/CA, TDMA, Hybrid, and Slotted Aloha where they were investigated and analyzed in terms of design objectives. Thirdly, a two-layered scientific categorization is exhibited for MAC protocols. Basic and subjective analysis is completed for each thought about MAC protocols. Comparative investigation of various MAC protocols is likewise done.

In the [60] authors did topical audit of movement versatile MAC protocols in WBANs. These authors divided movement versatile MAC protocols into three sorts:

- Traffic load estimation (TLE) based MAC protocols,
- Adaptive wake-up interval (AWI) based MAC protocols, and

- Adaptive time slot allocation (ATSA) based MAC protocols.

At that point, authors provide a similar investigation of the protocols depending on their activities in terms of delay, parcel delivery proportion, and power consumption.

2.3.3. Routing protocol in WBAN

Determination of power and communication efficiency, as well as reliable connection between sensors points etc., are highly dependent on routing protocol. To this end, in [61], [62] the authors undertook a comprehensive and objective review of protocols/algorithms for WBAN. The needed evaluation measurements for WBAN is taken into account. The characterization of the current routing protocols is clarified, furthermore, the Future difficulties and near examination of routing protocols.

In [63], [64] authors review cross-layer plans is to demonstrate to explore many issues in the PHY, MAC, and routing layers with their needed services while information transmission is occurring. They contemplated different existing examination commitments regarding WBAN as far as mobility, topology, delay, power utilization, categorization of patient information, channel (slot) assignment to nonemergency and emergency information, routing table, temperature-increment determination of the briefest way on the basis of dependability as far as least temperature, and Packet Delivery Ratio (PDR).

Energy is very vital in WBANs. Expanding the system life cycle brings about huge advantage significantly from sensor capacities, enhancing routing execution with minimized power utilization introduces a noteworthy test. In [65], [66], authors present a general survey of routing techniques in WBAN from the viewpoint of energy. in addition to this, distinctive directing routing influencing the parameter of vitality will be categorized, and contrasted concurring with their points of interest and disadvantages. The primary target of the sensors in WBAN is to gather the patients' indispensable physiological parameters and redirect it to the Medical Center in a dependable and effective way. The gathered information at every sensor is heterogeneous henceforth there is need to deal with information heterogeneity of human services condition and prioritize data according to requirements. In [67] the author reviews need-based directing convention with extensive study and correlation of related works for human services applications.

The expanding interest for real-time applications in such systems animates numerous research exercises in quality-of-service (QoS) depending on routing for information conveyance, in [68] authors characterize, review, model and look at the most important and late QoS depending on routing protocols forwarded in the structure of WBAN. A new classification of solutions is suggested, where the comparison is made for pertinent criteria. A diagnostic model is proposed so as to analyze the performances of all the solutions.

Due to constant contact and radiation output from radio frequency resulting in higher temperatures, which cause serious damage to the human body. As a result, the thermal-aware innovation is of incredible incentive in research, which likewise gives a certification for the further improvement of WBANs. In [69] authors provided brief understanding, examination and correlation of an assortment of essential thermal-aware directing protocols in WBANs.

2.3.4. Security Issue in WBAN

In WBANs, the protection and trustworthiness of the patient's private therapeutic information are extremely important, therefore, the WBANs interchanges and even correspondence with other E-Healthcare parts ought to be confirmed and secured.

In [70], [71], [72], [73] authors outline the main security and privacy issues, and potential assaults WBANs. Furthermore, they have investigated an unsolved issue, for example, quality benefit, which is a genuine security issue, has incredible potential for money in WBANs will clarify. Moreover, the review of various conventions utilizing basic security and protection issues with its professional and cons in WBANs.

What's more, [74], [75] author made an entire overview and investigation of the different authentication plans proposed in the writing to enhance the security of WBANs. in addition, the proposed documentation scheme is categorized on the basis of the applicable documentation technique and outlines each plan in detail.

Moreover, they have featured the points of interest and restrictions of the authentication schemes and presents a thorough correlation of their capacities and highlights. To this end, the [76] focus on scanning about security issues by ensuring internal communication in WBAN as well as external contact with external users. Internet medical of Tings is important in people's lives and it is known as MIoT, where it has contributed to nurturing and improving the health and safety of millions of people. The amount of information processed by MIoT devices increasing very dramatically, which means the higher introduction of touchy information. The security and confidentiality of the information gathered from MIoT adapters, when they are sent to the cloud or are stored, are major unsolved problems.

In [77] author survey the security and confidentiality necessities identified with the information stream in MIoT. In addition, they conducted an in-depth examination of the current solutions to security and confidentiality issues. the widespread security mechanisms generally rely heavily on the basic agreement system. Due to the unwavering quality necessities, power efficiency, and equipment constraints, building a key assertion conspire for a Body Sensor Network can be very a difficult.

In the [77] displayed a cutting edge diagram of security in Body Sensor Networks, concentrating on proposed key understanding plans, ways they are implicit, and the techniques used to assess their security and performance.

2.3.5. Interference in WBAN

IEEE 802.15.6 uses various frequency bands to transmit the information including: The Narrow band (NB) that incorporates the 400, 800, 900 MHz and the 2.3 and 2.4 GHz groups; the Ultra-Wideband (UWB) which utilizes the 3.1– 11.2 GHz; and the Human Body Communication (HBC) that utilizes the frequencies inside the scope of 10– 50 MHz Nonetheless, a portion of the groups are not appropriate for WBANs applications as they can't bolster video or voice transmission (e.g., HBC) or are just qualified to be used by approved clients (e.g., UWB) [12].

Thusly, authorities agreed that 2.4 GHz band is the most engaging extent to be utilized in remedial applications as well as its ability to prevent interference of channel adjacent. A common problem in all wireless technologies used so far is coexistence with different wireless networks. The use of wireless networks is widespread, for example in homes, public parks and hospitals, and these networks may interfere with WBAN networks [78].

Often many of WBAN networks operate at frequency 2.4 GHz ISM band, leading to overlapping with networks of the same frequency close to them.

In [79] in the WBAN techniques, the issues of co-existence and solutions to minimize interference were presented by the authors. Identity, they considered three fundamental WBAN wireless network that works at 2.4 GHz band:

- Zigbee,
- IEEE 802.15.6, and
- Low- power WIFI

In [78], [79], [80] provides a survey of existing WBAN mitigation techniques. First, the source of the interference is identified, studied and the interference type is classified in detail, then classifying and studying the techniques used to reduce and study the interference.

2.3.6. Antennas design in WBAN

The structure of wearable antennas provides the ability to monitor, communicate, power harvest, and store everywhere. Explicit necessities for wearable antennas are a planar structure and adaptable development materials.

In [81] the author presented an overview of the most important points for the structure and development of antenna material, from the decision of the materials to the encircling of the radio antennas. An investigation of the material that has been utilized is additionally presented.

2.3.7. Mobility problem in WBAN

The vast majority of the current works are fundamentally created by expecting all nodes in the static express, these plans consequently can't be connected in genuine situations, where organize of the network between sensors, changes a lot at that time and amazingly to the behaviorof the human moving.

In [82] modren approaches were presented by the authors, and the main and important features of the impending were discussed, like mobility in WBAN. They give a review of versatility model and sort the models as individual and gathering. In addition, a look at networking techniques is generally made in modern literature and a comparative summary is compiled in many respect.

2.3.8. IoT in WBAN

The Internet of Things (IoT) make intelligent objects the basic building blocks in the development of bright, smart physical frames. The IoT has an assortment of application areas, including medicinal services. The IoT revolution is capable of reshaping modern health care through the use of promising technological and economic horizons.

In [83] authors outline propels in IoT-based medicinal services innovations and surveys the best in class arrange designs/platforms, applications, and industrial slants in IoT-based health care arrangements. Also, they investigate particular IoT security and protection highlights, including security necessities, danger models, and attack scientific classifications from the medicinal services point of view.

CHAPTER 3

IMPROVEMENT OF UNDERLAY COOPERATIVE COGNITIVE NETWORKS BANDWIDTH EFFICIENCY UNDER INTERFERENC AND POWER CONSTRAINT

3.1. Introduction

With the fast deployment of wireless services over the last decade, the radio spectrum has become a valued and scarce resource. Furthermore, the Federal Communications Commission has reported that most of the licensed spectrum is severely underutilized [1]. As a promising technique a cognitive network (CN) is proposed to address the dilemma between spectrum scarcity and spectrum underutilization. CN allows unlicensed users to access licensed slots or sub-channels while taking into account the effect of interference on the licensed users, so it should not exceed the tolerable interference threshold [2]. Therefore, the underlay approach is utilized, where the unlicensed users is allowed to use the licensed slots or sub-channels with only a limited transmission power to prevent the interference of unlicensed users from exceeding the interference threshold that the licensed user can tolerate [31].

CT enable users to forward incoming data to each other, thus, and it creates a virtual multiple-input-multiple-output (MIMO) system for cooperative diversity [84], [85]. Although CT have some fundamental benefits compared to non-cooperative communication systems, it has undesirable features that affect communication. For example, when data is processed and transmitted using relays, some drawbacks occur, such as reduced BE [86], which increases the delay during communication [87].

In [88], analysis of BE for cooperative networks and the selection of the best relay node were investigated. That study relied on the harmonic mean of the links between source-relay and relay-destination to select the relay node based on the harmonic mean of these links. In addition to relay node selection, that author considered the incremental redundancy protocol that reduces the BE loss. In [89], the author proposed a joint next-hop node and a relay node selection (JNRS) protocol for wireless distributive multi-hop cooperative networks where the main goal of JNRS is to reduce loss in BE.

The CCN has recently inspected as a potential way to improve unlicensed users capacity using one of two approaches: cooperation between unlicensed users [90] , [91], and cooperation between licensed user and unlicensed users [92]. In [33], the relay selection methods in underlay CCN are widely studied and the outage probability of decode-and-forward (DF) in CCN with both proactive and reactive relay selection in underlay approach was widely analyzed. More precisely in [93], the best multiple relay(s) selection method is proposed. Where a relay selection method with a good trade-off performance of gain for secondary users and loss for primary user is proposed in [94]. In [31], [95], the effects of both proactive and reactive relay selection performance on Bit Error Rate (BER) are analyzed and studied in underlay CCN. Recently in [96], the security performance with relay selection methods under one or both of realistic operation conditions such as maximum transmit power constraint for unlicensed user's, or interference power constraint for licensed users are considered.

However, to the best of our knowledge, none of the previous works investigated and improved the BE of the CCN neither with reactive nor proactive relay selection. The contribution of this work is summarized as follow:

A reactive relay(s) selection method based on ARQ principles is proposed, named as RARQ, and it is used with the CT and CCN for the first time.

The BE is analyzed and improved in CT and CCN. Then, a formulation is provided to show the effects of interference and power constraints on relay selection and BE.

The BE with the multiple relays selection based on RARQ for the CT and CCN are investigated, then we show the effect of the multiple relays selection under interference and power constraints on the overall system performance.

The BE of CCN is affected by the distance of the interference links which are the links between the unlicensed transmitter to the licensed destination and unlicensed transmitter relay to the licensed destination.

3.2. System Model description

For the clarified CCN model in this section, an licensed user (LU) coexists with the unlicensed user as shown in figure 2, where, LT, LD, UT, UR and UD represent a licensed transmitter, licensed destination, unlicensed transmitter, unlicensed relay and unlicensed destination, respectively, and we have M possible UR. Cooperative decode-and-forward (DF) method is utilized, and it works in two phases. In the first phase, UT makes transmission to the M secondary relays and UD, then at second phase, a relay(s) decodes the received data, re-encodes it and then forwards it to a UD.

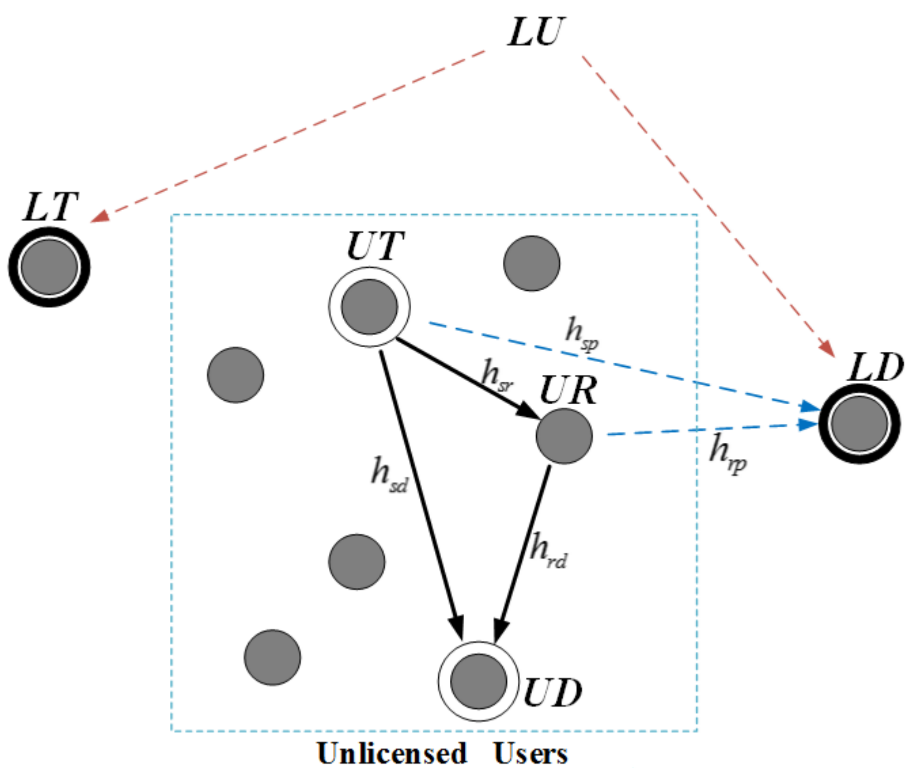

Fig. 2. System description of cognitive cooperative networks

For the considered slow fading (quasi-static) channels, let $h_{i,j}$ be a generic Rayleigh fading modeled channel for any link and it is represented with zero-mean complex Gaussian random variable and with variance $\sigma_{i,j}^2$. Therefore, the squared channel gains ($|h_{i,j}|^2$) are modeled with the parameter $\delta = 1/\sigma_{i,j}^2 = d_{ij}^{\rho}$ [85]. In what follows, we denote the links $UT - UD, UT - UR, UR - UD, UT - LD$ and $UR - LD$ by $h_{sd}, h_{sr}, h_{rd}, h_{sp}$ and h_{rp} ,respectively.

3.3. Cognitive Cooperative Networks

The DF scheme under consideration is summarized as follows. In the first phase, the source broadcasts the data to all the relays including the destination. If a relay decodes the received data correctly, the data is re-encoded, otherwise, the relay remains silent. In the second phase, the relay retransmits the encoded data to the destination. Moreover, if more than one relay decodes the received data correctly, multiple copies of the data will be retransmitted to the destination. The relay selection method used in this work is either reactive or resemble ARQ method, whereby the transmitter retransmits the lost data if and only if it receives a negative ACK from the destination in case of a failure in reception.

In this work, if the direct transmission (DT) fails to deliver the data packet to the destination correctly, the selected relay forwards the data packet from source to the destination. The proposed RARQ method comprises from two cases:

Case1: If the link quality of h_{sd} is better than the link qualities of the maximum of the minimum h_{sr} and h_{rd}, then DT is used by sending positive ACK to all the relays to keep them silent. This mode is expressed as:

$$\emptyset =: \; h_{max} < \; h_{sd} \; ; \; h_{max} = arg \underbrace{\max}_{m} min \, \{h_{sr} \,, h_{rd}\} \tag{1}$$

Cases2: If the link quality of h_{sd} is worse than the link qualities of the maximum of the minimum h_{sr} and h_{rd}, then the destination sends back a negative ACK to the relay(s), and the best relay forwards the received data to the destination, this mode is called CT mode, and it expressed as:

$$\ddot{\emptyset} =: h_{max} > h_{sd}; \;\; h_{max} = arg \underbrace{\max}_{m} min \{h_{sr}, h_{rd}\} \tag{2}$$

The criterion for selecting the best relay (which is given as h_{max}) depends on maximum of the minimum of the link quality of h_{sr} and h_{rd}, where $m = 1,2,3, \dots, M$ is the relay number.

The underlay approach is taken into consideration, in which the power of UT is not exceeded by I_{thd}, where I_{thd} is the maximum tolerable interference level on LD [3]. Therefore, the transmission powers of UT and UR are limited as $SNR_{sp} \leq I_{thd}$ and $SNR_{rp} \leq I_{thd}$, respectively. Where $SNR_{sp} = h_{sp} \cdot P_{UT}$ is signal-to-noise ratio from UT to LD and $SNR_{rp} = h_{rp} \cdot P_{UR}$ is signal-to-noise ratio from UR to LD. Therefore, the maximum power can be transmitted from UT is $P_{UT} \leq I_{thd} / h_{sp}$, and the maximum power can be transmitted from UR is represented as $P_{UR} \leq I_{thd} / h_{rp}$. In the sequel, the maximum transmission powers is given as;

$$P_{UT} = I_{thd} / |h_{sp}|^2 \qquad for \qquad P_{max}^{UT} < I_{thd}, \tag{3}$$

and

$$P_{UR} = I_{thd} / |h_{rp}|^2 \qquad for \qquad P_{max}^{UR} < I_{thd}. \tag{4}$$

Where, P_{max}^{UT} and P_{max}^{UR} are maximum transmission power from UT and UR. In this paper, the channel gains of h_{rp} and h_{sp} are assumed to be equal, so the P_{max}^{UT} is also equal to P_{max}^{UR}. To this end, the relay selection principle should be redefined while considering both the interference and the maximum power constraints. Hence, the Case 1 of the RARQ method under power and interference constraints is redefined as:

$$\emptyset =: h_{max}^{CC} < h_{sd} \tag{5}$$

Case 2 of the RARQ method under power and interference constraint modeled as:

$$\ddot{\emptyset} =: h_{max}^{CC} > h_{sd} \tag{6}$$

In which the h_{max}^{CC} is expressed as

$$h_{max}^{CC} = arg \underbrace{\max}_{m} min \left\{ (I_{thd}/h_{sp}) \cdot h_{sr} \ , (I_{thd}/h_{rp}) \cdot h_{rd} \right\} \tag{7}$$

Where, h_{max}^{CC} is maximum of h_{sr} and h_{rd} under power and interference constraints for CCNs.

3.4. The Bandwidth Efficiencies

3.4.1. Bandwidth Efficiency of Cooperative Networks

In this section, the average BE of the CT with RARQ method has been derived. Then, laterally BE of the CCN is derived and formulated. If M relays participated in cooperation, then $M + 1$ slots or sub-channels will be used to transmit single data packet from the source to the destination in the CT. Therefore, the BE of the CT will be denoted by $1/M + 1$, i.e., if the BE of DT denoted by BE_{DT}, then the BE of CT (BE_{CT}) is given as $BE_{DT}/M + 1$. The average BE with RARQ is given as [88].

$$BE_{RARQ}^{av,CT} = P_r(\emptyset) + 0.5\, P_r(\ddot{\emptyset}) \tag{8}$$

in which $\emptyset$ and $\ddot{\emptyset}$ are the events of DT and CT, respectively, $P_r(\emptyset)$ is the probability of DT, 0.5 $P_r(\ddot{\emptyset}) = 1 - P_r(\emptyset)$ is the probability of CT, the multiplication of $P_r(\ddot{\emptyset})$ by 0.5 is due to the half-duplex mode. The probability of DT is given as

$$P_r(\emptyset) = P_r\,(h_{max} < h_{sd}) = \; P_{h_{max}}\,(h_{sd}) \tag{9}$$

Where $P_r\,(h_{max} < h_{sd})$ is the cumulative distribution function (CDF) of DT. Considering the RARQ method, the best relay selection bases on the max-min link qualities of h_{sr} and h_{rd} and they are represented as exponential random variables with δ_{sr} and δ_{rd} parameters. Hence, $P_{h_{max}}\,(h_{sd})$ is given in [89].

$$P_{h_{max}}\,(h_{sd}) = 1 - \exp(\,-(\delta_{sr} + \delta_{rd})\;\cdot\;h_{sd}), \tag{10}$$

$$P_{h_{max}}\,(h_{sd}) = 1 - \exp\left(-\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2}\right)\cdot h_{sd}\right) \tag{11}$$

The average cumulative distribution function is given as [85]:

$$P_{h_{max}}^{av}\,(h_{sd}) = \int_0^\infty P_{h_{max}}\,(h_{sd})\;.\,p_{h_{sd}}(h_{sd})\;\;dh_{sd}, \tag{12}$$

$$P_{h_{max}}^{av}\,(h_{sd}) = 1 - \frac{1}{\sigma_{sd}^2}\left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2}\right) + \frac{1}{\sigma_{sd}^2}\right)^{-1} \tag{13}$$

Then, using eq.8, the average BE with RARQ method can be rewritten as:

$$BE_{RARQ}^{av,CT} = P_{h_{max}}^{av}(h_{sd}) + 0.5\left(1 - P_{h_{max}}^{av}(h_{sd})\right) =$$

$$0.5\left(1 + P_{h_{max}}^{av}(h_{sd})\right) \quad (14)$$

Then by inserting eq.13 into Eq.14, we directly obtain

$$BE_{RARQ}^{av,CT} = 1 - \frac{0.5}{\sigma_{sd}^2}\left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2}\right) + \frac{1}{\sigma_{sd}^2}\right)^{-1} \quad (15)$$

Here, eq.15 represents the expression of the average BE of a CT with the RARQ method. The RARQ method improves BE, by selecting the direct transmission if the channel gain of $UT - UD$ is better than the channel gain of max-min of the $UT - UR$ and $UR - UD$ this makes $BE_{RARQ}^{av,CT}$ better than BE_{CT}.

It is obvious that if the channel gain of the $UT - UD$ is much better than the max-min of the channel gains of $UT - UR$ and $UR - UD$, the BE approaches to ”1”, because the probability of the DT is increased. However, if the channel gain of the $UT - UD$ is much worse than the channel gain of max-min of the $UT - UR$ and $UR - UD$, the BE approach to 0.5 that is because the probability of CT is high. The RARQ method in the CT for determining the best relay node is given in Table 2.

Table 2: RARQ method Description in Cooperative transmission

Require: $(h_{sd}, h_{sr}, h_{rd}\ and\ h_{max})$

begin

Collect the channel gains of h_{sd} , h_{sr} , h_{rd} and evaluate h_{max}

for each relay node *m* in the secondary cooperative network

  $\boldsymbol{h_{sd}}$ and h_{max} are determined

endfor

if $h_{max} < h_{sd}$, **then**

  destination sends +ACK;

  Best relay node keeps silent and drops what received from the source;

Else if $h_{max} > h_{sd}$, , **then**

  destination sends -ACK; **then**

  Best relay node sends to destination whatever it has received from the source ;

endif

3.4.2. Bandwidth Efficiency of Cognitive Cooperative Networks

In this subsection, the average of BE of the CCN considering the power and interference limitation is derived. For our convenient, before driving $P_{h_{max}^{cc}}(h_{sd})$, let's redefine h_{max}^{CC} as:

$$h_{max}^{CC} = arg \underbrace{\max}_{m} min \left\{ \frac{I_{thd}}{x} y \cap \frac{I_{thd}}{w} z \right\} \tag{16}$$

Where x and y are independent random variables. Then $P_{h_{max}^{CC}}(h_{max}^{CC} > h_{sd})$ is given as;

$$P_{h_{max}^{CC}}(h_{max}^{CC} > h_{sd}) = P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x} y > h_{sd}\right). P_{h_{max}^{CC}}\left(\frac{I_{thd}}{w} z > h_{sd}\right) \qquad (17)$$

For our convenient, h_{sd} is assumed to be equal to P_{max}. So, $P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x} \times y > P_{max}\right)$ can be given as:

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x} \times y < P_{max}\right) = \int_{\frac{I_{thd}}{P_{max}} y}^{x=\infty} \int_{y=0}^{\frac{P_{max}}{I_{thd}} x} f_{X,Y}(x, y)\, dy\, dx, \qquad (18)$$

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x} \times y < P_{max}\right) = \int_{\frac{I_{thd}}{P_{max}} y}^{x=\infty} \int_{y=0}^{\frac{P_{max}}{I_{thd}} x} \delta_x\, \delta_y\, \exp\left(-\left(x\delta_x + y\delta_y\right)\right) dy\, dx. \qquad (19)$$

The average probability of direct transmission is written as (see appendix I)

$$P_{h_{max}^{CC}}^{av}(P_{max}) = 1 - \left(\frac{\sigma_{sp}^2}{\sigma_{sr}^2}\ \frac{I_{thd}}{P_{max}} + 1\right)^{-1} \left(\frac{\sigma_{rp}^2}{\sigma_{rd}^2}\ \frac{I_{thd}}{P_{max}} + 1\right)^{-1} \qquad (20)$$

Then the average BE under interference and power limitation is expressed as:

$$BE_{RARQ}^{av,CC} = 1 - 0.5\left(\left(\frac{\sigma_{sp}^2}{\sigma_{sr}^2}\ \frac{I_{thd}}{P_{max}} + 1\right)^{-1} \left(\frac{\sigma_{rp}^2}{\sigma_{rd}^2}\ \frac{I_{thd}}{P_{max}} + 1\right)^{-1}\right) \qquad (21)$$

The expression of the average BE under interference and power limitations given in eq.21 is completely different from the expression of BE using RARQ method given in eq. 15.

The average BE of CCN is governed by channel gains of the links $UT - LD$, $UR - LD$ and $I_{thd}/\, P_{max}$. $BE_{RARQ}^{av,CC}$ Approaches to 1 as the I_{thd} approaches to ∞ and P_{max} approaches to 0. Furthermore, $BE_{RARQ}^{av,CC}$ approaches to 0.5 as the I_{thd} approaches to 0 and P_{max} approaches to ∞. Table 3 gives the description of the RARQ method in underlay CCN under interference limitation and power limitation. The $BE_{RARQ}^{av,CC}$ is summarized in two scenarios,

Scenario 1: Is a situation that the UT and UR are located close to LD. In this scenario, the transmission power of UT (P_{UT}) towards the UR and the transmission power of UR (P_{UR}) towards the UD should be less than I_{thd} that it results weak signal-to-noise ratios between the $UT - UR$ and $UR - UD$. This makes the probability direct transmission high according to the RARQ method that is made the $BE_{RARQ}^{av,CC}$ increases.

Scenario 2: is a situation that the UT and UR are located faraway to LD. In this scenario, the transmission power of UT towards UR and the transmission power of UR towards the UD will not be limited by I_{th}, and this results with better signal-to-noise ratio between the $UT - UR$ and $UR - UD$.This makes the probability direct transmission low according to the RARQ method which is made the $BE_{RARQ}^{av,CC}$ decrease.

Table 3 algorithm: RARQ method Description for Cognitive Cooperative Network

Require: $(h_{sr}, h_{rd}, h_{sp}, h_{rp}, I_{thd}, P_{max}\ and\ h_{max}^{CC})$

begin

Collect the channel gains of h_{sp} , h_{rp} and interference threshold I_{thd}

Evaluate maximum power such that $P_{max} < I_{thd}$

for each relay node of totally m relays in the secondary cooperative network determine $((I_{thd}/h_{sp}) \times h_{sr})_{max}\ and\ ((I_{thd}/h_{rp}) \times h_{rd})_{max}$

then

determine h_{max}^{CC}

endfor

if $h_{max}^{CC} < P_{max}$, **then**

destination sends +ACK;

(Best relay node keeps silent and dropped what received from the source);

else if $h_{max}^{CC} > P_{max}$, **then**

destination sends -ACK;

(Best relay node sends what received from the source to destination);

endif

Proposition: Given the average BE_{RARQ}^{av} for a cooperative network under RARQ, the BE for multiple relay selection (BE_{RARQ}^{M}) for cooperative network can be redefined as:

$$BE_{RARQ}^{av,M} = \mathbf{1} + \sum_{\boldsymbol{m=1}}^{\boldsymbol{M}} \binom{\boldsymbol{M}}{\boldsymbol{m}} \frac{(\boldsymbol{-1})^{\boldsymbol{m}}}{2\,\sigma_{sd}^2} \left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2} \right) + \frac{1}{\sigma_{sd}^2} \right)^{-m} \tag{22}$$

Proof: where it is assumed for the convenient that all the links have equal gains such that, $h_{r_m d} = h_{rd}$, $h_{sr_m} = h_{sr}$, and $h_{r_m p} = h_{rp}$. By this assumption, the $BE_{RARQ}^{av,M}$ of multiple relays selection can also be defined based on:

$$P_{h_{max}}^{av}(h_{sd}) = \prod_{m=1}^{M}\left(1 - \frac{1}{\sigma_{sd}^2}\left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{r\ d}^2}\right) + \frac{1}{\sigma_{sd}^2}\right)^{-1}\right) \tag{23}$$

$$P_{h_{max}}^{av}(h_{sd}) = \left(1 - \frac{1}{\sigma_{sd}^2}\left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2}\right) + \frac{1}{\sigma_{sd}^2}\right)^{-1}\right)^{M} \tag{24}$$

Then applying the binomial series $(1-x)^M = 1 + \sum_{m=1}^{M}\binom{M}{m}(-1)^m x^m$ [97], (eq. (1.111), p. 25), we obtained eq.22. Now, the same steps can be applied on eq.21 to obtain the BE for multiple relays of CCN ($BE_{RARQ}^{av,CC,M}$) as:

$$BE_{RARQ}^{av,CC,M} = 1 + \frac{1}{2}\sum_{m=1}^{M}\binom{M}{m}(-1)^m\left(\left(\frac{\sigma_{sp}^2}{\sigma_{sr}^2}\ \frac{I_{thd}}{P_{max}} + 1\right)^{-1}\left(\frac{\sigma_{rp}^2}{\sigma_{rd}^2}\ \frac{I_{thd}}{P_{max}} + 1\right)^{-1}\right)^{m} \tag{25}$$

CHAPTER 4

RESULTS

Numerical Results

In this section, we aimed to prove the evaluated analytical results (for the BE performance in underlay CCN under interference and power limitations) of RARQ method over slow Rayleigh fading channels. In this section, we used a common model for the path-loss (fading variances), we set $\sigma_{ij}^2 \propto d_{ij}^{-\rho}$, where d_{ij} is the distance between node i and j, and ρ is the path-loss exponent and it is set to 3 [85]. In what follow, we denote the links $UT-UD, UT-UR, UR-UD, UT-LD$ and $UR-LD$ by $d_{sd}, d_{sr}, d_{rd}, d_{sp}, and\ d_{rp}$ respectively.

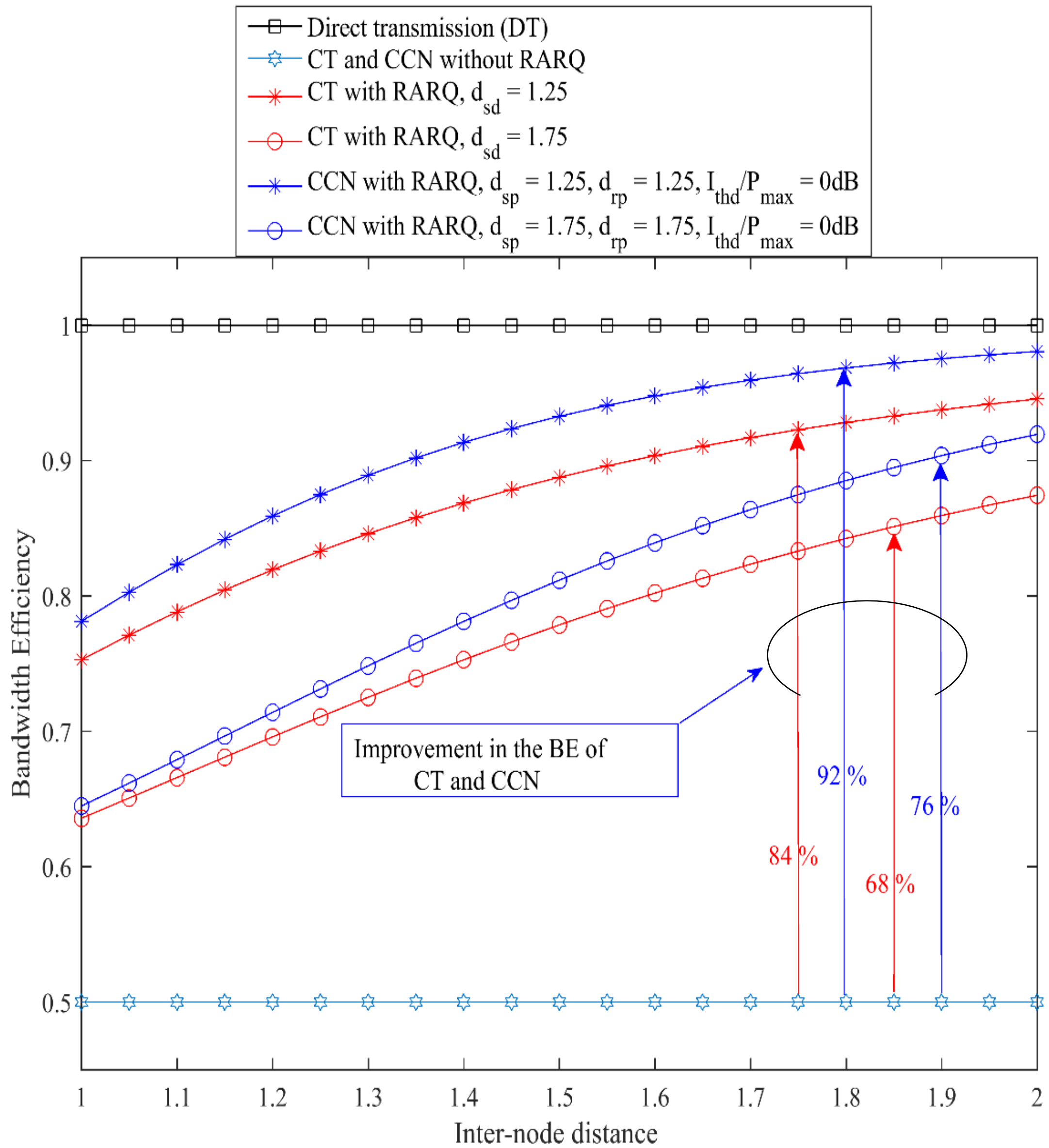

Fig. 3. Comparison of bandwidth efficiencies of cooperative transmission (with and without RARQ), cognitive cooperative network, and direct transmission with inter-node distances.

Figure 3 shows the BE versus inter-node distance. In this figure, the x-axis denotes distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. The important results appear in the figure are summarized as follows:

1. The BE of the direct transmission is always one that it is because a single time slot or sub-channel required to transmit single data packet.
2. The BE of the cooperative transmission is always 0.5, that it is because two time slots or subchannels are required to transmit a single data packet.
3. The BE of CT with RARQ at small distance of the $UT - UD$ (d_{sd} = 1.25) is better than the BE for large distance of the $UT - UD$ (d_{sd} = 1.75), that is because as the distance of $UT - UD$ link decresed and distance of $UT - UR$ and $UR - UD$ links increased, the probability of direct transmission increased which make improved the BE.
4. The BE of the CCN with RARQ is better when unlicensed cooperative network located near to licensed network for fix I_{thd}/P_{max} $(= 0dB)$ and at distance $UT - LD$ (d_{sp} = 1.25) and $UR - LD$ (d_{rp} = 1.25), that is because the direct transmission probability is increased which consequently increses the BE. The direct transmission probability increased due to transmission power constraint from the UT to UR and from UR to UD.
5. The BE of the cognitive cooperative and BE of cooperative transmission with RARQ are increased as distance between $UT - UR$ and $UR - UD$ increased.
6. The BE of the cognitive cooperative and BE of cooperative transmission with RARQ are better than cooperative transmission without RARQ.

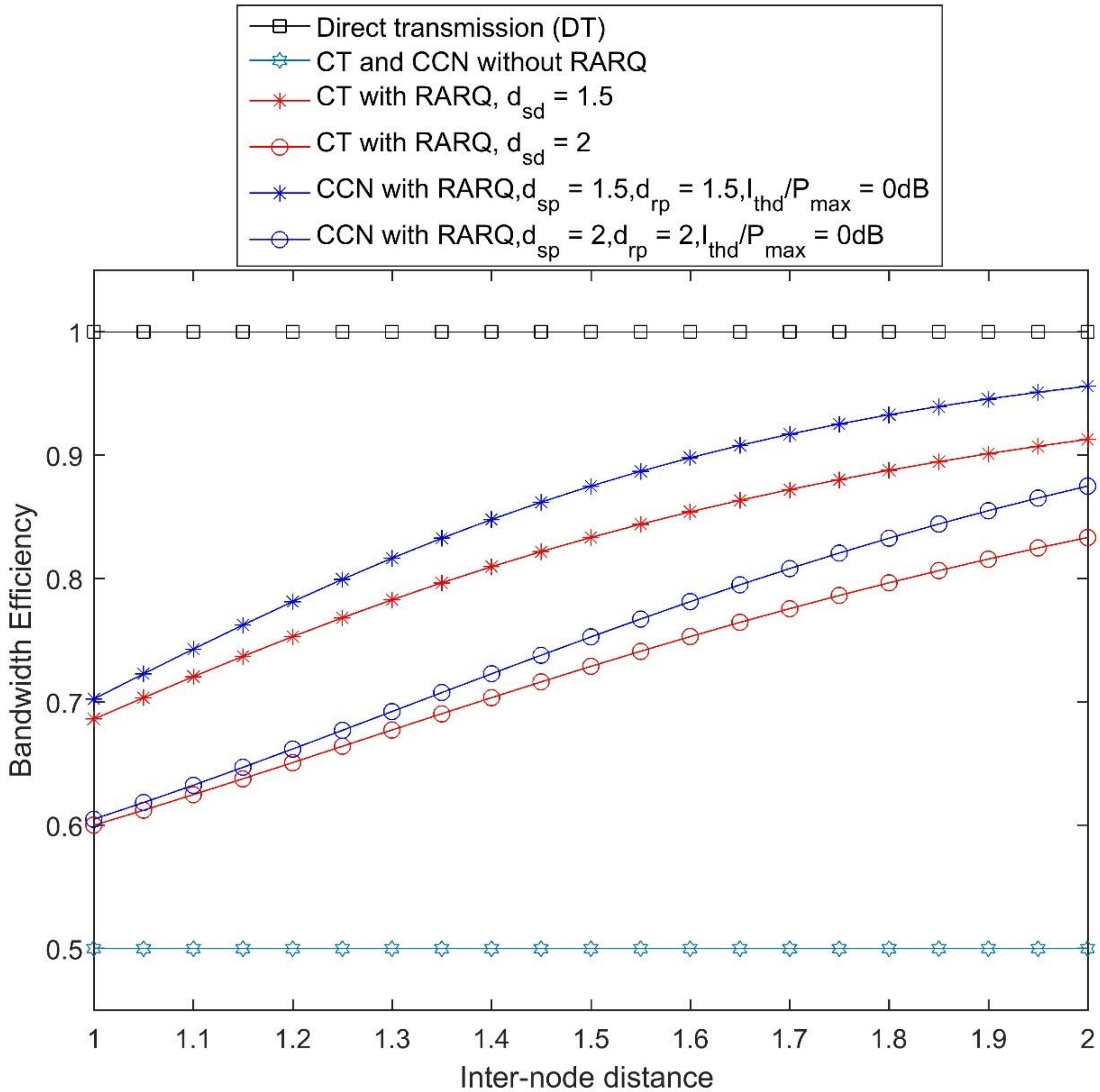

Fig. 4. Comparison of bandwidth efficiencies with inter-node distances

$(d_{sp}, d_{rp}, d_{sd}, is\ changed)$.

Figure 4 shows the BE versus inter-node distance. In this figure we can illustrate the following:

1. The BE of the direct transmission is always one that it is because a single time slot or sub-channel required to transmit single data packet.

2. The BE of the cooperative transmission is always 0.5, that it is because two time slots or sub-channels are required to transmit a single data packet.
3. This figure different from figure. 3., the distance of $UT - UD$, $UT - UR$, and $UR - UD$ is changed, therefore, the results will be different.
4. The BE of CT with RARQ at small distance of the $UT - UD$ (d_{sd} =1.5) is better than the BE for large distance of the $UT - UD$ (d_{sd} = 2), that is because as the distance of $UT - UD$ link decresed and distance of $UT - UR$ and $UR - UD$ links increased, the probability of direct transmission increased which make improved the BE.
5. Also in this figure, the BE of the CCN with RARQ is better when unlicensed cooperative network located near to licensed network for fix I_{thd}/P_{max} $(= 0dB)$ and at distance $UT - LD$ (d_{sp} = 1.5) and $UR - LD$ (d_{rp} = 1.5), when compared to a distance $UT - LD$ (d_{sp} = 2) and $UR - LD$ (d_{rp} = 2) that is because the direct transmission probability is increased which consequently increses the BE. The direct transmission probability increased due to transmission power constraint from the UT to UR and from UR to UD.
6. The BE of the cognitive cooperative and BE of cooperative transmission with RARQ are increased as distance between $UT - UR$ and $UR - UD$ increased.
7. The BE of the cognitive cooperative and BE of cooperative transmission with RARQ are better than cooperative transmission without RARQ.

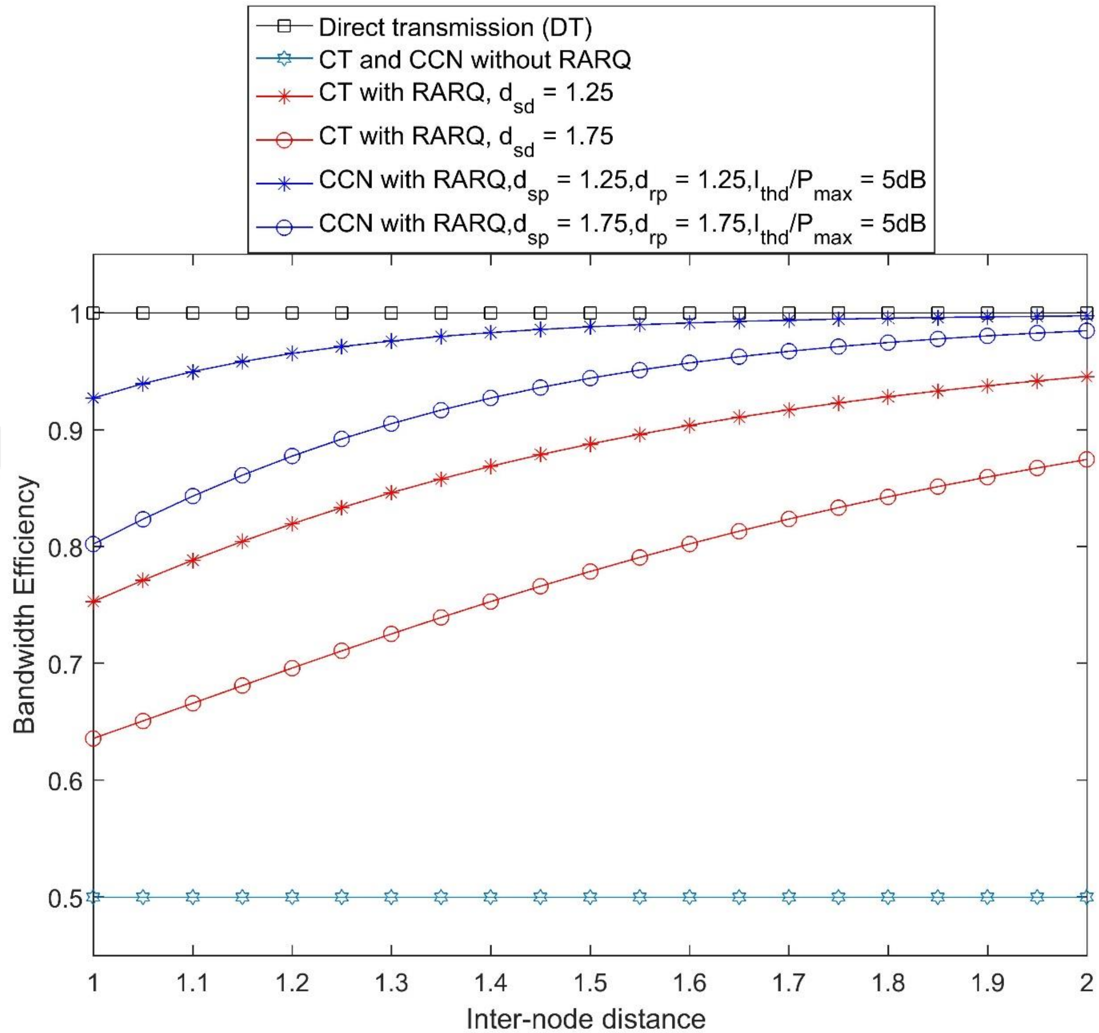

Fig. 5. Comparison of bandwidth efficiencies with inter-node distances (I_{th}/P_{max} is changed).

Figure 5 shows the BE versus inter-node distance. In this figure we can illustrate the following:

1. This figure different from figure. 4., I_{th}/P_{max} is changed to be 5 dB, therefore, the results will be different.

2. For large I_{thd}/P_{max} $(= 5dB)$, the BE of CCN with RARQ is increased and approximately approach the BE of direct transmission, because increased the probability of select best channel.

3. For low I_{thd}/P_{max} $(= 0\ dB)$ in figure 4, the BE of cognitive cooperative with RARQ is less compared to high I_{thd}/P_{max} .

4. RARQ method achieved better performance compared to traditional CT.

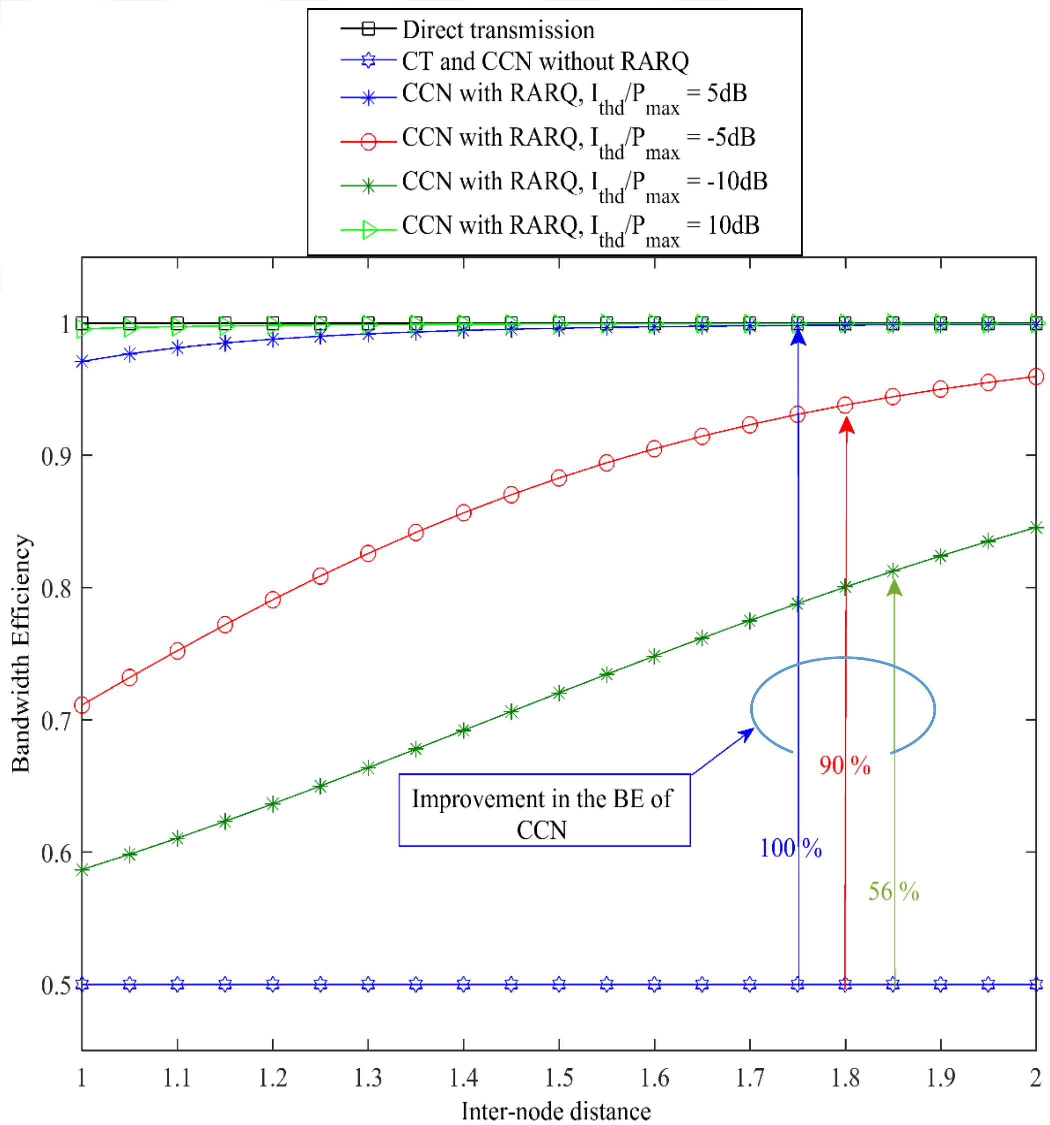

Fig. 6. Comparison of bandwidth efficiency of cooperative transmission (with and without RARQ), cognitive cooperative network, and direct transmission with inter-node distances.

Figure 6 shows the BE versus inter node distance. In this figure, the x-axis denotes distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. In addition, we set the $UT - LD$ (d_{sp} =1) and $UR - LD$ (d_{rp} =1) and they are fix. The important results appear in the figure are summarized as follows:

1. The BE of direct transmission is one and CCN without RARQ is 0.5.
2. For large I_{thd}/P_{max} $(= 10dB)$, the BE of CCN with RARQ is approach the BE of direct transmission.
3. For low I_{thd}/P_{max} $(= -10dB)$, the BE of cognitive cooperative with RARQ is less compared to low I_{thd}/P_{max} $(= -5dB, 0dB, 5dB\ and\ 10dB)$.
4. RARQ method achieved better performance compared to traditional CT.

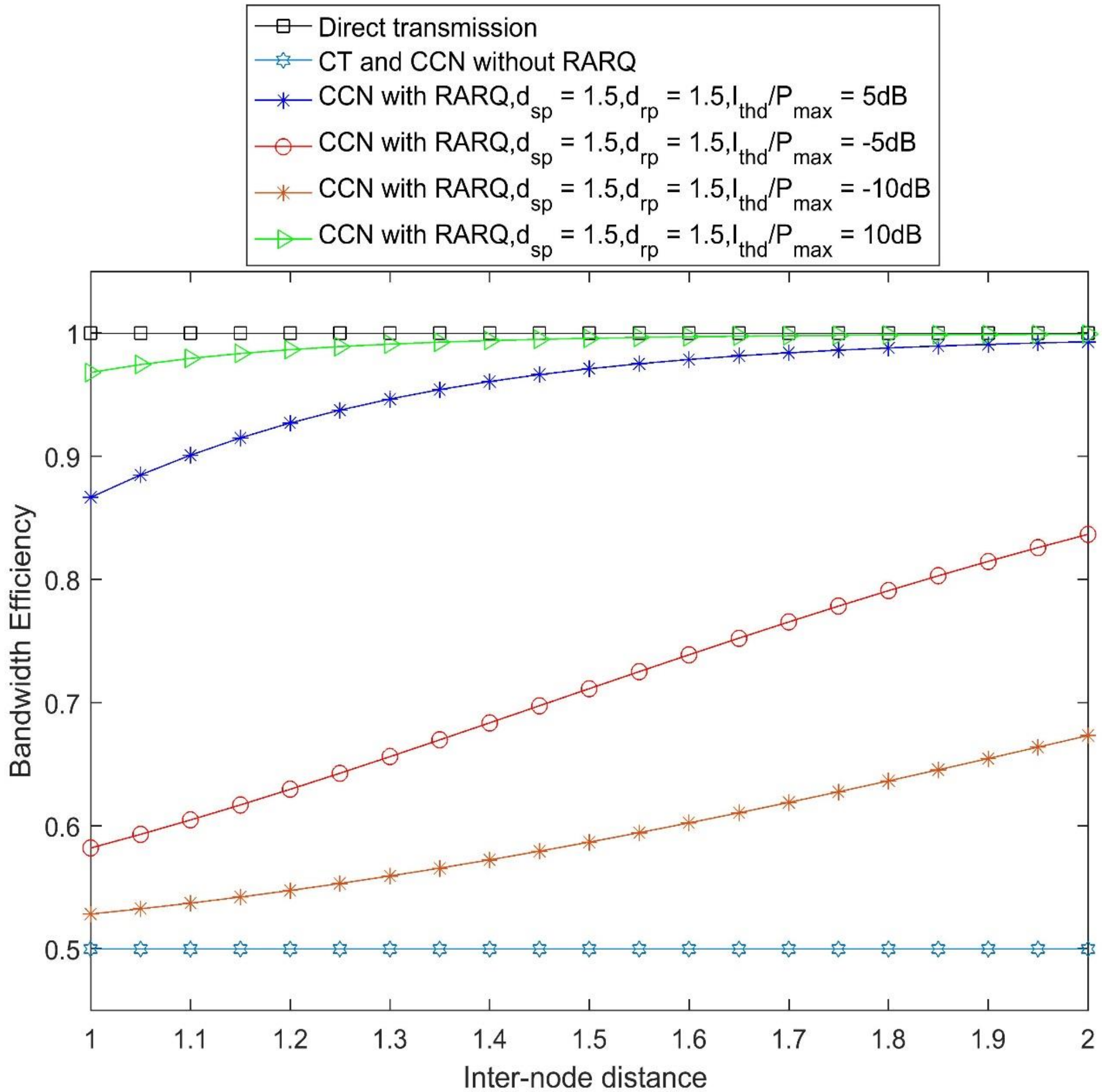

Fig. 7. Comparison of bandwidth efficiency with inter-node distances

$(d_{sp}, d_{rp}, d_{sd}, is\ changed)$.

Figure 7, shows the BE versus inter node distance. In this figure, the x-axis denotes distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2.

The results appear in the figure are summarized as follows:

1. This figure different from figure 6, the distance of $UT - UD$, $UT - LD$ and $UR - LD$ is changed to be 1.5, therefore, the results will be different.

2. The BE decreased due to the distance of *UT-UD and UT-LD and UR-LD* increased, The BE of CT with RARQ at big distance of the $UT - UD$ (d_{sd} =1.5) is worse than the BE for less distance of the $UT - UD$ (d_{sd} =1), that is because as the distance of $UT - UD$ link increased and distance of $UT - UR$ decreased.

3. The BE of the cognitive cooperative and BE of cooperative transmission with RARQ are better than cooperative transmission without RARQ.

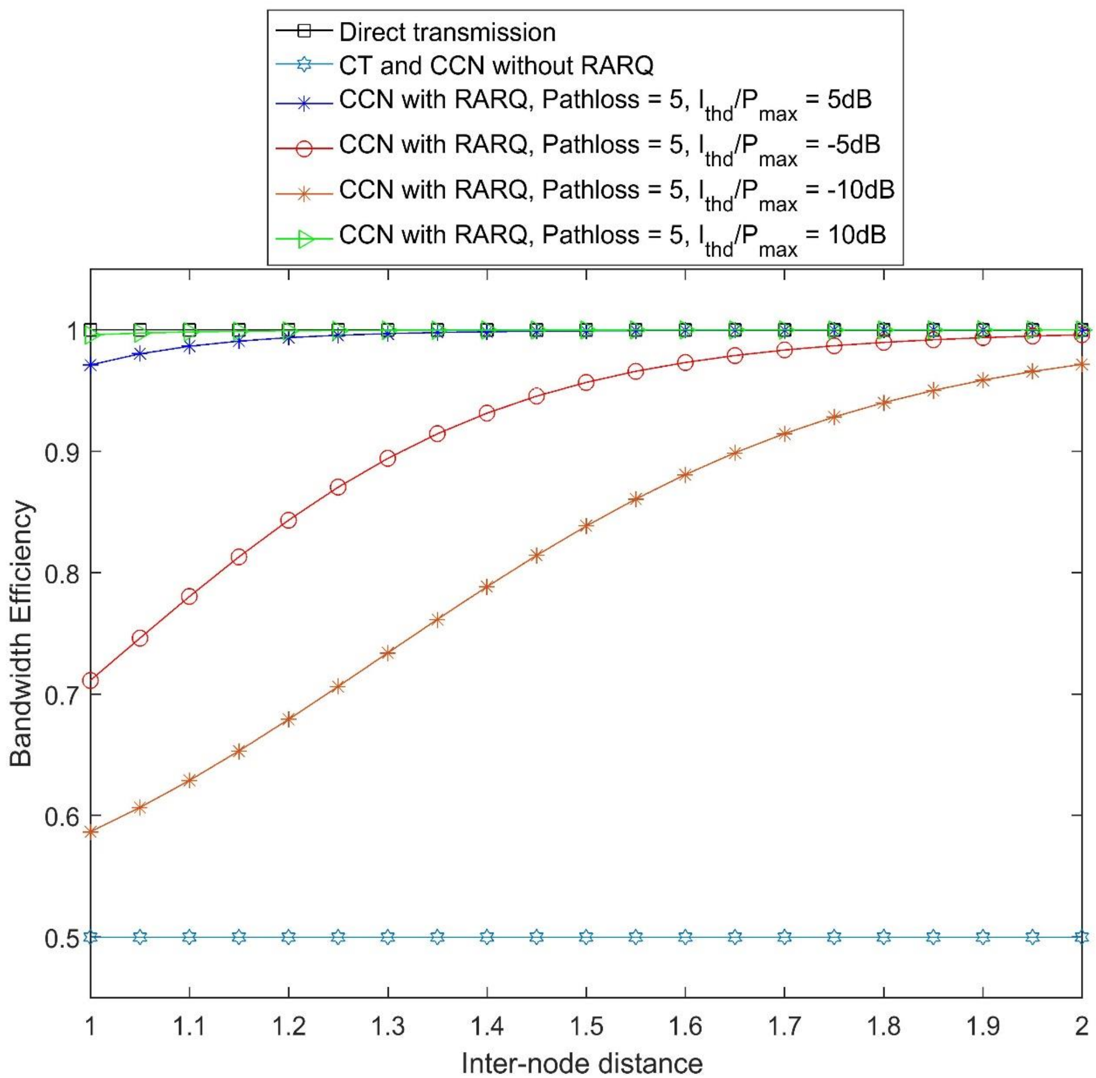

Fig. 8. Comparison of bandwidth efficiency with inter-node distances, (Path-loss is changed).

1. In this figure we changed the path loss from 3 to be 5, In addition, we set the $UT-LD$ (d_{sp} =1) and $UR-LD$ (d_{rp} =1) and they are fix.
2. We can see the path loss of $UT-UR$ and $UR-UD$ links increased, the probability of direct transmission increased which make improved the BE.
3. The BE of the cognitive cooperative and BE of cooperative transmission with RARQ are better than cooperative transmission without RARQ, even when increased the path loss.

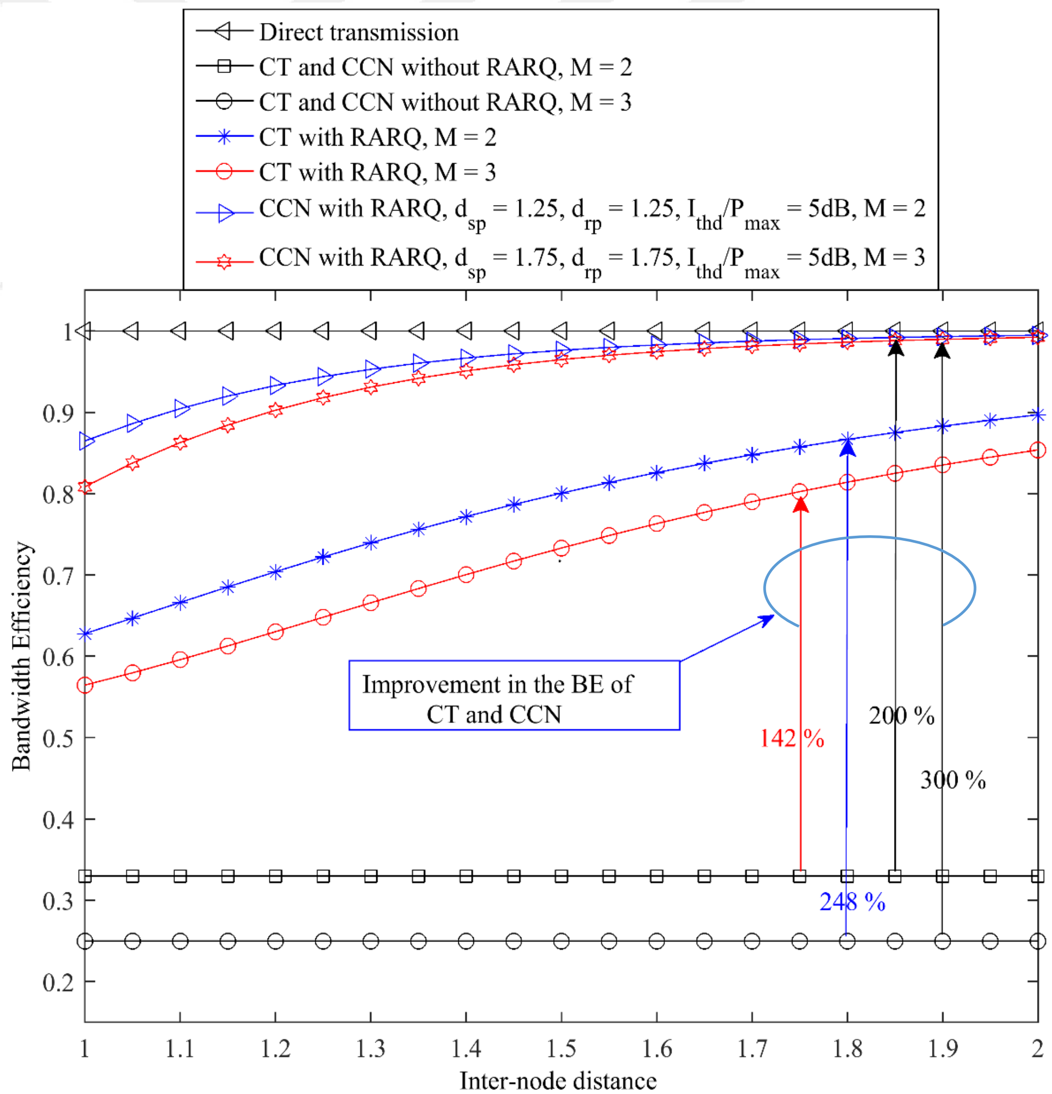

Fig. 9. Comparison of BE of CT (with and without RARQ), CCN, and direct transmission with inter-node distances.

Figure 9 shows the BE versus inter-node distance. In this figure, the x-axis denotes distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. Further, we use multiple relays to help UT. The important results appear in the figure are summarized as follows:

1. The BE of the CT for $M = 2$ is 0.33, because we use two time slots or sub-channels for relaying the data packet pulse signal time slots or sub channels for direct transmission, thus BE $= 1/(1+2) = 0.33$.
2. BE for $M = 3$ is 0.25, that is because, we use three time slots or sub-channels for relaying the data packet pulse signal time slots or sub-channels for direct transmission, thus BE $= 1/(1+3) = 0.25$.
3. For large M, the BE of CT and CCN with RARQ are low.
4. If the unlicensed network located near or far from licensed users and for large I_{thd}/P_{max} $(= 5dB)$, the BE of CCN with RARQ is better than BE of CT for $M = 2$ and $M = 3$.
5. RARQ method provides better performance compared to traditional CT for multiple relays.

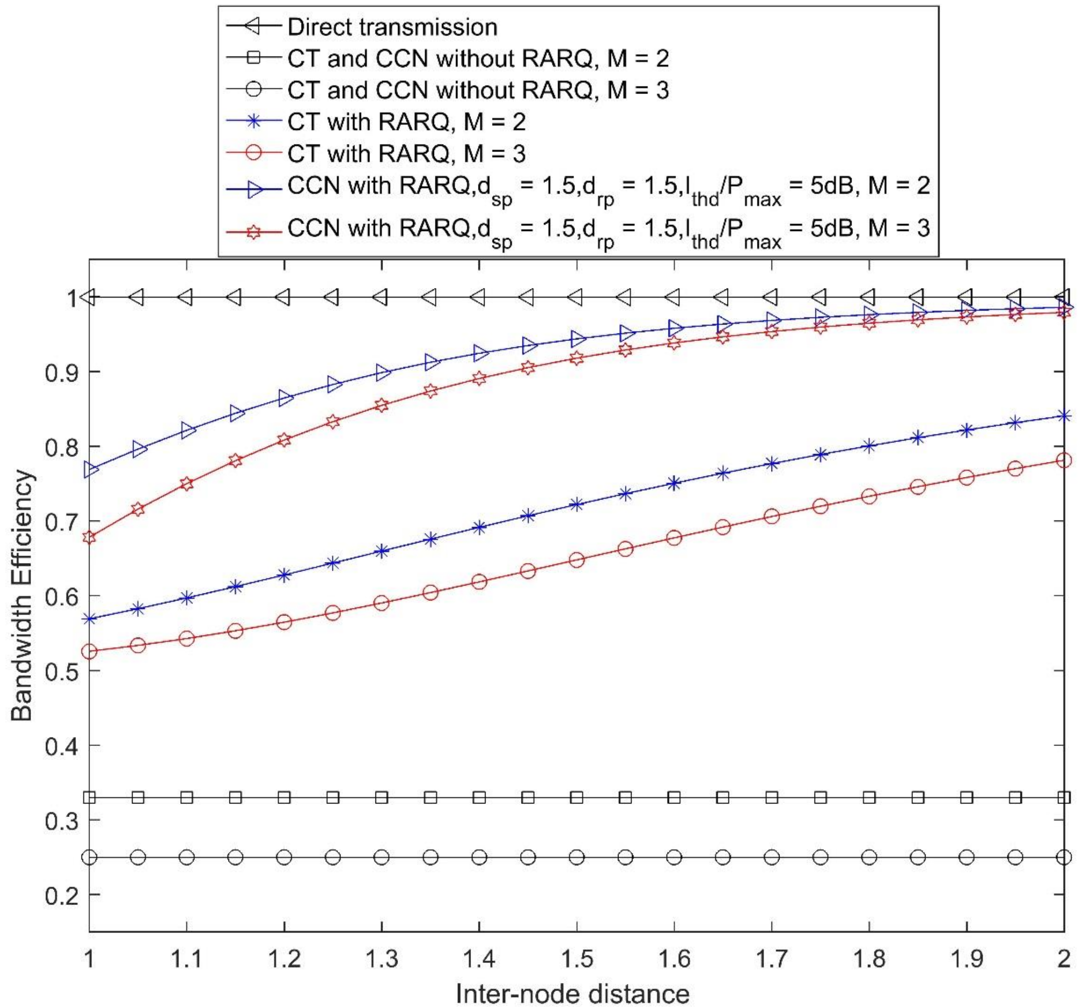

Fig. 10. Comparison of BE of CT, and CCN with inter-node distances

$(d_{sp}, d_{rp}, d_{sd}\ is\ changed)$

Figure 10 shows the BE versus inter-node distance. In this figure, the x-axis denotes distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. Further, we use multiple relays to help UT. The important results appear in the figure are summarized as follows:

1. The BE of the CT for $M = 2$ is 0.33, because we use two time slots or sub-channels for relaying the data packet pulse signal time slots or sub channels for direct transmission, thus BE $= 1/(1+2) = 0.33$.
2. BE for $M = 3$ is 0.25, that is because, we use three time slots or sub-channels for relaying the data packet pulse signal time slots or sub-channels for direct transmission, thus BE $= 1/(1+3) = 0.25$.
3. When compare this figure with figure 9, we can see the BE of CT with RARQ at small distance of the $UT - UD$ (d_{sd} = 1.25) is better than the BE for large distance of the $UT - UD$ (d_{sd} = 1.5), that is because as the distance of $UT - UD$ link decresed and distance of $UT - UR$ and $UR - UD$ links increased, the probability of direct transmission increased which make improved the BE.
4. RARQ method provides better performance compared to traditional CT for multiple relays, even when the distance increases.

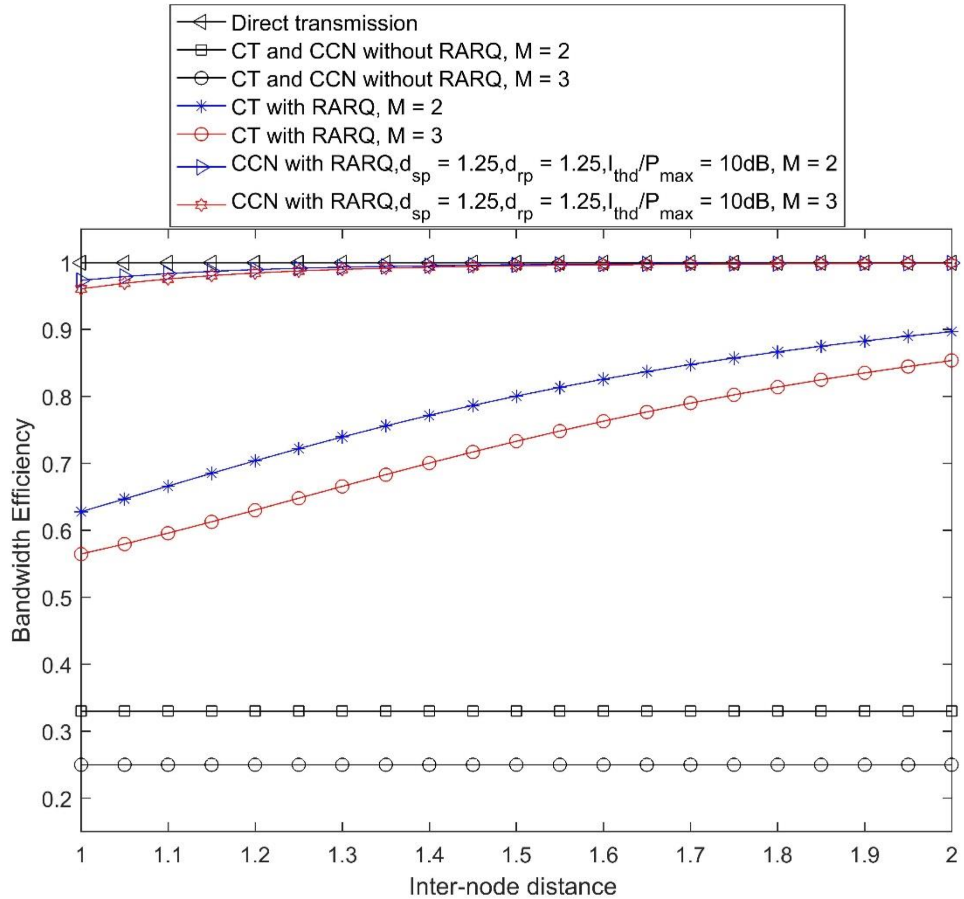

Fig. 11. Comparison of BE of CT, and CCN with inter-node distances (*change the* I_{thd}/P_{max})

Figure 11 shows the BE versus inter-node distance. In this figure, the x-axis denotes distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. Further, we use multiple relays to help UT. The important results appear in the figure are summarized.

1. If the unlicensed network located near or far from licensed users and I_{thd}/P_{max} changed from 5 to 10 *dB*, the BE of CCN with RARQ is better than BE of CT for $M = 2$ and $M = 3$.
2. RARQ method provides better performance compared to traditional CT for multiple relays, even when the I_{thd}/P_{max} increases.

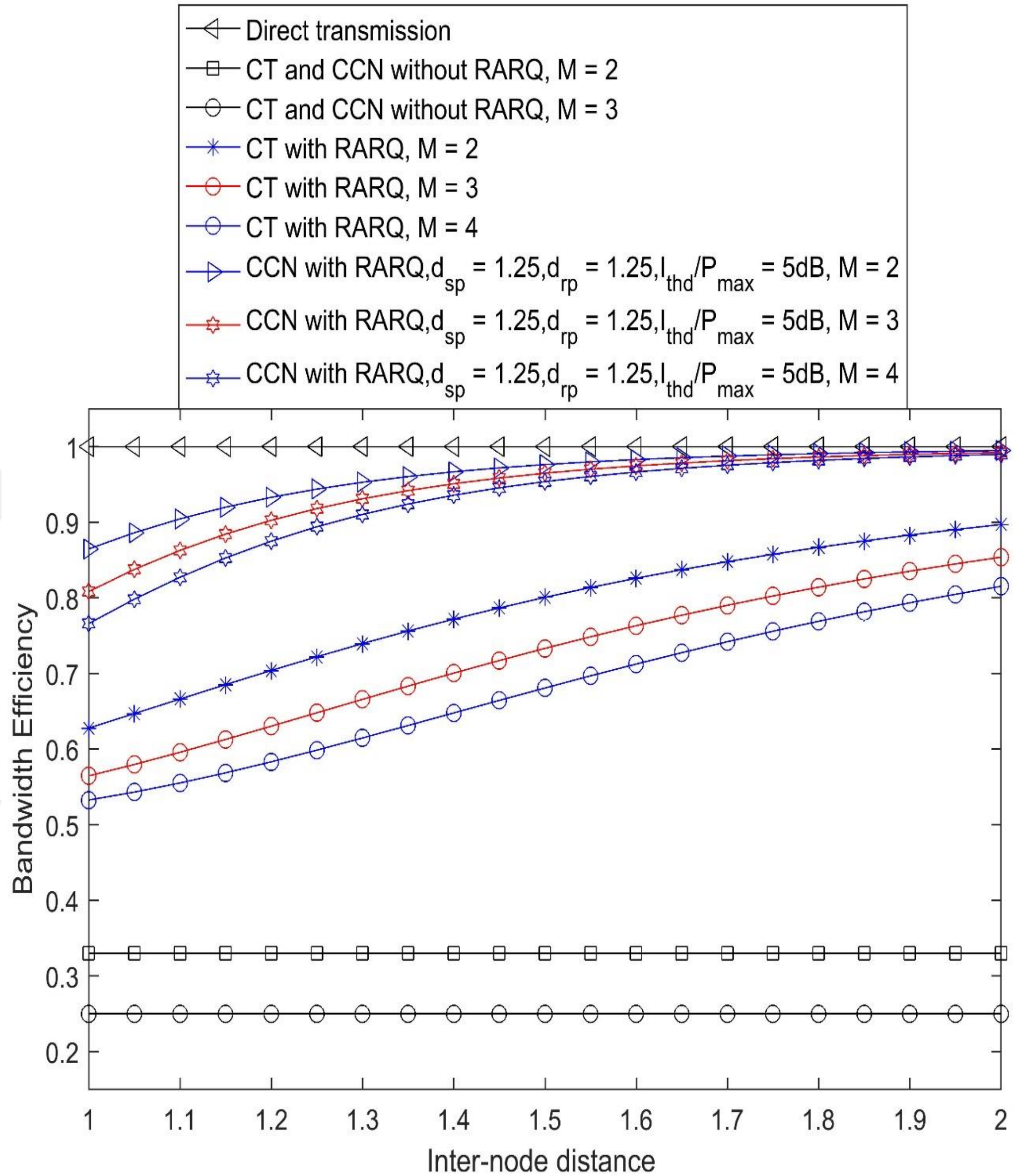

Fig. 12. Comparison of BE of CT, and CCN with inter-node distances (*change the M relays*)

Figure 12 shows the BE versus inter-node distance. In this figure, the x-axis denotes distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. Further, we use multiple relays to help UT. The important results appear in the figure are summarized.

1. In this figure we increase the number of relays from one up to four.

2. For large M, the BE of CT and CCN with RARQ are low.
3. RARQ method provides better performance compared to traditional CT for multiple relays.

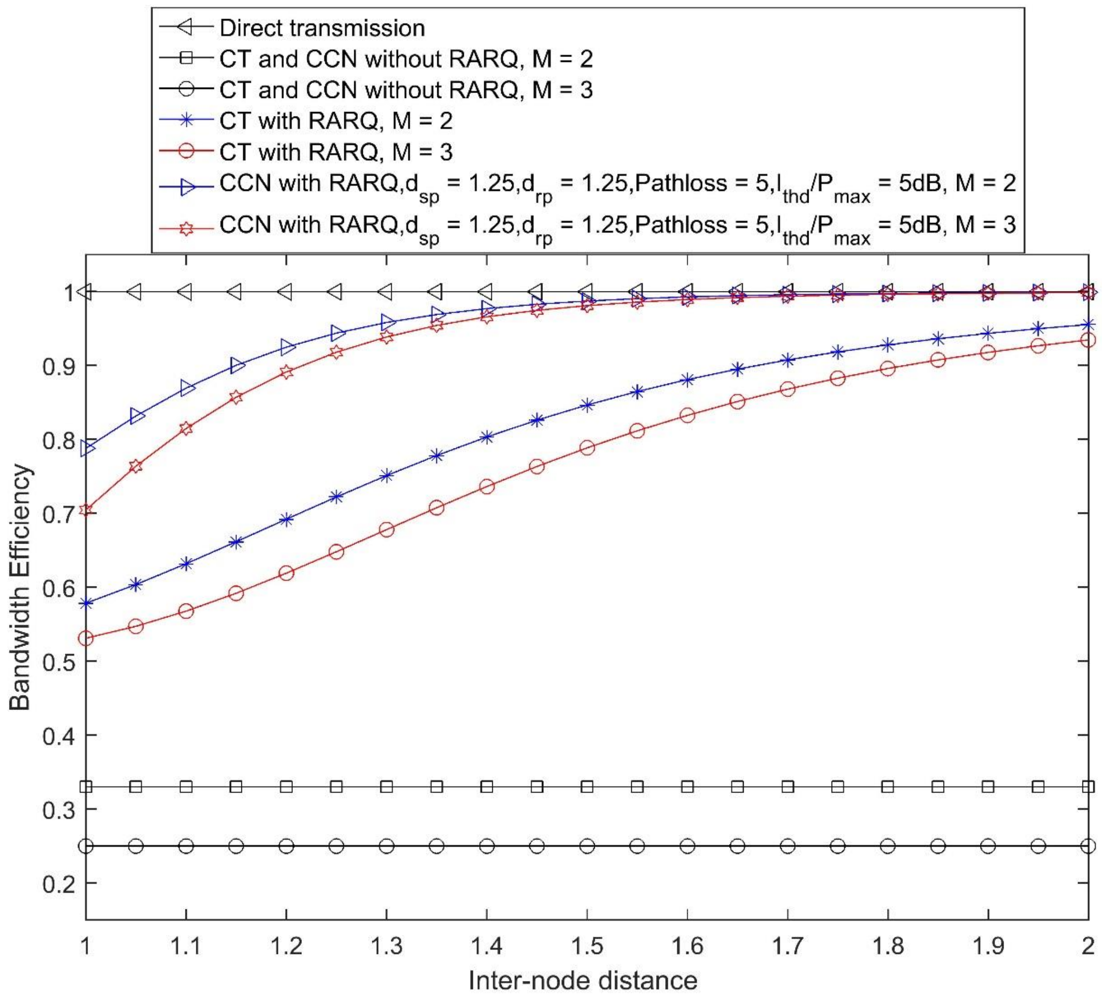

Fig. 13. Comparison of BE of CT with inter-node distances (*change the path loss*)

Figure 13 shows the BE versus inter-node distance. In this figure, the x-axis denotes distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. Further, we use multiple relays to help UT. The important results appear in the figure are summarized.

1. In this figure we changed the path loss from 3 to be 5, In addition, we set the $UT-LD$ (d_{sp} =1.25) and $UR-LD$ (d_{rp} =1.25) and they are fix.
2. We can see the path loss of $UT-UR$ and $UR-UD$ links increased, the probability of direct transmission increased which make improved the BE.
3. The BE of the cognitive cooperative and BE of cooperative transmission with RARQ are better than cooperative transmission without RARQ, even when increased the path loss.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1. Conclusion

This work analyzed and improved the BE of underlay CCN under interference and power constraints using proposed reactive relay selection over slow Rayleigh fading. Cooperative decode-and-forward (DF) method is utilized, and it works in two phases. In the first phase, UT makes transmission to the M secondary relays and UD, then at second phase, a relay(s) decodes the received data, re-encodes it and then forwards it to a UD. The relay selection method used in this work is either reactive or resemble ARQ method, whereby the transmitter retransmits the lost data if and only if it receives a negative ACK from the destination in case of a failure in reception.

At first, BE expression for CT with RARQ method is presented. Then, the BE expression for the CCN is presented with RARQ method in the underlay approach. As the result of the work, it is shown that the BE of CCN is directly affected by the gain of $UT — LD$ and $UR — LD$ links. The result showed, as the unlicensed users located far away from the LD, the BE reduced and vice versa. In addition, the BE of CCN is directly affected by interference threshold, where the result showed, as threshold increased, the BE of CCN increased as well. Furthermore, the BE is also examined under multiple relays scenario, and the results showed that the BE of CCN with RARQ method decreased as the number of relays increased.

5.2. Future works

- In the future, the bandwidth efficiency in underlay Cognitive Cooperative Network under interference limitation with reactive relay-next hop section can be studied and analyzed.

- In future work, we will design and investigate a MAC protocol for inter-WBAN cooperation.

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APPENDIX

In this appendix the probability of direct tansmission of CCN under interference constraint is derived. Let assume $= \sigma_x$, $b = \sigma_y$, $h_{sr} = y$, $h_{sp} = x$, $R_1 = I_{thd}/P_{max}$ and $R_2 = P_{max}/I_{thd}$. Where, R_1 and R_2 are real non-negative number. Then, the probability is written as

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \int_{R_1 y}^{x=\infty}\int_{y=0}^{R_2 x} f_{X,Y}(x,y)\,dy\,dx \qquad (A.1)$$

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \int_{R_1 y}^{x=\infty}\int_{y=0}^{R_2 x} a\,b\exp(-(ax+by))\;dy\,dx. \qquad (A.2)$$

Taking intergration with respect to y, we obtain

$$\int_{y=0}^{R_2 x} a\,b\exp\big(-(ax+by)\big)\;dy \;\rightarrow a\exp(-ax)\int_{0}^{R_2 x} b\exp(-by)\,dy \qquad (A.3)$$

This yield to

$$a\exp(-ax)\int_{0}^{R_2 x} b\exp(-by)\,dy = a\exp(-ax)\,(1-\exp(-bR_2 x)), \qquad (A.4)$$

Inserting the result in (), we obtain

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) =$$

$$\int_{R_1 y}^{x=\infty} a \exp(-ax)\ dx - \int_{R_1 y}^{x=\infty} \mathrm{a} \exp(-bR_2 x - ax)\ dx. \qquad (A.5)$$

We evaluate first term of the integral:

$$\int_{R_1 y}^{x=\infty} a \exp(-ax)\ dx \rightarrow \exp(-aR_1\, y) \qquad (A.6)$$

We evaluate 2nd term of the integral :

$$\int_{R_1 y}^{x=\infty} \mathrm{a} \exp(-x\,(bR_2 + a))\ dx \qquad (A.7)$$

Let assume $g = a + b\,R_2 \rightarrow a = g - b\,R_2$, we obtain

$$\int_{R_1 y}^{x=\infty} (g - b\,R_2)\exp(-x\,g)\ dx \rightarrow$$

$$\int_{R_1 y}^{\infty} (g \exp(-xg\,) - b\,R_2 \exp(-xg\,))\,dx \qquad (A.8)$$

Then,

$$\int_{R_1 y}^{\infty} (g\ exp(-xg\,) - b\,R_2\ exp(-xg\,))\ dx \rightarrow$$

$$\exp(-gR_1 y) - \frac{b\,R_2}{g}\exp(-gR_1 y) \qquad (A.9)$$

Hence, using first and second term of integration, we obtain

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \exp(-aR_1\, y) - \exp(-gR_1 y) + \frac{b\,R_2}{g}\exp(-gR_1 y),$$

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y\ >P_{max}\right)=$$

$$\exp(-aR_1\ y)+\left(\frac{b\ R_2}{g}-1\right)\ \exp(-gR_1 y) \tag{A.10}$$

Taking the average with respect to random variable y, we obtain [A.6]

$$\int_0^{\infty} P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y\ >P_{max}\right)\ p(y)dy \tag{A.11}$$

Where, $p(y)$ is the probability density function, and it is given as

$$p(y)=\frac{1}{\sigma_y}\exp\left(-\frac{1}{\sigma_y}\ y\right) \tag{A.12}$$

The average probability is given as:

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y\ >P_{max}\right)=\frac{1}{(aR_1\ \sigma_y+1)}+\frac{\left(\frac{b\ R_2}{g}-1\right)}{(gR_1\ \sigma_y+1)} \tag{A.13}$$

Where $\sigma_y = 1/b$, hence

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y\ >P_{max}\right)=\frac{1}{\left(\frac{a\ R_1}{b}+1\right)}+\frac{\left(\frac{b\ R_2}{g}-1\right)}{\left(\frac{gR_1}{b}\ +1\right)} \tag{A.14}$$

Let assume $= 1\ /\sigma_w$, $d = 1\ /\sigma_z$,$h_{rd} = z$, $h_{rp} = w$,

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{w}z\ >P_{max}\right)=\frac{1}{\left(\frac{c\ R_1}{d}+1\right)}+\frac{\left(\frac{d\ R_2}{g^*}-1\right)}{\left(\frac{g^*R_1}{d}\ +1\right)} \tag{A.15}$$

Where $g^* = c - dR_2$. Therefore,

$$P_{h_{max}^{CC}}^{av}(P_{max}) = 1 - \left(\frac{1}{\left(\frac{a\,R_1}{b} + 1\right)} + \frac{\left(\frac{b\,R_2}{g} - 1\right)}{\left(\frac{gR_1}{b} + 1\right)}\right)\left(\frac{1}{\left(\frac{c\,R_1}{d} + 1\right)} + \frac{\left(\frac{d\,R_2}{g^*} - 1\right)}{\left(\frac{g^*R_1}{d} + 1\right)}\right) \qquad (A.16)$$

Where, for large R_1,

$$\frac{\left(\frac{b\,R_2}{g} - 1\right)}{\left(\frac{gR_1}{b} + 1\right)} \approx \frac{\left(\frac{d\,R_2}{g^*} - 1\right)}{\left(\frac{g^*R_1}{d} + 1\right)} \approx 0 \qquad (A.17)$$

Hence,

$$P_{h_{max}^{CC}}^{av}(P_{max}) = 1 - \left(\frac{\sigma_{sp}^2}{\sigma_{sr}^2}\,\frac{I_{thd}}{P_{max}} + 1\right)^{-1}\left(\frac{\sigma_{rp}^2}{\sigma_{rd}^2}\,\frac{I_{thd}}{P_{max}} + 1\right)^{-1} \qquad (A.18)$$

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