ISTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

NOVEL INTERFERENCE AND SPECTRUM AWARE ROUTING TECHNIQUES FOR COGNITIVE RADIO AD HOC NETWORKS

Ph.D. Thesis By
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Department : Computer Engineering

Programme : Computer Engineering

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TASARSIZ BİLİŞSEL RADYO AĞLARI İÇİN GİRİŞİM VE SPEKTRUMA DAYALI ÖZGÜN YÖNLENDİRME TEKNİKLERİ

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FOREWORD

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EKİM 2011 Ahmet Çağatay TALAY

Computer Engineer,M.Sc.

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ABBREVIATIONS

AoA	:	Angle of Arrival
AODV	:	Ad hoc On demand Distance Vector
AuxCCC	:	Auxiliary Common Control Channel
BS	:	Base Station
CBR	:	Constant Bit Rate
CCC	:	Common Control Channel
CH	:	Cluster Head
CM	:	Cluster Member
CR	:	Cognitive Radio
CTBR	:	Cognitive Tree-Based Routing
DFS	:	Dynamic Frequency Selection
DSA	:	Dynamic Spectrum Access
DORP	:	Delay motivated On-demand Routing Protocol
ETT	:	Expected Transmission Time
FCC	:	Federal Communications Commission
FIFO	:	First In First Out
GPS	:	Global Positioning System
IEEE	:	Institute of Electrical & Electronics Engineers
ISM	:	Industrial, Scientific and Medical
MAC	:	Medium Access Control
MINLP	:	Mixed Integer Non-Linear Programming
PDA	:	Personal Digital Assistant
QoS	:	Quality of Service
RAC	:	Range Adaptive Cognitive Radio Networks
RSSI	:	Received Signal Strength Indicator
SAR	:	Self Adaptive Routing For Dynamic Spectrum Access in CR Networks
SEARCH	:	Spectrum Aware Routing Protocol for Cognitive Ad Hoc Networks
SINR	:	Signal to Interference-plus-Noise Ratio
SCRP	:	Spectrum-Aware Cluster-based Routing Protocol
SOP	:	Spectrum OPportunities
SORP	:	Spectrum Aware On-demand Routing in Cognitive Radio Networks
SPEAR	:	SPEctrum-Aware Routing Protocol
STOD-RP	:	Spectrum-Tree based On-Demand Routing Protocol
ToA	:	Time of Arrival

TPC	:	Transmit Power Control
UNII	:	Unlicensed National Information Infrastructure
UNITED	:	Cluster Based Routing Technique For CR Networks
VoIP	:	Voice Over Internet Protocol
WFQ	:	Weighted Fair Queueing
WiMAX	:	Worldwide Interoperability for Microwave Access
WRAN	:	Wireless Regional Area Network

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NOVEL INTERFERENCE AND SPECTRUM AWARE ROUTING TECHNIQUES FOR COGNITIVE RADIO AD HOC NETWORKS

SUMMARY

Everyday a new device, an application or a service is being developed requiring broadband wireless communication all of which are more frequently being used by majority of people. Consequently, there is a growing demand for high-speed wireless network that is acknowledged as a key technology for low-cost internet access as well as next-generation wireless networking services in personal use, as well as local, campus-wide, and metropolitan areas. Therefore, radio spectrum becomes one of the most heavily used and expensive natural resource around the world and have to be used efficiently. Radio spectrum is managed by the government authorities in many countries. Such authorities allocate the radio spectrum in bands of frequency of varying widths. Those frequency bands are licensed to specific users/purposes. Legally, those users own and have the right to use the frequency bands on a long term basis over vast geographical regions. Although almost the entire spectrum suitable for wireless communications has been allocated, recent studies and observations indicate that nearly 70% of the radio spectrum is not used for either a significant amount of time or in certain geographical areas while unlicensed spectrum bands are always crowded. Since inefficient usage and growing bandwidth demand constitute a bottleneck in communication, efficient and economic usage of the spectrum has become an important and challenging research area. Advancement of cognitive radio technology that allows dynamic spectrum access temporally and spatially in an intelligent way has potential to remedy the problems encountered from spectrum shortage since it is considered as a promising direction for improving the performance of wireless networks.

Cognitive radio technology is based on efficiently reusing and sharing the licensed spectrum bands as long as the interference power inflicted on the primary users of the band remains below a predefined threshold level. With the advances in cognitive radio networking which relies on exploiting unused spectrum, there is a growing need to study how to design a cognitive radio network using an automated methodology to fully exploit the potentials of the cognitive radio networking. To design such mobile cognitive radio networks, routing is one of the key challenging issues to be addressed and requires deep investigation. Thus, the problem of designing effective routing solutions in cognitive radio ad hoc networks is the main focus of this thesis. Additionally, the essential aim is to optimize routing by fully exploiting the sensing history and the spectrum occupancy statistics while avoiding the interference to the primary user. As a starting point, insights about previously suggested and potential routing approaches that can be employed are given. Taking these insights into consideration, novel interference and spectrum aware routing techniques for cognitive radio ad hoc networks are proposed. Since the performance of the routing techniques depends on the routing metric, the proposed routing metrics are specifically tailored

for cognitive radio ad hoc networks. Therefore, the spectrum usage characteristics, and the interference created by existing flows in the network both from the primary and secondary users are taken into account to define novel routing metrics. While protecting the primaries' ongoing activity and observing the activity behavior of the primary nodes, the designed metric should guarantee the stability of the route for the cognitive radio nodes. In order to realize this, the desirable properties of the spectrum availability cost and interference cost metrics are combined into a single metric by taking their weighted average with a tunable parameter. The weighted average can be viewed as an attempt to balance between the spectrum availability cost and interference cost metrics. The proposed metric provides higher performance in cognitive radio ad hoc network environment, since it takes into account the packet losses, the bandwidth of each link, primary user activity, and the stability of each link. Another approach used in this thesis is partitioning the network into smaller segments, that is, clustering. Clustering in mobile ad hoc networks provides with some important benefits including optimizing bandwidth usage, balancing distribution of resources and resolving scalability issues in combination with routing schemes. Making use of clustering, a cluster-based routing technique for mobile cognitive radio ad hoc networks, UNITED, is proposed for maximizing the network throughput and minimizing the end-to-end delay. The key concept is to use clusters to adapt such a dynamic cognitive radio environment and performing routing in intra- and inter-cluster levels. Initially, nodes organize themselves into several clusters by the clustering algorithm that is based on a combined weight metric which takes into account several system parameters such as distance, transmission power, mobility, remaining power of nodes, and the sensed information about available spectrum. Following completion of cluster formation, routing is done according to the spectrum usage and interference metrics in intra- and inter- cluster domains. Clusters adapt themselves dynamically with respect to spectrum availability, and the high mobility of the nodes based on the calculated metric. In addition to the mentioned contributions, an autonomous distributed adaptive transmission range control scheme for cognitive radio ad hoc networks is proposed. This scheme simultaneously considers the quality of service requirements of primary and secondary users. Range Adaptive Cognitive Radio Networks (RAC) is proposed by utilizing mentioned adaptive transmission range scheme. RAC mechanism is based on self-adjusting variable transmission range of secondary users to keep communication link alive or to find an alternative path that circumvents the primary user activity. It is a simple yet an efficient approach to utilize throughput by dynamically changing transmission range when needed. The key feature of the proposed strategy is that, a cognitive radio user can maximize its achievable throughput and minimize end-to-end delay by dynamically changing its transmission range without imposing interference to any primary user. As another contribution, the self adaptive routing (SAR) technique is also proposed. SAR technique incorporates novel metrics and autonomous distributed adaptive transmission range control mechanism to provide self adaptivity. In order to meet the requirements of self adaptivity, a route adaptation and route preservation method that continuously maintains and optimizes an established route is also incorporated into the self adaptive routing technique. As a consequence, the proposed technique routes traffic across paths with better spectrum availability and reduced interference via designed routing metrics.

Extensive experimental evaluations are performed in the ns2 simulator to show that proposed techniques provide better adaptability to the environment and maximize throughput, minimize end-to-end delay in a number of realistic scenarios. The simulation results illustrate that proposed techniques outperform recently proposed routing techniques developed for cognitive radio ad-hoc networks.

TASARSIZ BİLİŞSEL RADYO AĞLARI İÇİN GİRİŞİM VE SPEKTRUMA DAYALI ÖZGÜN YÖNLENDİRME TEKNİKLERİ

ÖZET

Günümüzde insanlar giderek artan bir hızda geniş bant kablosuz bağlantı özelliği bulunan cihazları kullanmaktadırlar. Örneğin, belirli bir sosyal alanda birçok kişinin dizüstü bilgisayarları ile internete bağlanmaya çalıştığını düşündüğümüzde dahi bu cihazların birbirlerine girişim yaratarak kendileri için ayrılmış erişilebilir tayf için bile yarış halinde olduklarını söyleyebiliriz. Söz konusu kablosuz cihazlara sadece dizüstü bilgisayarlar değil de cep/akıllı telefonlarının, çeşitli ölçüm ve gözlem işlemlerinde kullanılan duyargaların, büyük mağazalarda yaygınlaşan radyo frekansı tanımlama (RFID) etiketlerinin de dahil olduğunu eklememiz gerekir. Sonuç olarak, kablosuz iletişim teknolojisine dayanan pek çok cihaz ve bu cihazların kullanıldığı pek çok uygulama geliştirilmekte ve bizlerin hizmet ve beğenisine sunulmaktadır. Her geçen gün daha da artan yoğunlukta kullanılan bu cihaz ve uygulamalar ise yüksek performans sergilemek için büyük miktarda veri akışı gerçekleştirmekte ve geniş bant kablosuz veri iletişimine ihtiyaç duymaktadırlar. Bu tip kablosuz veri iletişiminin yapıldığı elektromanyetik tayf ise sınırlı bir doğal kaynaktır ve en etkin biçimde kullanılması gerekmektedir. Söz konusu elektromanyetik tayfın kullanımı birçok ülkede yetkili kamu kurumları tarafından yönetilmektedir. Yetkili kurumlar genel olarak tayfı belirli bölümlere sabit olarak ayırmakta ve belirli bir erişim/iş için lisanslayarak kullanıcılara sunmaktadır. Ancak yapılan araştırmalar söz konusu sabit dağıtım sonucu oluşan bölümlerden bazılarının neredeyse hiç kullanılmadığı ve anlık olarak elektromanyetik tayfın yaklaşık % 70'inin boş kaldığını gözler önüne sermektedir. Ortaya çıkan verimsiz kullanım ve yüksek hızlı kablosuz ağlara artan rağbet nedeniyle elektromanyetik tayfın etkin ve ekonomik kullanımı çok önemli bir araştırma alanı haline gelmiştir. Lisanslı elektromanyetik radyo tayfını etkin şekilde kullanma ve paylaşmaya olanak sağlaması nedeniyle radyo tayfından yararlanma potansiyelini önemli ölçüde arttıran bilişsel radyo teknolojisi bu alanda geliştirilmiş olan en önemli teknolojidir. Bilişsel radyo teknolojisi, temel olarak lisanslı (birincil) kullanıcı üzerinde yaratılan girişimin önceden belirlenmiş belirli bir sınır değer altında kaldığı sürece radyo tayfının lisanssız (ikincil) kullanıcılar tarafından verimli bir şekilde tekrar kullanımı ve paylaşımı ilkesine dayanmaktadır. Bu ilke, bilişsel radyo teknolojisinin anlık olarak lisanslı kullanıcısı tarafından kullanılmayan lisanslı tayftaki boşluklarda lisanssız kullanıcıların lisanslı kullanıcıların işleyişlerine zarar vermemek koşulu ile "yasal olarak" söz konusu lisanslı tayfı kullanabilmelerine olanak sağlamıştır. Bir başka deyişle, bilişsel radyo ağlarındaki ikincil kullanıcıların, birincil kullanıcıların radyo tayfına fırsatçı bir şekilde erişimine imkan sağlamaktadır.

Bilişsel radyo teknolojisi radyonun çalışma karakteristiklerini çevrenin anlık gerçek zamanlı koşullarına göre adapte ederek, esnek, verimli ve güvenilir radyo tayfı kullanımı için anahtar teknoloji haline gelmiştir. Bahsedilen özellikleri nedeniyle bilişsel radyo teknolojisi lisanslı kullanıcılara herhangi bir zarar vermeksizin büyük

miktardaki kullanılmayan radyo tayfını etkin bir şekilde kullandırma potansiyeline sahiptir. Söz konusu potansiyelden faydalanmak üzere bilişsel radyo ağları tasarlanırken üzerinde önemle durulması gereken en önemli konulardan bir tanesi de yönlendirmedir. Çalışmamızda bilişsel radyo ağlarında kullanılmak üzere önerilen yönlendirme teknikleri hakkında bir bakış açısı sunulmakla beraber asıl olarak girişim ve tayfa dayalı özgün yönlendirme teknikleri önerilmektedir. Öncelikle, tayf kullanım karakteristikleri ve ağdaki akışların yarattığı girişim göz önüne alınarak yönlendirme ölçütleri tasarlanmıştır. Yönlendirmenin etkin yapılabilmesi için önerilen ölçütler, tamamen tasarsız bilişsel radyo ağ özellikleri göz önüne alınarak üretilmiştir. Bilişsel radyonun en önemli özelliklerinden birisi etkin boş tayf seçimi ve kullanımı olduğundan öncelikle tayf kullanımı hakkında bilgi edinmeye yönelik olarak tayf sezme geçmişi ve tayf doluluk oranına dayanan bir ölçüt türetilmiştir. Söz konusu ölçüt bir kayan pencere kullanarak tayf doluluk süresini takip eden ve boş/dolu geçişlerini de dikkate alan bir ölçüttür. Göz önüne alınan diğer bir ölçüt ise, ağ başarımını doğrudan olumsuz olarak etkilediği önceki çalışmalarla ortaya konulmuş olan girişimi dikkate alan bir ölçüttür. Söz konusu girişim ölçütü, hem birincil hem de ikincil kullanıcıların aktivitelerinden kaynaklanan girişimi kontrol ederek, girişimin düşük olduğu tayfın ve rotanın seçilmesine olanak sağlamaya yöneliktir. Girişim ölçütü ortam gürültüsü ve hem birincil hem de ikincil kullanıcıların mevcut akışlarından kaynaklanan girişimi ölçmeye çalışmaktadır. Söz konusu ölçüt, düğümün kendi gönderdiği paketlerden ve çevre düğümlerden elde ettiği bilgileri kullanarak bir girişim değeri üretmektedir. Bahsedilen ölçütler bir parametre ile orantılı olarak birleştirilerek tek bir ölçüt haline getirilmiş ve tayf seçimi ve rota seçimi türetilen bu ölçüt göz önüne alınarak gerçekleştirilmiştir. Ayrıca, bahsedilen yönlendirme ölçütlerine ek olarak bilişsel radyo ağları için otonom dağıtık uyarlanır menzil kontrol stratejisi önerilmiştir. Önerilen menzil kontrol stratejisi, birincil kullanıcı sezilmesi durumunda birincil kullanıcıyı sezen tüm bilişsel radyo düğümlerinin iletim menzillerini sezilen birincil kullanıcıya girişim yaratmayacak şekilde otonom olarak değiştirmesi ilkesine dayanmaktadır. Bahsedilen önerilere ek olarak dağıtık ve etkin bir kümeleme tabanlı yönlendirme tekniği geliştirilmiştir. Söz konusu yönlendirme tekniği temel olarak bilişsel radyo düğümlerinin sezilen tayf bilgisi, iletim gücü, hareketlilik bilgileri gibi birçok sistem parametresine bağlı olarak kümelenmesine dayanmaktadır. Yönlendirme küme içi ve küme dışı olarak iki ayrı şekilde gerçekleştirilmektedir. Küme dışı yönlendirmede sadece küme başları kullanılarak iletim gerçekleştirilmektedir. Rota seçimi ise önerilen yönlendirme ölçütlerine dayanılarak gerçekleştirilmektedir. Ancak, tüm düğümler tek atlama uzaklıktaki komşuları ile doğrudan iletişime geçebilmektedir. Son olarak, bilişsel radyo ağları için otonom dağıtık uyarlanır menzil kontrol stratejisi ve radyo tayf erişebilirliği ve girişim maliyeti ölçütlerini bir arada kullanan özgün bir yönlendirme tekniği önerilmiştir. Söz konusu yönlendirme tekniği içerisine güncel bilgileri kullanan rota uyarlama ve koruma yöntemi dahil edilerek bulunan rotaların anlık duruma bağlı olarak değiştirilmesi veya onarılması amaçlanmıştır. Rota seçiminde önerilen yeni yönlendirme ölçütlerin kullanımı nedeniyle önerilen teknik trafiği kullanılabilir tayfın daha çok ve girişimin daha az olduğu rotalara yönlendirmektedir. Ayrıca, rotaların anlık durumları rota uyarlama ve koruma alt birimi tarafından sürekli olarak kontrol edildiğinden, güncel rotanın onarılması veya güncel rotadan daha iyi bir rota bulunması durumlarında etkin ve hızlı bir şekilde gerekli rota değişikliklerinin gerçekleştirilmesine olanak sağlanmıştır.

NS2 benzetim ortamı kullanılarak gerçekleştirilen testler, önerilen yöntemlerin bilişsel radyo ağlarına uygunluğunu ve ağ başarımını arttırdığını göstermiştir. Ayrıca güncel bilişsel radyo teknolojisini kullanan diğer yöntemlerle karşılaştırıldığında önerilen protokollerin hem uçtan uca veri aktarımını arttırdığı hem de uçtan uca gecikmeyi azalttığı ve başarımlarının daha yüksek olduğu gözlemlenmiştir.

1. INTRODUCTION

Everyday a new device or application is developed which requires broadband wireless communication and people are more frequently using these devices and services. Consequently, there is a growing demand for high-speed wireless networks that are acknowledged as a key technology for low-cost Internet access as well as next-generation wireless networking services in personal, local, campus, and metropolitan areas. Due to this tremendous interest to use wireless access to exploit such services, sharing of wireless medium has become a bottleneck and radio spectrum became one of the most heavily used and expensive natural resource around the world. Although almost the entire spectrum suitable for wireless communications has been allocated, recent studies and observations indicate that many portions of the radio spectrum are not used for either a significant amount of time or in certain geographical areas while unlicensed spectrum bands are always crowded. According to the Federal Communications Commission (FCC) measurements, roughly 70% of the frequency spectrum is not actively in use. On the other hand, the ”spectrum shortage” is often complained about in wireless communications arena essentially because of the use of outdated spectrum assignment policies such as allocating spectrum portions statically, which allow little sharing. Dynamic spectrum access (DSA) was proposed as a promising solution to scarce spectrum resource. DSA would enable unlicensed (secondary) users to access the licensed portions of the spectrum whenever there is no primary traffic. New promising technologies are required to accomplish a dynamic spectrum usage ruled by the national licensing authorities such as Information and Communication Technologies Authority (Bilgi Teknolojileri ve İletişim Kurumu, BTK) for Turkey and FCC for the USA. Accordingly, Cognitive Radio (CR) was first proposed by Mitola [1] to enable dynamic spectrum access temporally and spatially in an intelligent way. Based on this, cognitive radio networks were proposed to enable wireless secondary users to sense and learn the surrounding environment and correspondingly adapt their transmission strategies. The essential components of

Cognitive Radio networks are classified into two groups: the licensed network and the secondary network, i.e. called CR network. The licensed network is referred to as an existing network, where the primary users have licenses to operate in certain bands of the spectrum assigned by the national licensing authority. A CR network, which holds no license to operate in a desired band, is designed to share the licensed radio frequency with primary users by intelligently exploiting spectrum gaps named as Spectrum OPportunities (SOP) or white holes. Since frequencies are assigned for the use of primary users, their activities must not be affected by unlicensed users.

Spectrum access control that gives optimal solutions in a single-cell configuration may become inefficient for some multi-hop dynamic spectrum access scenarios. For example, an optimized medium access control (MAC) protocol may provide the best joint channel, power, and rate assignment for a particular link. However, such an assignment can be quite inefficient when considering end-to-end path of a given flow which may possibly traverse several primary networks. Hence, the importance of finding appropriate cognitive multi-hop protocols capable of optimizing solutions over end-to-end paths becomes a follow up concern. In fact, the issue in CR networks for dynamic spectrum access is how to ensure radio resources for cognitive transmissions while guaranteeing the service for all ongoing primary user communications over the exploited channels along the whole path. Besides, the number and width of the cognitively used frequency bands can vary. Thus, the need of simple and efficient routing algorithms in dynamic spectrum access CR networks is the main motivation of ongoing research.

Finding an appropriate path from a source node to a destination node in a topology that changes dynamically and which may cover multiple primary networks is a highly challenging problem. Moreover, an appropriate route should be constructed with respect to the specific behavior of all primary networks. This is a key challenge for the secondary network comprising of nodes keeping only local information.

CR networks enabling dynamic spectrum access, i.e. an ad hoc CR network, can be constructed by CRs that can relay information between any CR sender and receiver. Note that, these CR nodes are not necessarily homogeneous. This task becomes even more challenging because of the fact that cognitive radio domain still lacks of standards even rules or principles defined for secondary networks.

Unlike infrastructure-based networks, node mobility may also cause frequent route outages and the repeating the entire route setup process is costly in terms of resource usage. Nodes may also move into regions of primary user activity necessitating immediate route management procedures. Clearly, routing is the first issue to deal with in order to construct CR-aware dynamic spectrum access networks.

1.1 Motivation of the Thesis

Cognitive radio is an emerging and promising research area to improve the spectrum utilization significantly by making use of the spectrum holes in both time and space domains. A key challenge in the design of cognitive radio networks is dynamic spectrum allocation, which enables wireless devices to access portions of the spectrum opportunistically as they become available. Another highly challenging problem is to find an appropriate path from a source node to a destination node in a topology that changes dynamically. In addition to this, in cognitive radio ad hoc networks multi-hop communication is required. The dynamic nature of the radio spectrum calls for the development of spectrum-aware routing algorithms. The challenge in cognitive radio ad hoc network routing is based on the temporal and spatial nature of spectrum availability. Therefore, the available spectrum bands may be different at each relay node in a multi-hop path.

The problem of routing in multi-hop cognitive radio networks targets the establishment and the maintenance of wireless multi-hop routes among secondary users by deciding both the relay nodes and the spectrum to be used on each link of the path. Such problem exhibits similarities with routing in multi-channel, multi-hop ad hoc networks and mesh networks, but with the additional challenge of having to deal with the simultaneous transmissions of the primary users which dynamically change the SOPs availability. As a consequence, from the implementer perspective the main challenges for routing throughout multi-hop cognitive radio networks consist of the need of spectrum-awareness; the set up of ”quality” routes; the need of maintaining and adaptation of existing routes in such a dynamic environment.

In this thesis we consider dynamic routing functionalities and focus on the design of efficient and yet simple mechanisms to provide better adaptability to the environment and maximize throughput, minimize end-to-end delay. It is also observed during our preliminary research steps the transmission range adaptation could be a way to ease to live with primary users. Therefore we aim at

- to define routing metrics by taking the spectrum usage characteristics, and the interference created by existing flows in the network both from the primary and secondary users into account
- to design an autonomous distributed adaptive transmission range control scheme for cognitive radio networks
- to present a distributed and efficient cluster based routing technique, which benefits from new metrics
- providing self adaptivity by using autonomous distributed adaptive transmission range control mechanism and incorporating the novel metrics into the routing technique

Following different steps at design/implementation/simulations of both metrics and techniques the contributions have been shared with the academic arena as listed below.

1.2 Contributions of the Thesis

Our research has contributed to pioneering work in the field of CR networks, specifically on the network layer of the CR networks with the aim of maximizing overall network performance. The key contributions can be summarized briefly as follows:

- A novel self adaptive routing algorithm for multi-hop cognitive radio ad hoc networks (SAR) is proposed. The proposed routing algorithm incorporates novel metrics and autonomous distributed adaptive transmission range control mechanism to provide self adaptivity.
- A distributed and efficient cluster based spectrum and interference aware routing technique (UNITED) which utilizes the mentioned routing metrics is proposed.
- An autonomous distributed adaptive transmission range control scheme for cognitive radio networks (RAC) is proposed. The cognitive user's maximization

of its achievable throughput without interfering the primary user by adapting transmission range of the secondary users dynamically is the key feature of the proposed scheme.

- Novel routing metrics specific to cognitive radio networks are defined. The spectrum usage characteristics, and the interference created by existing flows in the network both from the primary and secondary users are taken into account to define introduced novel routing metrics.

- A distinctive classification of routing techniques based on the method used in spectrum decision is proposed.

Extensive experimental evaluations are performed in the ns2 simulator to show that proposed techniques provide better adaptability to the environment and maximize throughput, minimize end-to-end delay in a number of realistic scenarios and outperforms recently proposed routing techniques developed for cognitive radio networks.

1.3 Publications Produced

Throughout the PhD candidature, I have produced the following publications:

- Talay A. C., Altılar D. T., Submitted on April 12th 2010, revised on April 2011, under review: Self Adaptive Routing for Dynamic Spectrum Access in Cognitive Radio Networks. Elsevier Computer Networks.

- Talay A. C., Altılar D. T., 2011: United Nodes: Cluster based Routing Protocol for Mobile Cognitive Radio Networks. To appear in *IET Communications* (accepted in June 2011, doi:10.1049/iet-com.2010.0285).

- Talay A. C., Altılar D. T., 2011: RAC: Range adaptive cognitive radio networks. To appear in *Elsevier Computer Standards & Interfaces* (accepted in April 2011, doi:10.1016/j.csi.2011.04.002).

- Talay A. C., Altılar D. T., 2010: United Nodes: A Cluster Based Routing Protocol for Mobile Cognitive Radio Networks. 1st International Workshop on Cognitive Radio Interfaces and Signal Processing (CRISP 2010) in conjunction with IEEE

International Conference on Communications (ICC 2010), May 27 2010, Cape Town, South Africa.

- Butun I., Talay A. C., Altılar D. T., Khalid M., Sankar R., 2010: Impact of mobility prediction on the performance of Cognitive Radio networks. Wireless Telecommunications Symposium (WTS 2010), April 21-23 2010, Tampa, FL, USA.

- Talay A. C., Altılar D. T., 2009: Menzil Adaptif Bilişsel Radyo Ağları. IV. İletişim Teknolojileri Ulusal Sempozyumu, October 15-16 2009, Adana, Turkey.

- Talay A. C., Altılar D. T., 2009: ROPCORN: Routing protocol for cognitive radio ad hoc networks. The International Conference on Ultra Modern Telecommunications ICUMT, October 12-14 2009, St. Petersburg, Russia.

- Talay A. C., Altılar D. T., 2009: RACON: a routing protocol for mobile cognitive radio networks. The ACM workshop on Cognitive radio networks (CoRoNet 2009) in conjunction with MobiCom, September 21 2009, Beijing, China.

- Talay A. C., Altılar D. T., 2009: RAC: Range adaptive cognitive radio networks. 4th International Conference on Communications and Networking in China, ChinaCOM 2009, August 26-28 2009, Xi'an, China.

1.4 Organization of the Thesis

The remainder of this thesis is organized as follows.

Chapter 2 presents previously proposed routing approaches. While giving a description, a detailed analysis on their properties, advantages and disadvantages is also provided. Moreover, a distinctive classification of routing techniques based on the method used in spectrum decision is proposed.

Chapter 3 defines the proposed novel routing metrics while describing the rationale behind the metrics that comprise of the effects of variation in link loss ratio, differences in link transmission rate as well as inter-system and intra-system interferences. The chapter shows how metrics can be derived.

Chapter 4 introduces the UNITED cluster based routing technique that is based on location, communication efficiency, network connectivity and spectrum availability. The chapter focusses on the clustering algorithm and how routing performed based on the metrics.

Chapter 5 proposes the RAC mechanism which is based on self-adjusting variable transmission range of secondary users to find an alternative path to keep communication link alive.

Chapter 6 presents the SAR routing technique that is designed for range adaptive cognitive radio networks for efficient data transportation in CR networks. The chapter addresses the use of transmission range adaptivity, link modeling and interference avoiding.

Chapter 7 draws conclusions on the proposed routing technique for cognitive radio networks and summarizes the results of this dissertation based on the performance analysis covered in the preceding chapters.

2. ROUTING IN COGNITIVE RADIO NETWORKS

Cognitive radio is the key enabling technology for dynamic spectrum access networks. It is a flexible and intelligent wireless system that is aware of its surrounding environment and changes its transmission or reception parameters to communicate efficiently avoiding interference with the primary or secondary users. Secondary users benefit from a CR to utilize the licensed band of the primary system as long as the Quality of Service (QoS) of the licensee's operation is not compromised. Based on the CR's interaction with the primary network system, transmission modes are classified into three types: interweave, overlay and underlay modes [2]. The interweave mode is based on the idea of opportunistic communication, and was the original motivation for cognitive radio. In the interweave mode, the secondary system can occupy the unused licensed band, i.e., the spectrum opportunity, under the assumption that the majority of the spectrum is typically under-utilized. These SOPs change temporally and spatially. Therefore, in this mode, the secondary transmitters need to have the real-time functionality for monitoring spectrum and detecting the SOPs. A number of spectrum-sensing techniques [3, 4, 5] are proposed and spectrum-sharing techniques mainly based on game-theory have been analyzed [6, 7].

Overlay mode allows the secondary system to use the licensed band even if the primary system is using the band. In overlay systems, the cognitive radios use sophisticated signal processing and coding to maintain or improve the communication of primary radios while also obtaining some additional bandwidth for their own communication. The secondary transmitter is assumed to have knowledge of the primary message [2]. This precious information can be used to cancel the interference completely due to the primary signals at the cognitive receiver by sophisticated techniques. On the other hand, the secondary users can utilize this knowledge and assign part of their power for their own communication and the remainder of the power to assist (relay) the primary transmissions.

In the underlay mode, simultaneous transmissions of primary and secondary systems are also allowed on condition that the secondary system interferes less than a certain threshold with the primary system [2]. Accordingly, the concept of interference-temperature [8] has been introduced to determine a tolerable interference level at the primary receiver.

Another issue in dynamic spectrum access is the sharing protocol which can be named as the spectrum access control. The spectrum access control that gives optimal solutions in a single-cell configuration may become inefficient for some multi-hop dynamic spectrum access scenarios. For example, an optimized medium access control (MAC) protocol may provide the best joint channel, power, and rate assignment for a particular link, but such an assignment can be quite inefficient when considering the end-to-end path of a given flow possibly traversing several primary networks. Hence, the importance of finding appropriate cognitive multi-hop protocols capable of optimizing solutions over end-to-end paths becomes a follow up concern. In fact, the issue in CR networks for dynamic spectrum access is how to ensure radio resources for cognitive transmissions while guaranteeing the service for all ongoing primary user communications over the exploited channels on the whole path. Besides, the number and width of the cognitively used frequency bands can vary as required.

The topology and connectivity map of the CR networks for dynamic spectrum access are determined by the available frequency bands of primary users and their instantaneous state. More specifically, finding the appropriate path from a source node to a destination node in a topology that evolves dynamically is usually a highly challenging problem. Moreover, with respect to the specific primary users' behavior, an appropriate routing approach should be considered. This is a key challenge as nodes only have limited local information. Since it is clear from previous studies that cognitive nodes can relay on each other spreading across different primary networks communication area. CR networks enabling dynamic spectrum access, i.e., an ad hoc CR network can be constructed by CRs relaying information between a CR sender and a CR receiver. Note that, these CR nodes are not necessarily homogeneous. This task becomes even more challenging because the cognitive radio domain still lacks several defining rules and principles. The sudden appearance of a primary user may render certain channels unusable in the vicinity of CR users, necessitating a local change in the existing routes. In such situations, the routing layer is presented with two options. The first of these involves circumventing the affected region, thereby increasing the path length and consequently, the end-to-end delay. As an alternative, the channel may be changed in the region of primary user activity keeping the routing path constant, thus incurring a one-time channel switching delay. Unlike infrastructure-based networks, node mobility may also cause frequent route outages and the repeating the entire route setup process is costly in terms of resource usage. Nodes may also move into regions of primary user activity necessitating immediate route management procedures. Clearly, routing is the first issue to deal with in order to construct CR-aware dynamic spectrum access networks.

In the literature a few attempts have been made to classify routing protocols. Some of them claim that, the classification of routing solutions for dynamic spectrum access networks should be made according to the activity and holding time of the exploited primary users' bands, such as, steady or static, unsteady or dynamic, and highly dynamic. This classification would yield one to design protocols separately. However, if the protocols are designed for those three categories separately, each protocol would cover only a part of the spectrum subject to spatial and temporal use. However, considering the similarities of dynamic spectrum access networks and multi-radio multi-channel mesh networks and mobile ad hoc networks, classifying routing protocols according to the method used in spectrum decision would be more significant.

A distinctive classification of routing protocols proposed for the CR networks is given along the following dimensions:

- *Spectrum decision making with self awareness:* The routing protocol at the network layer chooses the next hop among the candidate relay nodes while accounting for the spectrum usage characteristics as well as retrieved local information such as location and energy level. The use of multiple criteria in routing other than the spectrum availability provides flexibility in spectrum decision. Moreover, the overall communication performance would be improved, since spectrum decision and path selection have a mutual impact on each other because of using multiple criteria on decision making. Considering that a change in spectrum decision at each relay node produces a switching delay, the possibility of assigning a single channel for end-to-end communication should also be taken into account. Also note that, if the same spectrum is used at consecutive links, the spectrum access time is shared by the nodes on the link that are within the range of each other affecting the throughput adversely.

- *Spectrum decision making with primary user awareness:* The routes in a dynamic spectrum access network must explicitly provide a measure of protection to the ongoing communication of the primary users. If the CR users are aware of behaviors of primary users, such as having an ability to identify the locations of the primary users, they would construct the routes to avoid collision with primary users. Note that, such information may either be broadcasted from primary user network directly or the CR nodes produce this information by deriving the acquired environmental data intelligently. The constructed route must avoid the regions known to have high primary user activity entirely or jointly allocate transmission power to incur greater number of hops and minimize the probability of interfering with the primary users.

- *Spectrum decision making and adaptation:* Routing protocols falling into this category, have the key ability to recover from changes in the spectrum caused by primary user activities. The route adaptation requires an additional decision making for either establishing a new path or employing store-and-forward like approach to provide connectivity. Once decided on repairment (re-establishment), either local or global solutions are available. Local solutions include re-establishment of links to prevent any primary user communication interference. Global solutions require re-establishment of end-to-end connection. Store-and-forward based approach for adaptation aims at keeping the constructed path for some short periods of primary user activity. Relay nodes would store the received packets for a given duration which may include an additional time for primary user activity subject to the application running on CR nodes. Obviously, this would provide an acceptable duration to recover the communication before switching to costly operation of re-establishment of the route.

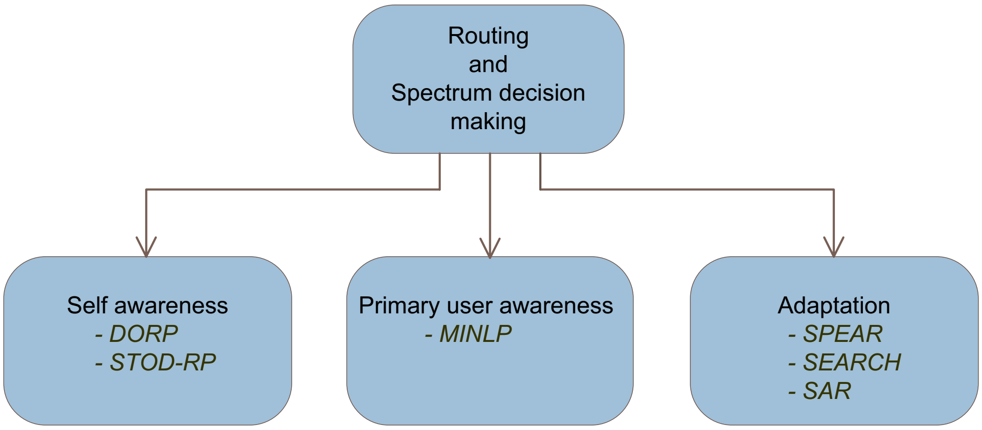


Figure 2.1: Classification of routing and spectrum decision making schemes with their representative samples.

In reference to the given classes depending on the assumptions taken on the issue of spectrum-awareness, Fig.2.1 illustrates the classes with their representatives. In the following section of this chapter, several routing solutions are commented while discussing their advantages and disadvantages based on the aforementioned main challenges.

2.1 The State of The Art

The need of simple and efficient routing algorithms in dynamic spectrum access CR networks is the main motivation of ongoing research. However, there is only a limited amount of work available for the routing problem in multi-hop CR networks enabling dynamic spectrum access. Selected state of the art studies are analyzed according to the proposed classification to investigate further. There are more studies in the first category than the other two. A layered graph model was proposed for modeling network topology and routing in interference-based dynamic spectrum access networks in [9]. This model provides solutions for DSA networks with static link properties. In that paper, it is claimed that their routing strategy considers the time-varying nature of the links as well as the intermittent connectivity in the network. In [10], the authors focus on the case where the metrics for the horizontal links are proportional to traffic load and interference. Here, a centralized heuristic algorithm is proposed based on the calculation of shortest paths in the layered graph. The proposed path-centric route calculation algorithm works iteratively by routing one source-destination flow at a time. Once a flow is routed, a new layered graph is calculated from the previous one by eliminating all unused incoming horizontal/vertical edges and re-calculating the weights assigned to the remaining edges to account for the routed traffic load. The proposed path-centric routing approach is fundamentally centralized requiring network-wide signalling support to generate the layered-graph. Moreover, the proposed iterative algorithms suboptimal being based on a greedy approach. Finally, resorting to iterative path computation over graph abstractions may not scale well as the network dimensions increase. Wang and Zheng proposed decoupled and joint route selection and spectrum management methodologies with single transceiver half duplex cognitive radios [11]. Given the network topology, all available routes between source destination pairs are enumerated, and for each route all available channel assignment patterns are considered. The ”best” combination of routing/channel assignment is derived by running a centralized algorithm on a ”conflict graph”. Each wireless link in the network maps to a vertex in the conflict graph. An edge is defined between two vertices if the corresponding wireless links cannot be active at the same time. The conflict graph is used to derive a conflict-free channel assignment by resorting to a heuristic algorithm to calculate the maximum independent set (or maximum clique). As in the two previous cases, the proposed approach is centralized and assumes full knowledge of the network topology (available spectrum bands, neighboring nodes, etc.). Moreover, the problem of defining the most efficient conflict-free scheduling can be reduced to a problem of calculating the maximum independent set on a properly defined ”conflict graph”, which is known to be NP-Hard. Besides, the route selection in the decoupled case is performed by using a shortest path algorithm. However, it has been shown that the shortest path algorithm may not result in an optimal solution when the link propagation time and the channel capacities are both taken into account [12]. In [13, 14], Hou et al. focus on the problem of designing efficient spectrum sharing techniques for multi-hop cognitive radio networks. To this extent, they introduce a Mixed Integer Non-Linear Programming (MINLP) formulation whose objective is to maximize the spectrum reuse factor throughout the network, or equivalently, to minimize the overall bandwidth usage throughout the network. The proposed formulation captures all major aspects of multi-hop wireless networking, i.e., link capacity, interference, and routing. However, the proposed scheduling/routing algorithm has to run at a central entity which has perfect knowledge of the network topology (presence, position and traffic pattern of the primary users, presence and position of the secondary users). Moreover, traffic splitting is allowed throughout the secondary network. As expressed above, the assumption of having split traffic between secondary users may be unfeasible in practical secondary networks. Finally, the interference is modeled through the concept of interference range, which automatically excludes effects related to interference accumulation from multiple transmitters far away and the definition of link capacity is based on the assumption that the surrounding interference is Gaussian.

Some proactive approaches were proposed based on centralized infrastructure to achieve overall optimal network performance [9, 11, 15, 14]. However, those proactive methods cannot be deployed in multi-hop CR networks, where both the node positions and spectrum distribution are hard to obtain. Another approach proposed by Krishnamurthy et al was based on on-demand manner to reactively select routes and assign channels simultaneously by disseminating the information of channel usage in on-demand routing process [16]. An extension of tree based routing, the Cognitive Tree-Based Routing (CTBR) protocol which takes the cognitive radio base-station as root and therefore can only be used for infrastructured CR networks, was proposed by Zhang et al [17]. A Delay motivated On-demand Routing Protocol (DORP) investigates the scheduling-based channel assignment, switching delay between channels and the back off delay within channel in CR nodes to select routes [18]. The authors assume that each node has a traditional transceiver in addition to the CR transceiver to form a common control channel. However, it is known that using two separate radios is relatively expensive, cumbersome, and would consume additional energy that is often limited. Cheng et al also proposed another on-demand protocol for routing and spectrum assignment in CR networks [19]. The authors benefit from on-demand routing and borrow from Ad hoc On demand Distance Vector (AODV) routing protocol and modify route request and route reply packets in their scheme. Their study focuses on constructing a path solely on the basis of delay. A local coordination based routing scheme for multi-hop CR networks was proposed by Yang et al based on their previous work [20]. A single layered protocol design was considered. Khalife et al proposed a probabilistic routing protocol based on probabilistically estimating the available capacity of every channel [21]. Their Probabilistic Routing chooses the most probable path to satisfy a required demand.

Abbagnale et al. [22], the link stability is considered. The link stability is associated, in a innovative way, to the overall path connectivity via a mathematical model based on the Laplacian spectrum of graphs. Paths are measured in terms of their degree of connectivity that in a multi-hop CRN is highly influenced by the PUs behavior. The behavior of a PU is modeled by its average activity factor. The authors introduce a novel metric to weight routes (paths) which is able to capture path stability and availability over time. Indeed, the core idea is to assign weights to routes and paths proportionally to the algebraic connectivity of the Laplacian matrix of the connectivity graph abstracting the secondary network. On the basis of this model authors design a routing scheme, named Gymkhana, which routes the information across paths that avoid network zones that do not guarantee stable and high connectivity. Gymkhana uses a distributed protocol to collect some key parameters related to candidate paths from an origin to a destination. These parameters are then fed into the basic mathematical structure based on Laplacian matrixes which is used to compute efficient routing paths that are found by using an AODV-style protocol.

Studies classified along the third category address the adaptation problem which is the key enabling issue for a routing protocol to serve effectively in a dynamic spectrum access network. This issue is addressed either locally or globally. Since, there is a tradeoff between network resource consumption and the optimality of the solution; both local and global solutions have their own benefits and drawbacks. The SPEctrum-Aware Routing protocol (SPEAR) identifies multiple feasible routes during the route setup phase [23]. In the SPEAR, source node initiates routing discovery by on-demand mode, and destination node decides the channel assignment and reserved time slot of each node along the reverse path to source node. Each node, however, may locally change the spectrum during route operation as long as the end-to-end routing metrics, such as throughput and delay are maintained. SPEAR is strictly synchronized, short of robustness to the activities of licensed users, and hard to be implemented in real network environment. Zhu, Akyildiz, and Kuo introduce a Spectrum-Tree based On-Demand Routing Protocol (STOD-RP) that establishes a ”spectrum-tree” in each sensed available spectrum band [24]. Their study was based on taking advantage of combining tree-based proactive routing and on-demand route discovery. Additionally, each spectrum tree must have a root node which requires a root selection procedure. However, constructing all spectrum-trees in the network produces a significant amount of overhead since construction involves message exchange and computation power. Authors assume that all nodes are fixed or move very slowly. This assumption may not be the case for an ad hoc network all the time. Also authors state that overlapping/gateway nodes has equipped with multiple spectrum-agile radios. Since each node in the network has the potential of becoming a gateway node to provide a better performance considering mobility in a realistic scenario, all nodes have to be equipped with multiple radios. Obviously such an approach will increase the network deployment cost as it is for the DORP. Zhou et al have proposed a colored multigraph based model for the temporarily available spectrum bands [25]. They developed a routing and interface assignment algorithm based on this colored multigraph model. However, their routing algorithm optimizes only the hop count. A geographic forwarding based SpEctrum Aware Routing protocol for Cognitive ad-Hoc networks (SEARCH) that jointly undertakes path and channel selection to avoid regions of primary user activity during route formation, adapts to the newly discovered and lost spectrum opportunity during route operation, and considers various cases of node mobility in a distributed environment by predictive Kalman filtering [26]. Since their algorithm has to know the exact location of the nodes, they use GPS or triangulation to locate the nodes in the network.

Existing schemes as described in this section may be inadequate to meet some of the desirable objectives of CR networks or may be too costly compared to the obtained performance. The system in hand is ad hoc with arbitrary topology and the problem falls into distributed solutions with single-radio for data communication. Like some of the mentioned studies, it is evident that on-demand routing is suitable for multi-hop, single transceiver cognitive radio networks, as the topology changes quite often. Some of the mentioned studies are chosen to compare to proposed techniques since all of the chosen techniques try to improve similar overall performance criteria. These recent and typical examples are thought to be sufficient to make a good comparison.

3. DESIGNED ROUTING METRICS

In response to the increasing demand for low latency, high capacity wireless communications, the concept of cognitive radio has become a popular research area. However, earlier works lack adequate resource management and service provisioning mechanisms, without which cognitive radio networks are unable to meet consumers' increasing demand while guaranteeing an acceptable level of QoS. Creating such a necessary resource management framework starts with an effective routing protocol including an adapted routing metric. There are known causes of difficulty in routing for cognitive radio ad hoc networks such as inability to find an empty communication channel, interference, mobility and temporary obstructions. Upon detecting any link failure due to these causes, the constructed path should either be repaired or replaced. Unestimated unnecessary rerouting process costs in misuse of network resources, and the extra routing latency may affect QoS for network applications, degrading overall network performance. In order to reduce the cost of routing, it is critical to choose optimal routes based on a suitable metric. A few different decision making metrics have been used in earlier algorithms for routing in cognitive radio ad hoc networks [24, 27, 28, 29, 30, 31]. To the best of my knowledge, these metrics suffer from focusing on a single dimension of the problem. In this thesis, the essential aim is to optimize routing while limiting the interference to the primary user by fully exploiting the sensing history and the spectrum occupancy statistics. It is evident that incorporating multiple dimensions in terms of reliability and available time into a single metric is required to achieve a better overall network performance. The metric that is taken into account in this thesis comprises of both spectrum usage characteristics and interference posed by both primary and secondary users to find optimal routes.

Cognitive radio users are not likely to access spectrum randomly. Neither they have a path to a specific node in random. They get connected in a predictable fashion based on repeating behavioral patterns. For example, if a node has gained opportunity to access a specific unused spectrum band and has connection to a specific node several times lately, it is likely that it will gain connection to that node again. In order to have a better understanding of the recent spectrum usage, recent spectrum history is sampled within a 1s sliding window so that a number of disconnection-to-connection transition can be accommodated. For detecting such transitions, proposed techniques rely on sensing algorithm which is out of the scope of this thesis. However, it is known that there are various spectrum sensing algorithms that differ from each other in the required sensing duration, detection accuracy, and complexity in the literature. Moreover, there is increasing interest in the use of white spaces that are identified by a radio based on the use of geolocation databases. Sensing period is found to be 25-100ms in some papers such as [32, 33, 34]. Such a period range would provide with 10-40 transitions in a second. Moreover, the IEEE 802.22, the only standardized cognitive radio network, suggests the shortest frame size (can be thought as packet size) as 10ms long and allows use of superframes consisting of up to 16 frames (i.e. in total 160ms). Since spectrum sensing could be done at the end of a transmission, sensing period can be considered as 10-160ms and 6-100 transitions can be observed for a second-long window. Window size values lower than a second would not allow to observe sufficient number of transitions especially when longer frames are being transmitted. Obviously window size values higher than a second result in both skipping the effect of fluctuating behavior of spectrum usage and a slower response time. It is predictable that making use of these observations and information would improve routing performance. Therefore, a cost metric comprising these values is derived and routing is designed according to this metric.

Considering the primary users operate on the primary channels and CR users access the temporarily unused portions of the primary channels on an opportunistic basis. It is assumed that the usage pattern of the primary users which affects an arbitrary CR link i follows an independent two-stage ON/OFF random process. An ON period, $T_{on,i}$, represents the time that the primary users are active by transmitting in the given channel and a CR link i transmission would interfere with the primary. An OFF period $T_{off,i}$ represents the time that the primary users are inactive and virtually let CR link i to access to the given channel. Both $T_{on,i}$ and $T_{off,i}$ are assumed to be exponentially-distributed with means $1/\mu_i$ and $1/\lambda_i$ second respectively. The ON/OFF random processes of the primary users activity pattern affecting different CR links are assumed independent. There are two different perspectives to be considered in the route selection process. From the perspective of inside the CR system, routes with the best end-to-end performances should be chosen and from the perspective of system coexistence, routes should be selected with the minimum interference to the primary systems. Moreover, considering the CR system's end-to-end throughput of a route, interference from other CR links along the route should also be taken into account. This interference is named as intra-system interference in this study. Yet, I would like to make use of these observations and information to improve routing performance by defining an interference aware metric. Therefore, the combined metric considers the effects of variation in link loss ratio, differences in link transmission rate as well as inter-system and intra-system interference. In other words, the combined metric comprises of spectrum availability cost and interference cost.

3.1 Spectrum Availability Cost

Spectrum availability is an inherent characteristic in mobile CR ad hoc networks where nodes usually get disconnected due to the nature of ad hoc networks (e.g., mobility, temporary obstructions) and CR technology (e.g., ability to find a non-interfering communication channel with the primary users). To capture the characteristics of the spectrum availability and to select the spectrum for each link of the route, different metrics can be used. Such metrics also need to capture the activity behavior of primary nodes since the sporadic spectrum availability for the CR nodes is directly dependent on primary activities. While protecting the primaries' ongoing activity and observing the activity behavior of the primary nodes, the designed metric should guarantee the stability of the route for the cognitive radio nodes. In proposed techniques, a link's connectivity behavior is tracked and a persistent cost metric that is updated periodically to reflect its overall state is assigned. Accordingly, if a link is disconnected for a long time, the cost is increased to a high value rather than removing the link from the connection graph. For a well connected link the cost will be set to a small value depending on the availability of the link. In this way, a route can be found between a source and a destination even if there is no continuous end-to-end connectivity. The metric is designed with the focus on minimizing data delivery latency with minimal network resource usage. It is accomplished by assigning larger costs to links with larger spectrum unavailability durations. Moreover, when multiple such links have similar average spectrum unavailability durations, links are ordered with respect to disconnection-to-connection transition history and the lowest cost is assigned to the least frequent one. The rationale behind this approach can be explained as follows: for a given duration, a link of which has a lower transition number, indicating less frequent disruption, is a better link as it reflects a node has more opportunity to forward a packet to the other nodes. Having these principles kept in mind, the cost of a directional link $L_{i,j}$ between node i and node j is defined as:

$$C_{i,j} = 1 + \frac{\left(T_{cost\_window} - \sum_{k=1}^{\tau_{i,j}^{transition}} T_{i,j}^{k} \right)}{1 + \tau_{i,j}^{transition}} \tag{3.1}$$

$C_{i,j}$, cost of link $L_{i,j}$, is dynamically computed by node i based on its spectrum usage history over a discrete sliding window of length T_{cost_window}. Within a measurement window, the number of times the link status transitions from having opportunity to transmit without any interference to any primary user to causing interference is represented by the parameter $\tau_{i,j}^{transition}$, and the duration of the k^{th} connectivity instance is represented by $T_{i,j}^{k}$. The term $\sum_{k=1}^{\tau_{i,j}^{transition}} T_{i,j}^{k}$ represents the total cumulative connectivity duration within the last measurement window. For a non-disturbed secondary link, this term equals the duration of the measurement window itself, and since there was no primary user activity $\tau_{i,j}^{transition}$ equals to zero hence the cost reduces to unity. Since this is the minimum possible link cost, a link that has more connection time will always be preferred over interfering links by any link state routing algorithm. Also, since the numerator of the expression for $C_{i,j}$ is dominated by the cumulative link primary user activity time, links with longer interfering times will have higher cost and thus will be avoided by the least cost algorithms. However, among multiple links with similar cumulative disconnectivity durations, the ones with lower transition counts $\tau_{i,j}^{transition}$ will have lower costs. This ensures that among all links that have similar cumulative disconnection periods, the least cost routing algorithms will not prefer links that cause interference to primary users and enter idle mode more frequently. It is evident that this reasoning should help minimizing the data delivery latency. Note that the upper bound of the link cost will be decided by the parameter T_{cost_window} which is set as 1s. Initial experiments to decide on the window size indicate that a second-wide window provides a better performance and a balance between the above mentioned effects. Window size values lower than a second would not allow to observe sufficient number of transitions especially when longer frames are being transmitted. Window size values higher than a second result in both skipping the effect of fluctuating behavior of spectrum usage and a slower response time.

3.2 Interference Cost

The impact of interference on the network performance is difficult to estimate. In order to describe channel (link) state accurately, indicators of the channel quality such as nominal throughput or packet loss would not be sufficient. It is also critical to estimate the transmission delay resulting from concurrent data transmissions. Note that in wireless communication, the nodes within the interference range of a given source and destination have to wait for the end of active transmission. A novel routing metric is properly tailored for cognitive radio networks that accounts for these different factors in order to improve the overall network performance by avoiding lossy links and congested zones caused by interference.

If it is assumed that there is no interference in the network, a previously proposed routing metric for ad hoc networks, expected transmission time (ETT) [35] metric gives an idea about the quality of the link quite well as links with less expected transmission time would give better throughput. ETT measures the MAC layer transmission time of a packet over a link. It considers the impact of link transmission rate and packet size so as to improve the performance of another previously proposed metric ETX [36]. ETT was defined as:

$$ETT = ETX\frac{S}{B}\,, \quad ETX = \frac{1}{P_f \times P_r} \tag{3.2}$$

where S is the packet size, and B is the bandwidth of the link. The expected number of transmissions required to successfully deliver a packet, i.e. ETX, is computed by the underlying packet loss probability in both the forward and reverse directions which are denoted by P_f, P_r respectively. Since both long paths and lossy paths have large ETXs, the ETX metric captures the effects of both packet loss ratios and path length. However, it does not consider either interference or the fact that different links may have different transmission rates. ETT improves ETX by considering the differences in link transmission rates. By introducing the bandwidth (B) into the path weight, the ETT metric captures the impact of link capacity on the performance of the path. Although it has been shown that ETT works for a limited number of interfering flows, it does not perform as expected for higher number of interfering flows in the both primary and CR networks[35]. In the varying levels of interference experienced by a cognitive link have to be factored into the routing metric to find routes with better overall quality. In order to realize this, it is needed to model interference accurately and factor it in the routing metric accordingly in an appropriate way.

The physical interference model used in self adaptive routing to capture the interference experienced by links in the network is borrowed from Gupta and Kumar [37]. In this model, a communication between nodes *m* and *n* is assumed to be successful if the *SINR* (Signal to Interference and Noise Ratio) at the receiver *n* is above a certain threshold which depends on the desired transmission characteristics. *SINR* provides useful information on how strong the desired signal is compared to the sum of interferer and the noise in the network. A packet on the link $L_{(m,n)}$ from node *m* to node *n* is correctly received if

$$\frac{P_n(m)}{N + \sum_{k \in V'} P_n(k)} \geq \beta \tag{3.3}$$

where N is the background noise, V' is the set of nodes simultaneously transmitting and β is a constant. Considering all partially interfering nodes *SINR(n)* can be defined as

$$SINR(n) = \frac{P_n(m)}{N + \sum_{k \in \vartheta(n) \setminus \{n,m\}} \Gamma_k \, P_n(k)} \tag{3.4}$$

where $P_n(m)$ is the signal strength of a packet from node *m* at node *n*, *N* is the background noise, and the received interfering signal from node *k* is weighted using node *k*'s transmission rate Γ_k, which is the normalized rate averaged over a period of time. Packet header is modified to keep the signal strength and the background noise values. Whenever a packet is received, CR inserts these information prior to relay it. When a node receives a packet from a neighbor, CR engine stores the ID, signal strength and the background noise values to a buffer which is exported to the routing module. In practice, the signal strength values only for the packets that are received properly are known. But for the calculation of the metric of a link, signal strength information is needed from nodes that are not within the transmission range but can cause interference. Such information is acquired from the sensing algorithm that samples the environment, which provides the interference noise in the environment. CR is also modified to report the sending rate to the routing module. Every node computes its sending rate on each of its bands and communicates to its neighbors by piggybacking it in the packets it sends. So each node knows the sending rate of its neighbors and use it in the computation of metric. $\Gamma_k\ P_n(k)$ gives the fraction of time node k occupies the spectrum. The set of nodes that node n can hear or sense is associated with the set $\vartheta(n)$. Total interference ratio $I_i(n)$ for a node n in a link $L_{n,m}$ is defined as the ratio of interference to the maximum interference P_{int}^{max} that a node can still communicate properly, and denoted as

$$I_i(n) = \frac{\sum\limits_{k\in\vartheta(n)\setminus\{n,m\}} \Gamma_k\ P_n(k)}{P_{int}^{max}} \tag{3.5}$$

Note that $\sum\limits_{k\in\vartheta(n)\setminus\{n,m\}} \Gamma_k\ P_n(k)$ is the sum of all undesired power from other transmissions at node n.

A bidirectional link is considered as two overlapping unidirectional links. Link interference value for that bidirectional link is accepted as the greater one of the corresponding unidirectional ones. Considering a bidirectional link $L_{n,m}$, I_i is

$$I_i = max(I_i(n), I_i(m)) \tag{3.6}$$

The interference metric of a link l is defined as

$$int_l = ETT_l * \varphi(I_l) \tag{3.7}$$

where $\varphi(x)$ is the scaling function defined as $1+\frac{1}{2}(\frac{x}{\sqrt{x^2+a}})$ while a is the smoothing constant which is experimentally found and set to 100. Note that the scaling function $\varphi(x)$ provides a new range between 1.00 to 1.05 for a given I_l which initially ranges between 0 to 1. ETT_l is weighted with I_l to capture the interference experienced by the link from all of its neighbors including primary users (Eq. 3.7). The contribution of I_l is limited to 5% as a result of initial experiments. Thus, int_l becomes the new cost value comprising of both ETT and interference.

3.3 Combined Routing Metric

The desirable properties of the two metrics described in (3.1) and (3.7) can be combined by taking their weighted average:

$$cost = \alpha * C_{i,j} + (1-\alpha) * int_l, \quad 0 \leq \alpha \leq 1 \tag{3.8}$$

where α is a tunable parameter. The weighted average can be viewed as an attempt to balance between the spectrum availability and interference cost metrics. The proposed metric provides higher performance in cognitive radio ad hoc network environment, since it takes into account the packet losses, the bandwidth of each link, primary user activity, and the stability of each link. In order to analyze and asses the designed routing metric, self adaptive routing technique presented in this thesis, which incorporates designed metrics, is used. With respect to the simulation results, the impact of α on both throughput and end-to-end delay is shown in Fig. 3.1. The peak performance is achieved for $\alpha = 0.6$ where the throughput is 920Kbps. Also, the shortest delay (40.6 ms) is achieved for $\alpha = 0.6$. Therefore, α is set to 0.6 for the conducted experiments. Although, it is not included in this thesis, my current research also includes the dynamic decision mechanism for the value of α.

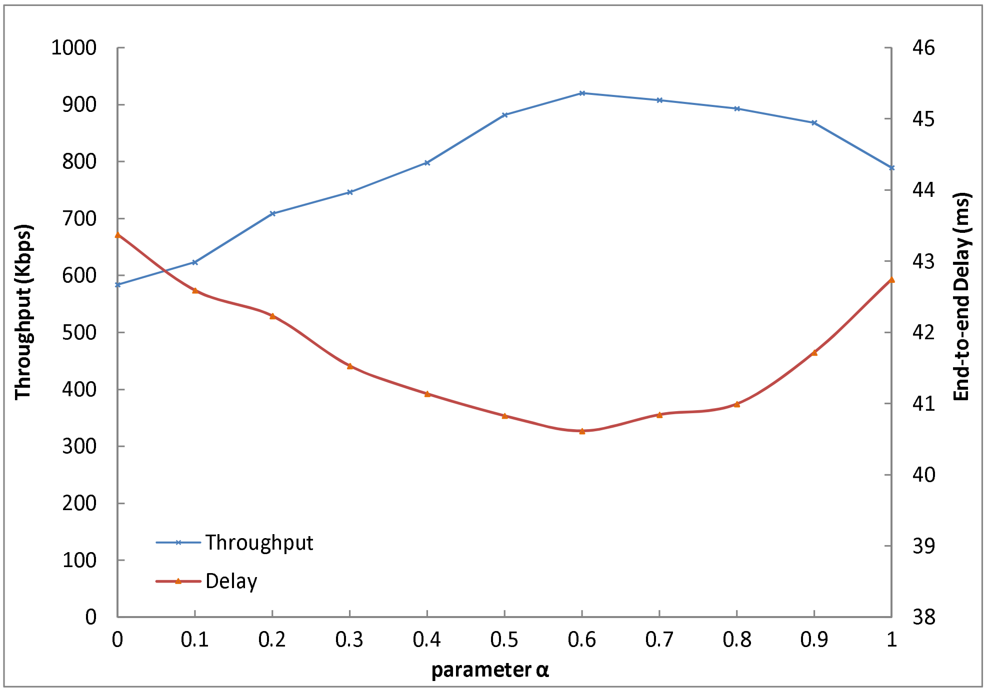


Figure 3.1: Throughput and end-to-end delay with respect to parameter α.

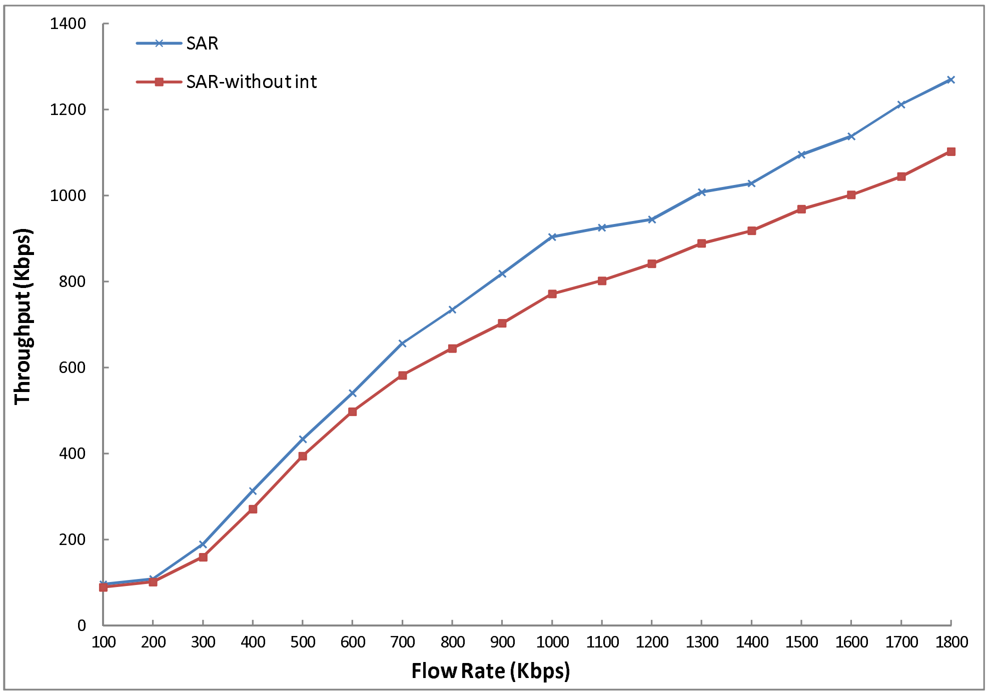


Figure 3.2: Throughput as the flow rate increases.

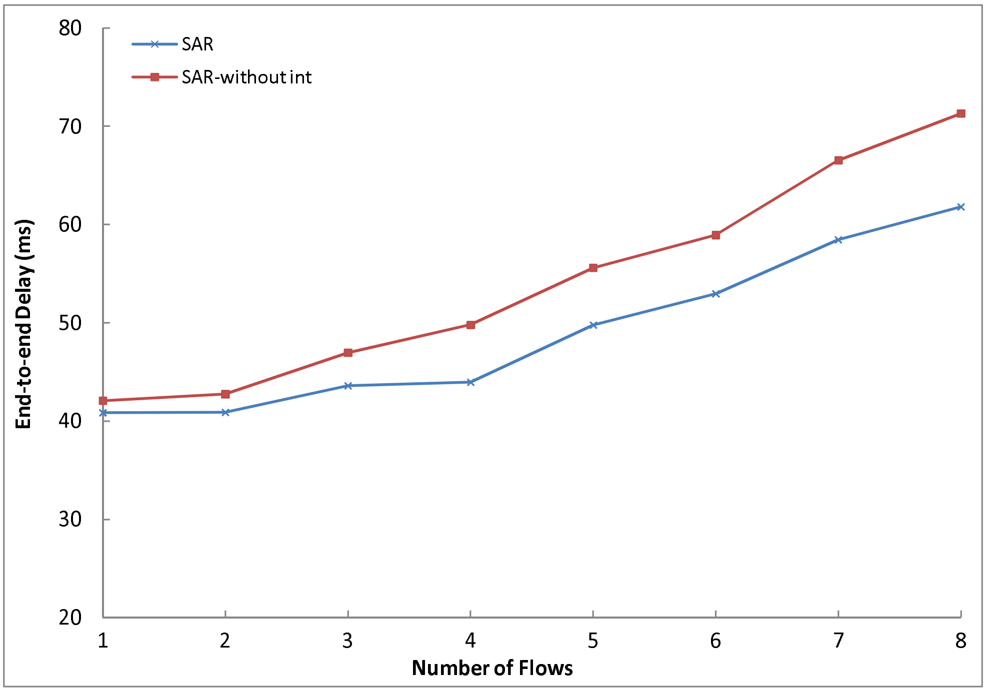


Figure 3.3: Average end-to-end delay performance as number of flows increases.

To demonstrate the performance of the proposed metric, results of the simulation for throughput and end-to-end delay are plotted. For first set of simulations, interference cost is taken out of the metric and just ETT metric is used to show the impact of interference on the performance of used technique. As seen in Fig. 3.2, throughput decreases when interference does not taken into account. Used routing techniques

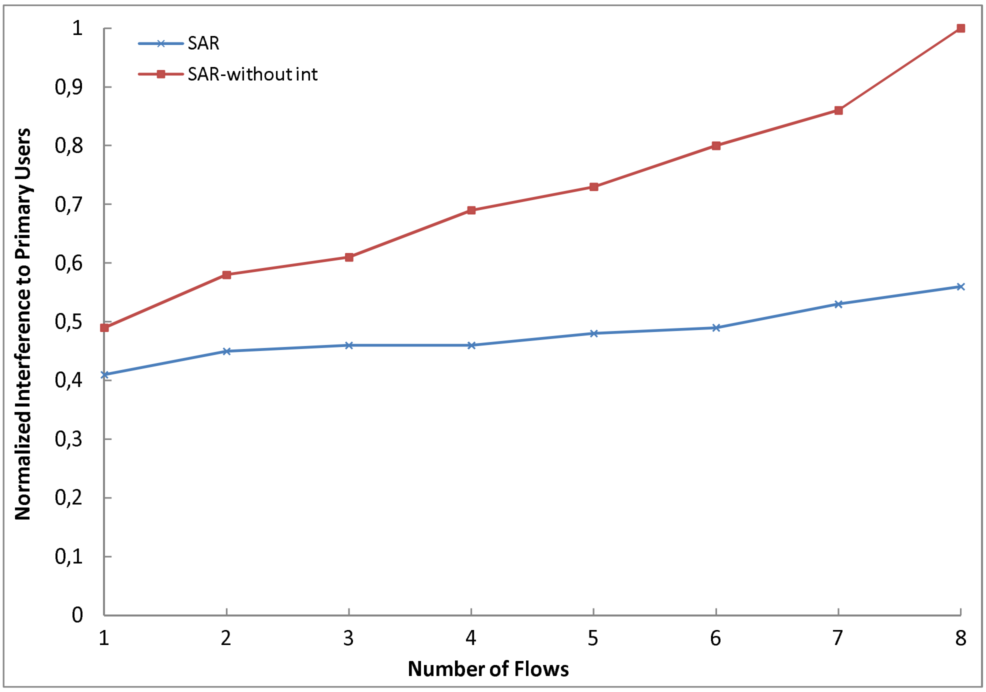


Figure 3.4: Number of flows vs. interference in SAR with and without interference metric.

suffers from interference that significantly reduces achievable throughput. This is reasonable since the increasing flow rate causes more collision and interference. It is observed that SAR achieves almost 10% better when interference cost is incorporated. This is primarily because proposed metric eliminates interference resulting in finding better routes. Also, it is observed that end-to-end delay increases considerably in the absence of interference cost as illustrated in Fig. 3.3.

Fig. 3.4 shows an example of results for SAR routing technique before and after considering the interference metric to the primary user, respectively. The values are all normalized against the corresponding performances of the proposed routing metric without interference cost. Fig. 3.4 illustrates that interference to the primary users increases with the increasing values of x-axis. This is reasonable since the increasing number of flows actually means more hops and more secondary nodes, which produces more interference to the primary user.

3.4 Concluding Remarks

New routing metrics specifically tailored for cognitive radio networks are proposed in this chapter. The proposed metric utilizes different features of the CR ad hoc networks. First part of the metric tries to utilize the spectrum availability by making use of recent spectrum occupancy statistics sampled within a 1s sliding window. Second part of the metric reflects the intensity of the interference caused by both primary and secondary users. To capture both performances at the same time, those parts are combined into a single metric. These two metrics contributes to the final metric value by a weight factor α to make trade-off between the two kinds of performances. In order to combine to metrics into one, initially metrics are adjusted to provide values at the same order with close average values. Then their contribution to final value is taken into consideration. Excessive test runs have been performed to make a decision on the best value of constant alpha providing the best throughput and end-to-end performance for the given traffic. Simulation results indicate that proposed metric achieves to incorporate mentioned performances into a single entity.

4. UNITED NODES: CLUSTER BASED ROUTING TECHNIQUE FOR CR NETWORKS

Using spectrum bands in an opportunistic way comes at the expense of some important challenges such as routing problem in such a dynamic environment. Facing the challenges and research issues based on cognitive radio, several approaches have been introduced. One of the proposed approaches is partitioning the network into smaller segments, i.e. clustering. Clustering in mobile ad hoc networks provides with some important benefits including optimizing bandwidth usage, balanced distribution of resources and resolving scalability issues in combination with routing schemes.

Clustering schemes can be classified into two groups, clusters with or without cluster heads (CHs). Clusters without CHs provide a fair share of total communication load. However, CHs may serve for many purposes within a cluster, such as the allocation of resources to member nodes and coordinating transmission events for nodes in the cluster in order to avoid re-transmissions by reducing packet collisions [38]. Clusters controlled by CHs can be organized as either 1-hop or *k*-hop (multi-hop) clusters. In 1-hop clustering schemes all of the cluster members (CMs) are within transmission range of the CH. In *k*-hop clustering schemes, the maximum distance between the CH and any CM is at most *k* hops. Note that a CM may reside outside the communication range of the CH, where intermediate CMs relay messages to and from CHs.

A number of clustering algorithms have been proposed for wireless ad hoc networks [38, 39, 40, 41], as well as for CR networks [42, 43, 44, 45, 46]. All of these mentioned algorithms considered other issues than routing, except for one [47]. In [47], the users of different SOPs are gathered under different clusters. In this chapter, a novel algorithm, United Nodes (UNITED), for maximizing the network throughput and minimizing the end-to-end delay is proposed. UNITED operates autonomously in a distributed manner at every node. Initially, nodes organize themselves into several clusters by the clustering algorithm that is based on location, communication efficiency, network connectivity and spectrum availability. Following completion of cluster formation, routing is done according to the spectrum usage and interference metrics. Clusters adapt themselves dynamically with respect to spectrum availability, and the high mobility of the nodes based on the calculated metrics.

4.1 The Clustering Algorithm

In this chapter, a mobile cognitive radio ad hoc network environment with a number of primary and secondary nodes, where all nodes communicate with each other in their own networks, is considered. It is assumed that there is no communication (i.e., no cooperation) between primary and secondary networks. The network is modelled as a graph $G = (N,L)$ where N is a finite set of nodes, $N = \{x_1, x_2, \ldots, x_n\}$ and L is a finite set of links, $L = \{(x_i, x_j)\}: 1 \leq j \leq n \ for\ x_i \in \Re^d, 1 \leq i \leq n$. If a node m is within the transmission range of node n, then n and m are assumed to be connected by a communication link $l_{nm} \in L$. A route or path from node s to node d is an alternating sequence of nodes and links, representing a continuous traversal from node S to node D. Note that each node has the same wireless optimal transmission range of R_{opt}.

The set of nodes N will be partitioned into M (i.e., we have M CHs) clusters $\{C_1, C_2, \ldots, C_M\}$. Let $E = \{e_i = (x_i, y_i), i = 1, \ldots, N\}$ be the set of node coordinates. The Euclidean distance between node p and node q is defined as

$$dist(e_p, e_q) = \| e_p - e_q \| = \sqrt{(x_p - x_q)^2 + (y_p - y_q)^2}. \tag{4.1}$$

The minimum distance from node p of one cluster to another cluster C_j is

$$dist^*(e_p, C_j) = min\{dist(e_p, e_q) : e_q \in C_j\}. \tag{4.2}$$

The maximum directed distance from cluster C_i to C_j for e_p, denoted as $D(C_i, C_j)$ is

$$D(C_i, C_j) = max\{dist^*(e_p, C_j) : e_p \in C_i\}. \tag{4.3}$$

Consequently, the maximum distance between clusters C_i and C_j is the greater of the two directed distances,

$$D^*(C_i, C_j) = max\{D(C_i, C_j), D(C_j, C_i)\}. \tag{4.4}$$

Equation 4.4 shows that every node in the cluster C_i must be within a distance $D^*(C_i, C_j)$ from some node in C_j. Let us assume that the minimum distance between node n and the other nodes in the network is d_n. To keep the network connected, the minimum distance value of two nodes residing at the edge of a cluster, that is denoted as R_{min}, should be $R_{min} = max d_1, d_2, \ldots, d_N$. As a consequence, the $dist^*$ distance of a joining node and a cluster should be smaller than R_{min}.

The algorithm must operate even in conditions where mobility of the nodes and fluctuation in the available spectrum is very high. The clusters should be capable of adapting to cope with dynamic conditions imposed by mobility and more importantly the primary user activity. Even these challenges indicate that both mobile ad hoc networks and cognitive radio issues have to be addressed in a clustering algorithm concurrently.

The proposed clustering algorithm for mobile CR ad hoc networks makes autonomous decisions in a distributed manner. All nodes in the network are clustered $(C_1 \cup \ldots C_M)$, and each node is allowed to join only one cluster ($C_i \cap C_j = \emptyset$, $\forall\, i, j :\ 1 \leq i, j \leq M$). The CH election procedure is invoked at the time of the system activation, and every time when there is a drastic change in the network and also when a CH is under the influence of primary users. As a consequence, the CH election procedure is not periodic. This reduces system updates, hence computation and communication costs. Initially each node constitutes a cluster itself. Whenever a node acquires data from its neighbor, it starts establishing a new cluster by taking part with that neighbor. Depending on the metrics, discussed in the further sections, either a new cluster is established by merging or the original status is kept. Once a new cluster is established, further cluster merge operations are controlled by the CH. Note that after all merging operations there might still be clusters consisting of a single node. On the other hand, the number of nodes (η_n) within a single cluster C_n could not exceed a preset value of (δ). Therefore, the network load would be balanced and the efficiency of the network would be kept above an expected level.

The proposed clustering algorithm also utilizes a common control channel (CCC) that is shared within a cluster. Using CCC provides the system with a fast way of transmission for management/control messages [3, 48]. Various ways of implementing CCC has been researched for nearly five years [49]. An in-band CCC is implemented within this PhD research. In this implementation, best two channels that have the highest spectrum access availability are set as the CCC and as the auxiliary CCC

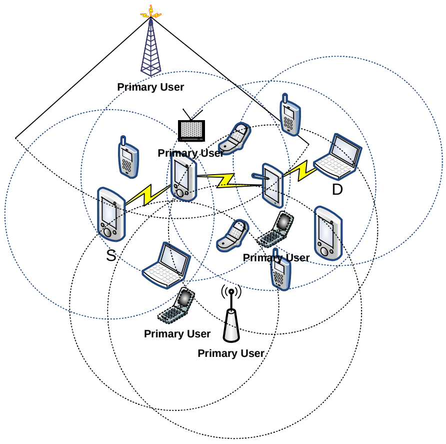
(AuxCCC) respectively. While establishing the cluster, the messaging also works for establishing a couple of CCC for the cluster. The CCC selection process starts at each node in a distributed manner. Sensing algorithm provides the nodes with 5 candidate channels for CCC and AuxCCC. After a negotiation process CH's determine the two channels that is going to be valid for respective clusters. In case the CCC (AuxCCC) become unavailable the cluster nodes switch to AuxCCC (CCC). If neither of them are available nodes in the cluster seek for new candidates. If a couple of new channel cannot be established in a given time, reclustering algorithm starts running. Similar approaches have been implemented in various papers in the literature such as [44]. Although the above mentioned scheme is used in the simulations, the performance analysis of the implemented CCC technique and comparison to the other CCC techniques are kept out of scope of this thesis.

The proposed clustering algorithm is based on a combined weight metric that takes into account several system parameters such as distance, transmission power, mobility, remaining power of nodes, and sensed information about available spectrum. Depending on both the application and the environment, the contribution of these parameters to the final metric value may vary. Given the above mentioned details, the cluster head selection algorithm is given in Algorithm 1.

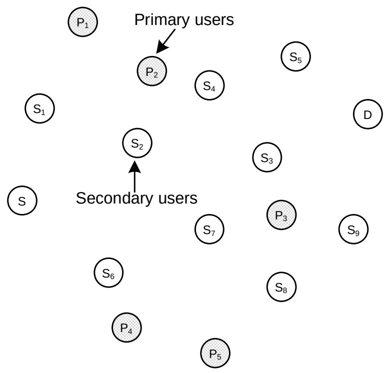
Algorithm 1: Cluster Head Selection (G)

begin
    repeat
        $\forall$ node n, compute :
          the node degree difference $\Delta_n = |\eta_n - \delta|$;
          the mobility measure $M_n(t)$;
          spectrum availability $Sp_n(t)$;
          weighted value $W_n = \alpha\Delta_n + \beta M_n(t) + \gamma Sp_n(t)$;
        choose the node with the highest weighted value as the Cluster Head;
        if *n_j is CH for n_i and n_k is CH for n_j* **then**
          n_i reselects CH excluding n_j;
        remove neighbor nodes of the chosen CH from set G
    until $G = \emptyset$;

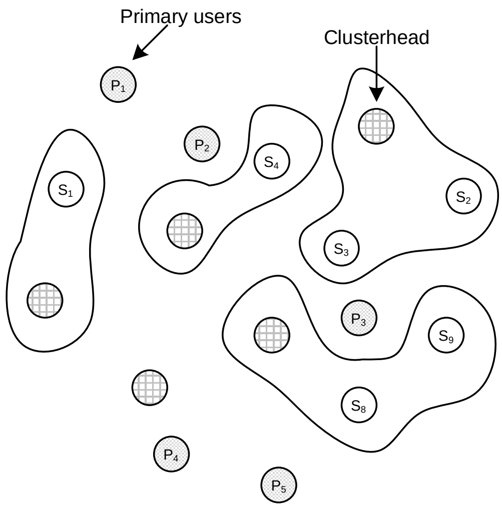
A node that does not belong to any previously constructed cluster is said to be in an unclustered state. Every node starts in an unclustered state at the time of the deployment. Nodes will go into an unclustered state if all of its links to other nodes within the cluster fail. Also whenever a primary user activity is detected, all nodes



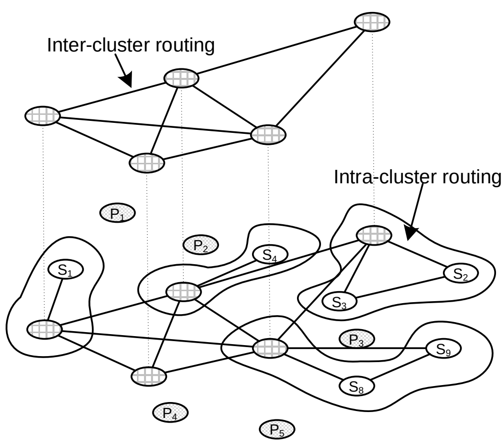
(a) CR network illustrated



(b) 2D mapping of the CR network



(c) Clusterheads selected and clusters formed



(d) Connectivity in illustrated cognitive radio network for routing

Figure 4.1: An illustration of a mobile CR ad hoc network.

within the range of the primary transmission activity will return back to an unclustered state if they do not have any SOPs in any channels. Whenever a node falls into an unclustered state, it runs cluster formation process which is described in Algorithm 2.

Algorithm 2: Cluster formation

```
Input: S;
Output: id of CH;
begin
    NewList = false;
    while !NewList do
        if S = ∅ then
            NewList = true;
            repeat
                send hello packet with reply request;
            until S ≠ ∅;
        order(S);
        while S ≠ ∅ do
            i ← max(∀j ∈ S);
            send Join_Request(i);
            if Join_Response received then
                if connection accepted then
                    return clustered(i);
                else
                    S ← S − {i};
        return clustered(self);
```

Nodes in the network have to keep a neighborhood table that holds local information about the neighboring nodes such as *ID*, *Speed*, *Location*, *Direction*, *Cluster Size* and *Cluster Membership*. Data in this table have to be time-stamped to allow expiration after a predetermined time threshold, Δt_i. Non-expired data would be used in Algorithm 2. A node that falls into an unclustered state due to primary user activity usually has valid neighbor information in its table. If the set of valid neighbors is not empty, the algorithm starts with checking for these nodes to join a cluster. Otherwise, which is the rare case, the algorithm proceeds with searching of new neighborhood nodes. The set of 1-hop neighbors S is produced by collecting replies to periodic *HELLO* packets sent by the unclustered node.

The *HELLO* packet contains the node ID, the spectrum and the mobility information. Nodes receiving the *HELLO* packet use this information to decide whether to reply or to ignore. Packets, either originating from the nodes that are moving away or having little spectrum access opportunity due to heavy primary user activity in the area, are ignored. When the *HELLO* packet is not ignored, the receiving node checks whether the maximum connection limit δ is reached. It responds with unicast response (*RESP*) packets, containing information about the receiving node if δ is not exceeded. This information includes its spectrum and mobility parameters, i.e. spectrum opportunities, location, speed and direction of travel. Upon receiving the first (*RESP*) packet, the unclustered node sets a timer to the request response wait period and waits for all responses from its neighbors until the timer expires. This gives all neighboring nodes a chance to find a clear channel and respond to the request. The request process is repeated while $S = \emptyset$.

After an unclustered node produces the set of its 1-hop neighbor CHs, the set is sorted with respect to their eligibility for being the CH in descending order. The sorting algorithm uses weighted metrics of nodes to determine their eligibility. Note that the weighted metric is based on sensed spectrum availability and mobility information.

Once the set of candidate nodes is sorted, a search for actual connection is started. The node sends a join request *JOIN_REQ* packet to the first node in the sorted set to establish a link to the node as the CH (Algorithm 2). The neighbor receiving the *JOIN_REQ* packet replies with join response *JOIN_RESP* packet, assigning the role of CM to the node that sent a *JOIN_REQ* packet, or denying the connection by sending a *JOIN_DENY* packet. If the neighboring node is already a CH, the initiating node joins that cluster given that the cluster size limit δ is not reached. If the neighboring node is a member of another cluster it resigns from the current cluster to form a new one and to become a CH. And finally, if the neighboring node is in an unclustered state, it becomes the CH of newly formed cluster. The unclustered node removes the neighboring node from the set of S when it receives a *JOIN_DENY* packet or it will not receive any message within a preset time-out value. This process is repeated for each node in the sorted set of S in order until a cluster is formed or $S = \emptyset$. Since previously created set of S has been tested, the algorithm enters to the request phase and tries to establish a new set of S. The above explained procedure is also applied to the newly created set of S. If there is no available neighbor as a CH for the newly created set, the unclustered node creates its own cluster by declaring itself a CH and terminates the algorithm.

4.2 The Routing Algorithm

The effectiveness of adaptive routing algorithms relies on the timeliness and details of the topology information that nodes are provided with. In cognitive radio ad hoc networks, topological changes at significant rates are expected. Consequently, the distribution and collection of up-to-date information can easily degrade the network performance even saturate the network. Furthermore, information arriving late due to latency can cause routing instability and unreliability. Since link failure relies on mobility of nodes and availability of spectrum, a routing metric that is properly tailored for cognitive radio ad hoc networks should account for these mentioned factors in order to improve the overall network performance. Thus, algorithm design objectives should include in short and effective response time to link failures and spectrum availability alternations. Note that the network is dynamically organized into partitions called clusters, with the objective of maintaining a relatively stable effective topology in dynamic cluster-based routing techniques. The membership in each cluster changes over time and is determined by the weighted metric mentioned in Chapter 3.

4.2.1 Design Issues

In the design of the technique, a unique *message identifier*, a *hop count*, and an optional *ACK request* are associated with each message for routing. The message identifier is a unique 32-bit number. This identifier is a concatenation of the host's ID and a locally-generated message ID (16 bits each). The hosts in the network are assigned with static ID's In the implementation.

The hop count field determines the maximum number of exchanges that a particular message is subject to. While the hop count is similar to the TTL (Time to Live) field in IP packets, messages with a hop count of one will be delivered if and only if one of the neighborhood nodes matches with the final destination. The packet will be dropped otherwise. As discussed below, such packets are dropped subject to the requirements of locally available buffer space as well. Larger values for hop count will yield to distribute a message through the network wider and for some cases quicker.

This will typically reduce average delivery time, but will also increase total resource consumption for message delivery. In order to minimize resource consumption, high priority messages might be marked with a high hop count, while most messages can be marked with a value close to the expected number of hops for a given network configuration.

Certain applications may require acknowledgement to a delivered message. The *ACK* request field signals the destination of a message to provide an acknowledgement of message delivery. These acknowledgements are modelled as short return messages from the receiver back to the sender. Of course, the acknowledgement can also be piggybacked with any other message destined to the sender.

Each host sets a maximum buffer size to allocate for message distribution. The buffer size limits the amount of memory and network resources consumed by the UNITED. As expected, there is an inherent trade-off between aggregate resource consumption and message delivery rate/latency. In order to ensure delivery of messages, at least a subset of nodes should have sufficiently large buffers. Otherwise, it is possible for some messages to be flushed from buffers before having a chance of delivery.

A number of management strategies are possible for individual message buffers. The simplest policy is first-in-first-out (FIFO). This policy is simple to implement and bounds the amount of time that a particular message is likely to remain ”live” (i.e., resident in at least one buffer). Once enough new messages have been introduced into the system, messages are likely to be flushed from most buffers. As long as the buffer size on all hosts is larger than the expected number of messages in transit at any given time, FIFO is a very reasonable policy. However, if available buffer size is limited relative to the number of messages, FIFO is sub-optimal with respect to fairness and quality of service (QoS). For example, a host’s aggregate buffer utilization is directly proportional to the number of messages it sends, which may not be fair to other hosts. Furthermore, FIFO does not provide any mechanisms for preferentially delivering or storing high priority messages. Fair Queueing algorithms, including Weighted Fair Queueing (WFQ), logically distribute available buffer space among competing hosts, providing differentiated QoS on a per-message granularity. The experiments are done by using FIFO implementation. Other algorithms are considered for future study.

UNITED is a hybrid routing technique, utilizing both proactive and on-demand (reactive) routing. CHs collect timestamped routing paths in a *route cache* table indicating either the CH in which the destination node is a member of or the CHs that would relay the packet to such a CH eventually. Since initial attempt to access a inter-cluster node starts with a request to locate the node, it constitutes on-demand portion of the technique. The destination node collects several paths when it receives route request messages from the source node in a period of time, selects the most stable path according to the cost metric and send route reply messages back along the path, each path is has a collection of information about traversed CHs as well as available spectrum. Once a path is established, it is kept in the *route cache* table for a previously set amount of time. Any packets destined to a previously explored node is relayed with respect to the table if the record is still valid. The communication between the nodes of a cluster and the cluster head is proactive, i.e., cluster head keeps a list of the clustered nodes along with communication properties such as available channels.

The performance of UNITED relies on the performance of cluster heads since CHs are responsible for forwarding route discovery request to neighboring clusters; forwarding data packets to its next cluster head hop along the route; maintaining routes and maintaining information about the member nodes. Stability and reliability of a route are also dependent on the CHs involved in that route. Given the fact that overall performance is dominated by cluster head performance, cluster selection algorithm has to find the best candidate.In case, an algorithm suggests a node that has limited spectrum opportunity and if it is selected as the CH, that node could cause route disconnections, trigger route errors and could be a bottleneck for the network yielding a significant performance degradation. In order to avoid such a low overall performance, UNITED utilizes an algorithm based on the combined weight metric that takes into account several system parameters such as distance, transmission power, mobility, remaining power of nodes, and sensed information about available spectrum as mentioned before.

4.2.2 Routing Strategy

In UNITED, routing is classified as intra- and inter-cluster routing. Intra-cluster routing is achieved by hiding the topology details within a cluster from external nodes

Algorithm 3: Routing Strategy for Cluster Members

```
//For any node n_i and packet p;
begin
    next_hop ← search_neighborTable(dest(p));
    if next_hop≠ ∅ then
        forward(p, next_hop);
    else
        forward(p, CH);
```

Algorithm 4: Routing Strategy for Cluster Heads

```
//For any node n_i and packet p;
begin
    if is_clusterMember(dest(p)) then
        create route to dest(p);
        reply with route;
    else
        next_hop ← search_routeCache(dest(p));
        if next_hop≠ ∅ then
            forward(p, next_hop);
        else
            send RREQ;
```

and using hierarchical aggregation. When a node has data to send, the neighbor table is checked firstly as given in Algorithm 3. If no entry is found, the source node simply sends a route request to the CH. Upon receiving the request, CH checks whether the destination node resides in the same cluster or not. If destination node is in the same cluster, CH replies with the route information. No further route request will be initiated and the data will be sent directly to the destination by the requesting node.

When a packet is to be sent from one cluster head to another cluster head, and if a route is not currently available in the *routecache* table, the cluster head broadcasts a route request to create the new route according to the algorithm given in Algorithm 4. When a neighboring cluster head receives the route request, if it is not the destination, it forwards the request; otherwise, the return path is cached in the cluster head, and when the predetermined time threshold expires the destination cluster head chooses one path according to the cost metric and sends back a route reply along the path to the source. Route reply is sent in a unicast manner.

4.2.3 Route Preservation and Adaptation (Local Repair)

It is necessary to have a maintenance scheme in the routing protocol due to the node disconnection caused by the nature of ad hoc networks (e.g., mobility, temporary obstructions) and CR technology (e.g., ability to find a non-interfering communication channel with the primary users). Each node has to corroborate the area it belongs to, and update information for the mobility factor and spectrum availability. Whenever a new CH is selected, all neighboring nodes receive a notification message to set the new address to transmit packets. In UNITED, both spectrum handoff and path re-routing methods are used for route recovery. Route maintenance can be done by: (a) employing spectrum handoff when feasible, (b) skipping the broken node if the next hop in the path is reachable; (c) choosing another reachable node(s), which is out of the transmission range of the active primary use, to be the next hop which is reachable by the previous node and the next node in the path. If nothing is possible, a brand new path is constructed from scratch.

4.3 Simulation and Performance Analysis of UNITED

Through simulations constructed in ns2, the performance and functional correctness of the UNITED and its relative performance compared to that of DORP [18], STOD-RP [24], SEARCH [26] and SCRP [47] are investigated. Simulations run with the following parameters. Two-ray ground propagation model is used at the radio layer. The bit rate for each channel is set to 2Mbps. Varying number of mobile nodes up to 100 moving in a rectangular area 1800m x 1800m in dimension is modelled. Each node picks a random destination in the rectangle and moves there with a speed uniformly distributed between $0-10$ m/s. Upon reaching the destination, the node picks a new destination and repeats the process. The activities of the primary user are modelled by using the exponential ON/OFF process as mentioned before. The coverage range of the primary user on its operation channel is taken as 250m. These values are taken from previous studies on a number of techniques to provide a mean for comparison. The communication pattern used in the simulation is a combination of both constant bit rate (CBR) and voice-ocer-IP (VoIP) traffic to

Table 4.1: Simulation Parameters

Parameters	Value
Area	1800m x 1800m
Number of CR users	[10...100]
Number of primary users	[10...100]
Primary users' Tx range	250m
Max node speed	10m/s
Pathloss	2-ray model
Channel capacity	2 Mbps
Traffic	UDP-CBR-VoIP
Threshold signal-to-noise ratio	10 dB

make a more realistic scenario. Each source node generates and transmits CBR traffic and each message is 1KB in length. The transmission interval for each node is set to 100ms. The injected Voice-over-IP traffic is modelled by a two-state ON/OFF model with exponentially distributed duration of talk spurts and silence periods. A total of six VoIP CR users are randomly distributed over $8-128$Kbit/s with random arrival rates (including packetization intervals according to the codec G.711, G.726 and G.729 recommendations). 50 experiments are performed in random multihop network topologies, for each different parameter settings.

As noted earlier, DORP [18], a modified version of AODV, and spectrum-tree based on demand routing STOD-RP [24] and recently proposed a geographic forwarding based SpEctrum Aware Routing protocol for Cognitive ad-Hoc networks SEARCH [26], and Spectrum-aware Cluster-based Routing Protocol (SCRP) [47] that forms spectrum-cluster for each spectrum band are used for comparisons. The characteristics of UNITED are explored under a number of different scenarios. Packet delivery ratio, throughput and end-to-end delay have been computed for DORP, STOD-RP, SEARCH, SCRP and UNITED. The comparisons show that the UNITED can fit well the multi-flow multi-channel environment and effectively exploit the potential large communication capacity in CR Networks. In the simulations, the rate of flows is varied from 100 Kbps to 1800 Kbps along with the injected VoIP traffic. The nodes are randomly placed in the area, and 8 flows having the same traffic generation rate are initiated with VoIP traffic.

Simulations are performed to investigate the clustering performance of UNITED as well. The stability of clusters are measured from the perspective of both cluster heads

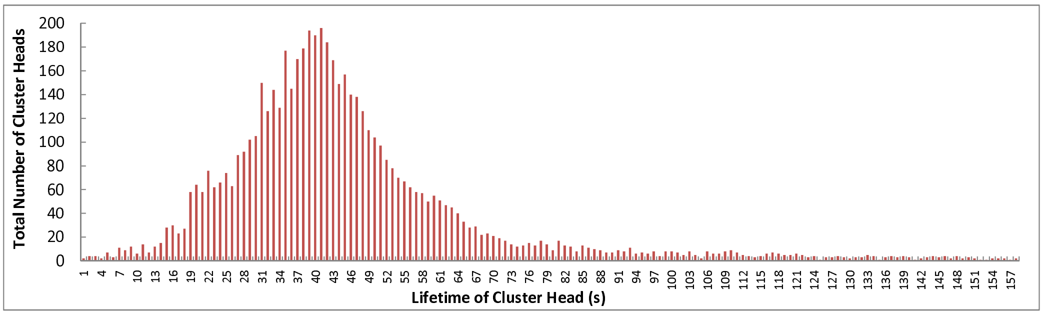


Figure 4.2: Lifetime distribution of cluster heads.

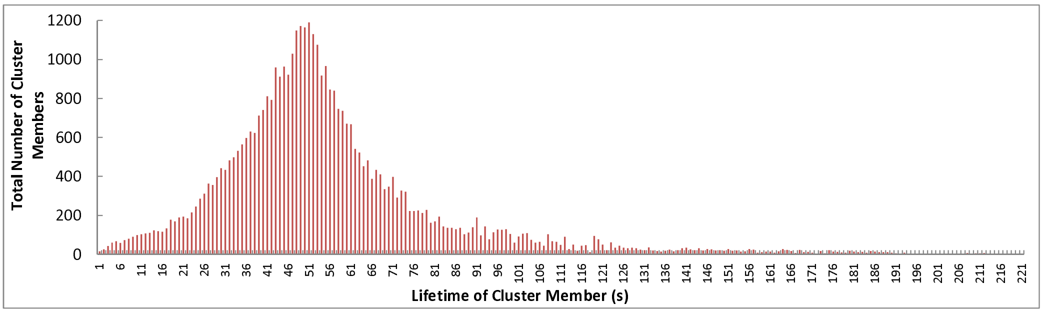


Figure 4.3: Lifetime distribution of cluster members.

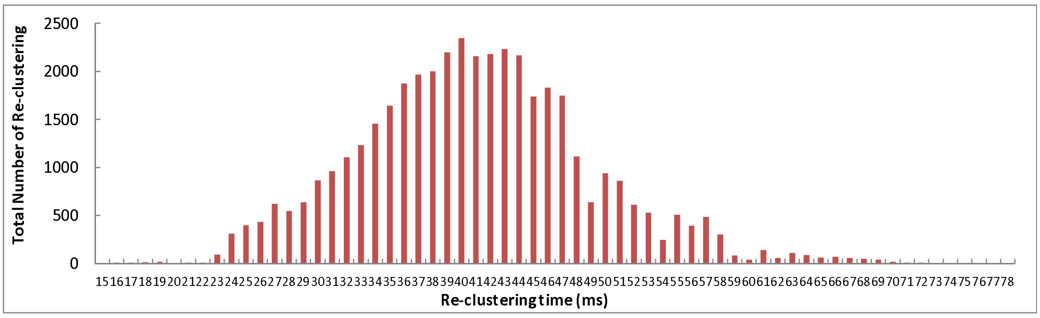


Figure 4.4: Re-clustering time distribution.

and cluster members. Although average lifetimes of both cluster heads and members are significant indicators about the performance, distributions of those would draw a clearer picture. Lifetime of a cluster head starts with declaring itself as the head of the cluster and terminates when the cluster head starts to seek for new members, i.e. cluster head selection process. Lifetime of a cluster member starts with being accepted as a member by a cluster head and terminates when no reply is received from the cluster head. The average lifetime of a cluster head is computed as 38.62*s* and the average membership time is computed as 49.16*s* for the above mentioned simulation results.

For a deeper understanding of the performance, the distributions of lifetimes of cluster heads and cluster members are depicted in Fig. 4.2 and Fig. 4.3 respectively. These distribution graphs are produced via the previously explained simulations. Averages

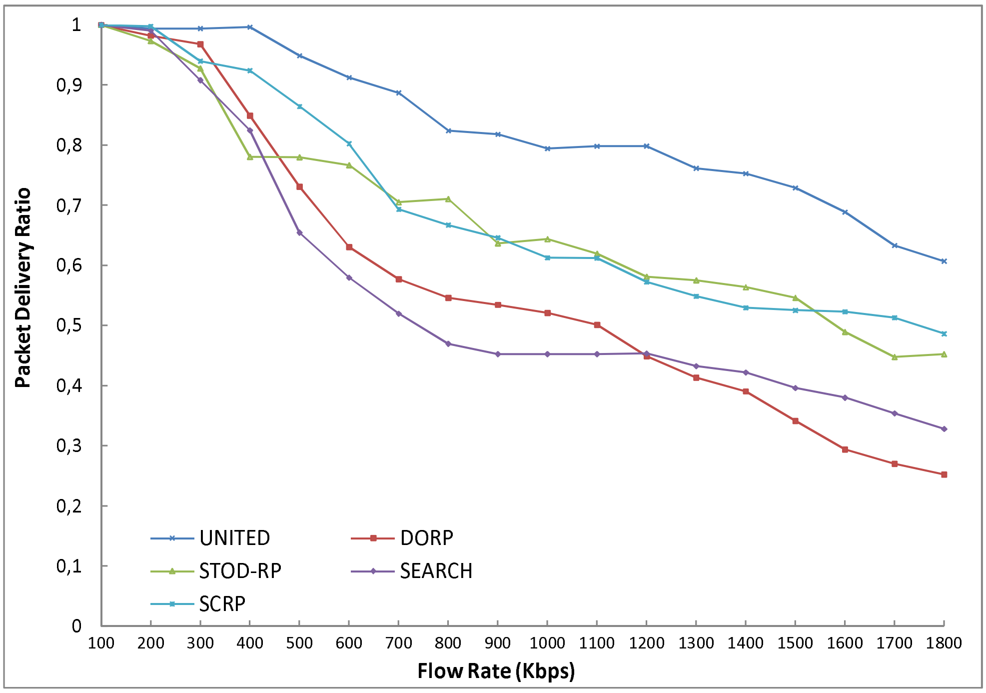


Figure 4.5: The packet delivery ratio as the flow rate increases.

and distributions indicate that UNITED forms stable clusters. To the best of my knowledge clustering papers in the literature do not have such detailed distribution graphs which prevents us to make comparisons with other clustering techniques using these graphs.

Average re-clustering time of the nodes is also investigated and found to be 41.22*ms*. Re-clustering time distribution of all cluster members in the course of all simulations are also given in Fig. 4.4. The re-clustering is relatively quick since the nodes utilize the information in their neighbor tables to quickly identify 1-hop neighbors and re-cluster.

Fig. 4.5 illustrates how packet delivery ratio changes with flow rate. The measurements of the packet delivery ratio over all traffic flows are averaged and plotted for each protocol. Contrary to the other protocols, UNITED has a smooth trend especially for lower flow rates. Other protocols suffer from the congestion and unable to deliver more packets for higher flow rates. As seen clearly, the UNITED significantly improves the packet delivery ratio especially for higher flow rates. Although no congestion avoidance/prevention techniques has been implemented in UNITED, it has a better packet delivery ratio because of the utilization of proposed metrics and the route preservation and adaptation scheme. Note that, UNITED tries to direct the traffic

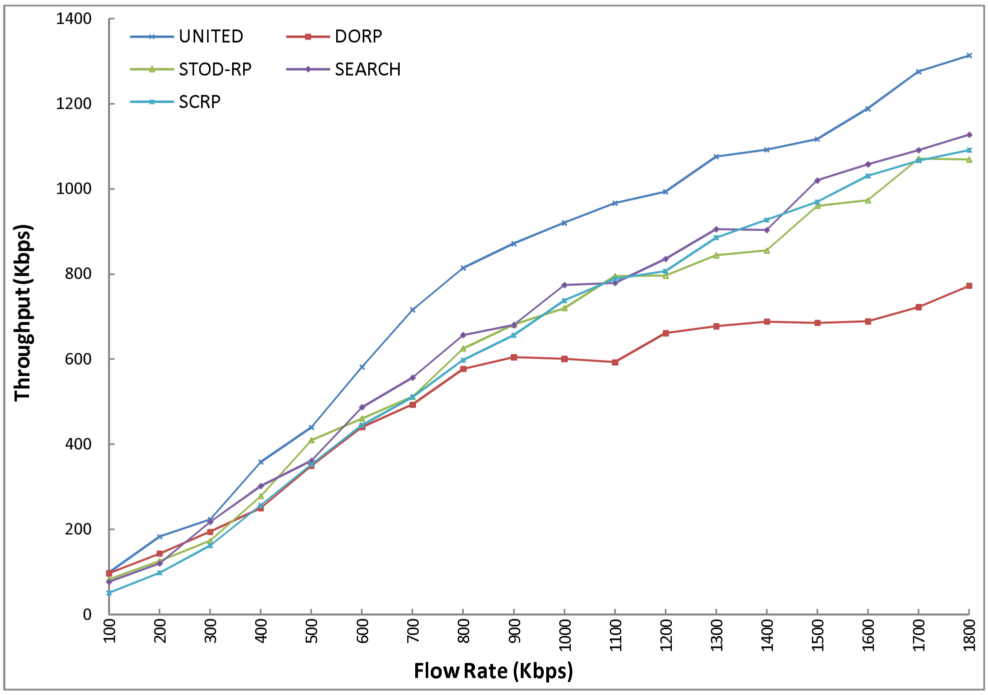


Figure 4.6: Throughput when two hosts, *S* and *D* communicate.

from paths/regions with high interference value to lower ones. Thus, a natural way of bypassing high traffic paths is provided in the UNITED.

As another performance criterion, throughput analysis is conducted (Fig. 4.6). When the traffic load is low (i.e. less than 400kbps), all schemes perform with similar aggregate throughput. As the flow rate increases, the throughput of DORP increases slowly towards the limit of the established path. Also in DORP, nodes become disconnected due to primary user activity, and no packets are forwarded. STOD-RP, SEARCH and SCRP perform better than DORP since STOD-RP and SCRP employ route recovery algorithms and SEACRH has a route maintenance algorithm. As the traffic load increases, the performance improvement of UNITED compared to the other schemes becomes more significant due to used routing decision metric, effective spectrum usage and route preservation and adaptation scheme. In such a dynamic environment (i.e. the network topology changes frequently), UNITED adapts itself to the environment to retain the secondary nodes communication path by making use of the clustering or to perform a local repair when the distance to the destination is not reachable without interfering primary user. Moreover, the established route in the UNITED is better than the route built in the other schemes in a frequently changing environment since interference is used as a routing metric. The change of throughput performance is also investigated as the number of available channels degraded to 16.

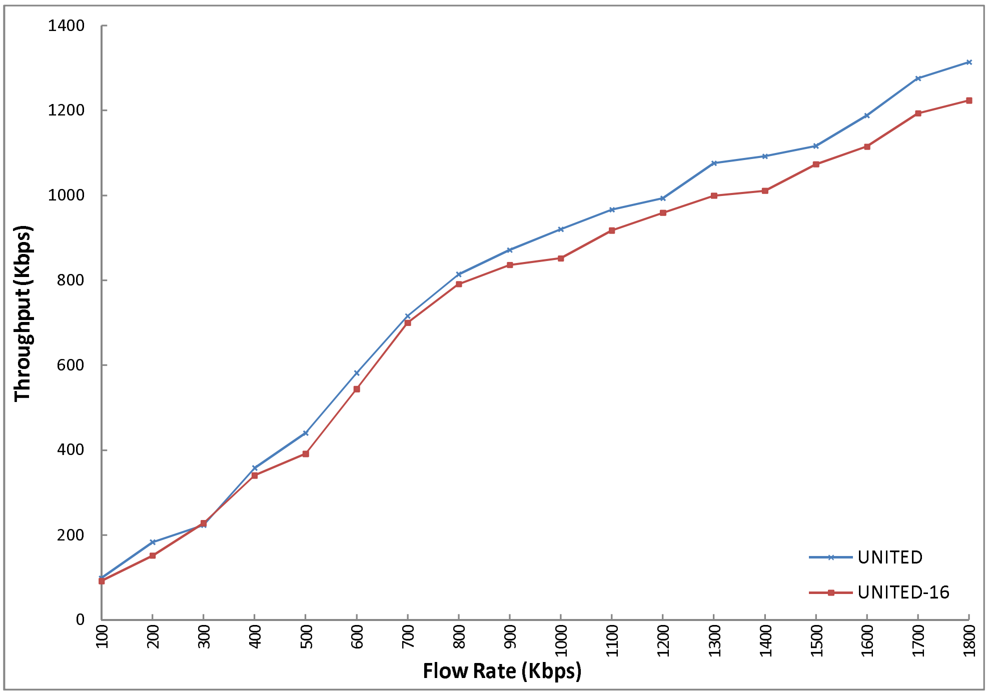


Figure 4.7: Throughput with 16 and 64 available channels.

As seen in Fig. 4.7, UNITED still has good performance over the other schemes. However, as the flow rate increases UNITED has some performance degradation since it is not able to find any available channels for spectrum handoff.

Obviously, the number of secondary nodes would have an impact on the throughput. Such an impact has also been studied by carrying out a set of simulations. The simulation setting is kept as the same as described above, except for the number of secondary nodes which is varied from 100 to 1000. Fig. 4.8 shows the throughput as a function of the number of secondary nodes. It can be seen that the throughput starts at roughly 1Mbps and remains almost the same up to 300 secondary nodes. However, when the number of secondary nodes gets higher, the throughput decreases dramatically. This indicates that 300 secondary nodes ($\tilde{1}00$ nodes per km^2) is the critical value for the given area, number of primary nodes, primary traffic and secondary traffic. Since the total capacity of all available channels provides a total bandwidth that would allocate up to 300 secondary nodes there is no decrease in the throughput. Over 300 secondary nodes the provided total bandwidth saturates yielding rapid performance degradation.

The end-to-end delay performance of the UNITED with other schemes is also compared. The number of intersecting flows is adjusted between 1 and 8 to evaluate

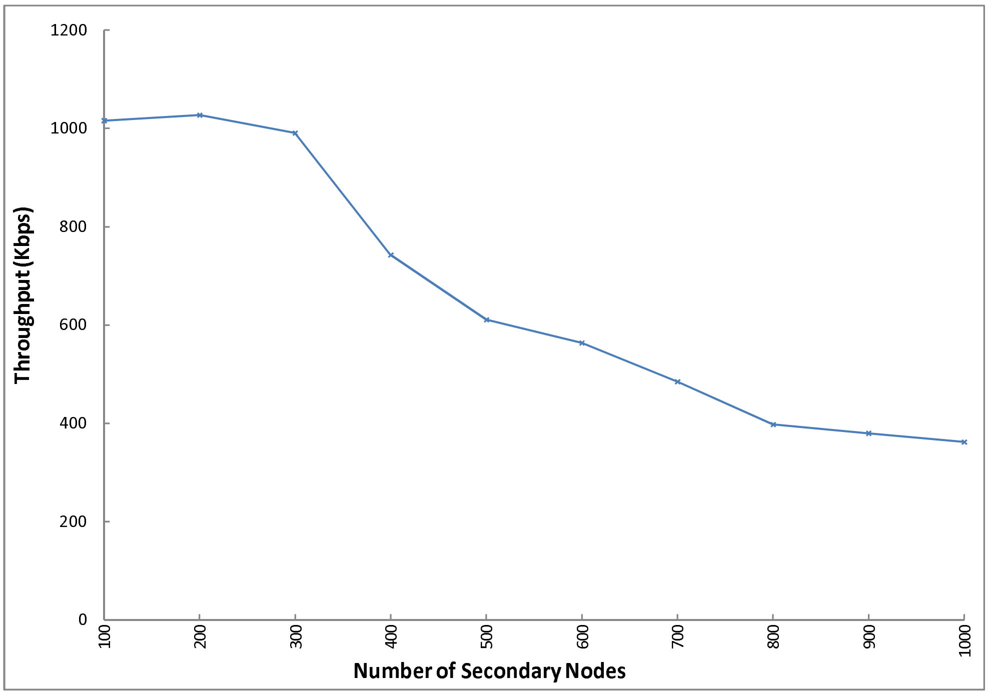


Figure 4.8: UNITED's throughput with changing secondary node's density.

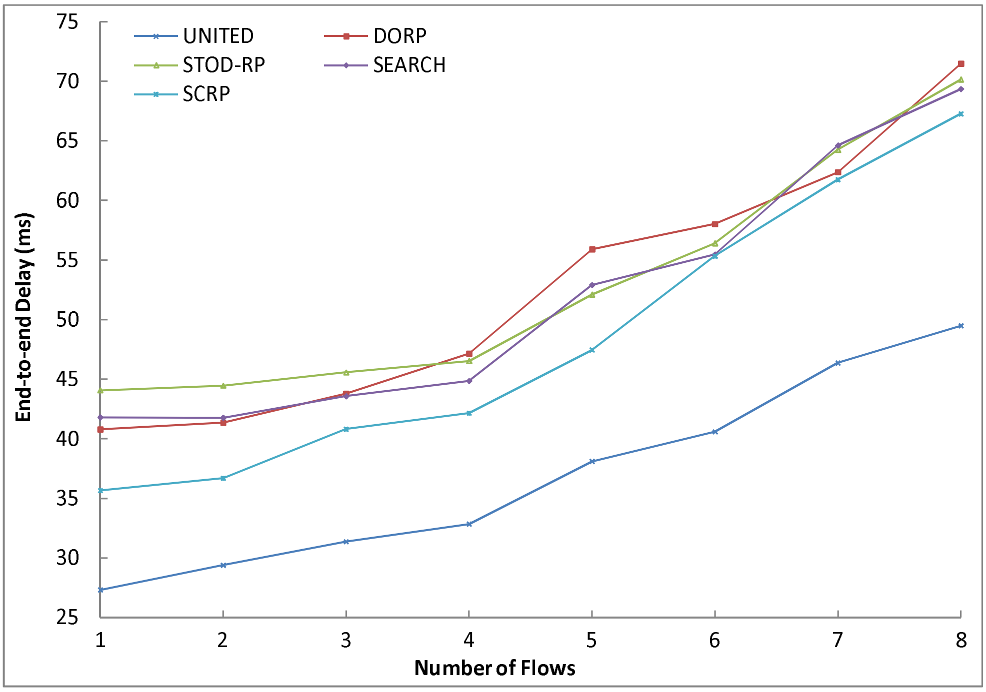


Figure 4.9: Average end-to-end delay performance vs. number of flows.

the performances on intersecting flows. The simulation result is shown in Fig. 4.9. When the number of flows increases, the UNITED seeks a balance between assigning new frequency bands to allow simultaneous transmission and accommodating some nodes on one band to avoid switching delay. Also the re-route establishment time is low in the UNITED upon a primary user activity detection than the others since those

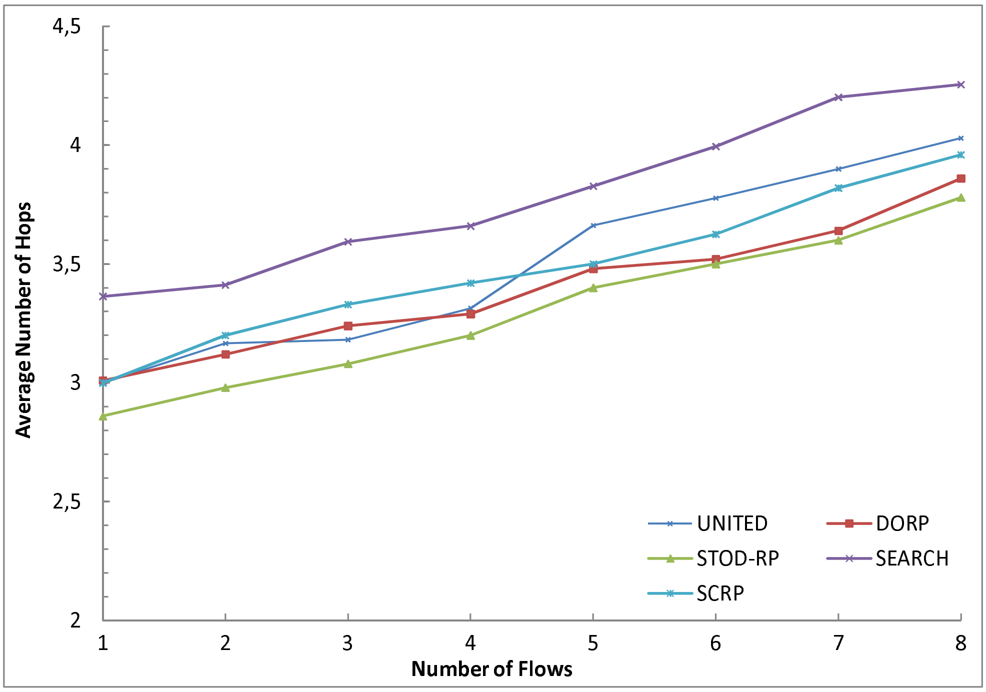


Figure 4.10: Average number of hops vs. number of flows.

Table 4.2: Jitter Values for UNITED

Number of Flows	1	2	3	4	5	6	7	8
Jitter_{mean} (ms)	1.53	1.57	1.69	1.72	1.72	1.73	1.81	1.97
Maximum-Minimum (ms)	5.21	5.72	6.29	6.32	6.33	6.40	7.02	7.54

techniques have to reconstruct a path from source to destination upon primary user activity detection. Consequently, the UNITED achieves an overall minimum delay considering the other schemes as the number of intersecting flows grows as shown in Fig. 4.9. Average number of hops as the number of flows increased is given in Fig. 4.10 to enable better understanding of end-to-end delay performance.

Since, speech quality with VoIP is primarily impaired by packet loss, total end-to-end delay and the jitter, it is also important to assess the jitter on the cognitive radio network in order to determine the performance. Jitter is the variation in the latency of packets at the destination. The values are computed based on the time stamps taken at the send/receive interface to reflect the perceived jitter by the VoIP application. If the jitter value is high the performance in some time-sensitive applications, such as VoIP, might get affected. Excessive jitter degrades system performance and might cause pops or clicks in audio communications which means severe degradation in call quality. Jitter_{mean} is the mean of jitter values experienced in UNITED. Maximum-minimum jitter is the difference between maximum and minimum delay measurements. The

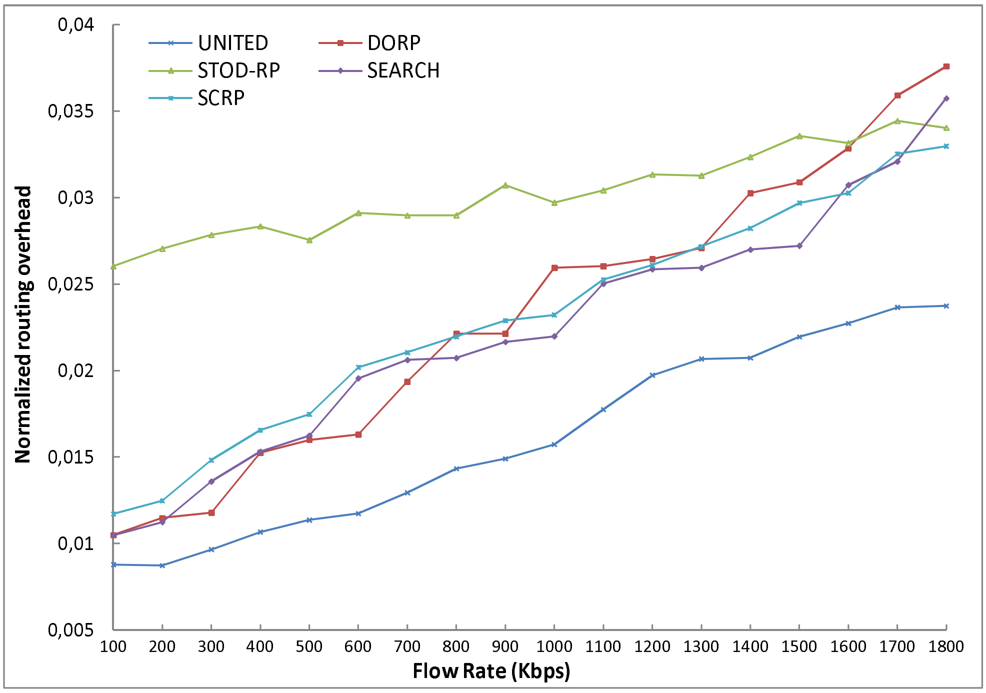


Figure 4.11: Normalized routing overhead as the flow rate increases.

jitter values for UNITED are measured and reported in Table 4.2. Jitter typically is between 1.5ms and 2ms. These values indicate that using UNITED allows good call quality for VoIP applications.

To assess the effectiveness of the UNITED, the normalized routing overhead has been used as a performance metric. Normalized routing overhead can be defined as the total number of control ($N_{control}$) and data packets sent (N_{data}) normalized by the total number of packets successfully delivered in the CR network, also considering the number of flows. The normalized routing overhead of the UNITED is illustrated in Fig. 4.11.

Route preservation and adaptation performance is also evaluated for UNITED and given in Fig. 4.12. The number of generated RREQ messages signaling the need for a fresh route formation is plotted against increasing flow rate. When the route adaptation mechanism is not employed, the resulting link failure results in the need of a fresh route formation from the source. These failures consists of both mobility and lack of spectrum availability. When route adaptation mechanism is employed, UNITED tries to fix link breakages locally and tries to adapt the link changes. It is observed that such an adaptation keeps the route connected, leading to much fewer route outages. Fig. 4.13 illustrates the mobility induced fresh routing requests. As the

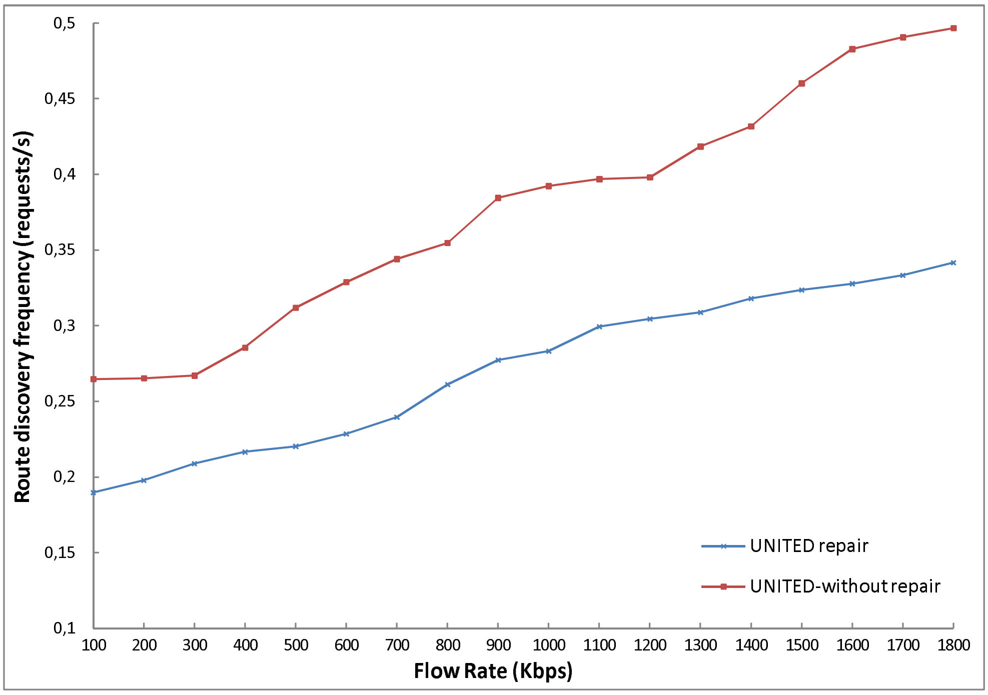


Figure 4.12: The route discovery frequency for UNITED technique.

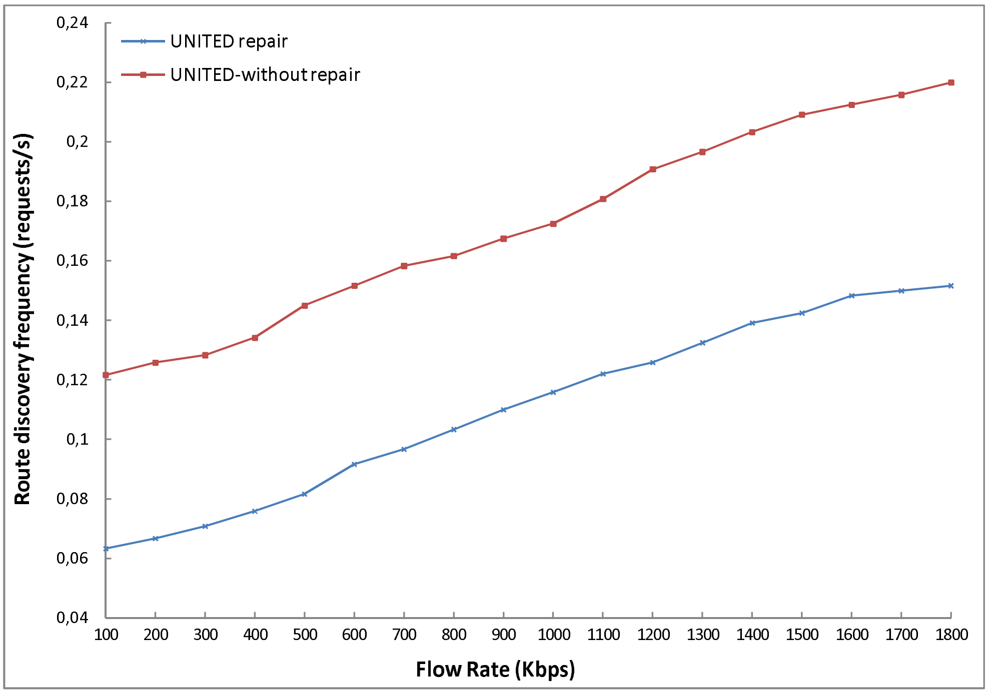


Figure 4.13: Mobility induced fresh routing requests.

figure indicates, route preservation and adaptation leads to fewer fresh routing requests as expected.

4.4 Concluding Remarks

A cluster-based routing protocol for mobile CR ad hoc networks, UNITED, is proposed for maximizing the network throughput and minimizing the end-to-end delay. The key concept is to use clusters to adapt such a dynamic environment and performing routing in intra- and inter-cluster levels. Initially, nodes organize themselves into several clusters by the clustering algorithm that is based on a combined weight metric that takes into account several system parameters such as distance, transmission power, mobility, remaining power of nodes, and sensed information about available spectrum. Following completion of cluster formation, routing is done according to the spectrum usage and interference metrics in intra- and inter- cluster domains. Clusters adapt themselves dynamically with respect to spectrum availability, and the high mobility of the nodes based on the calculated metric. Through an implementation in the ns2 simulator, it has been shown that the UNITED achieves significant improvement on the throughput and the end-to-end delay. Simulation result also represents the adaptability and efficiency of the UNITED.

5. RAC: RANGE ADAPTIVE COGNITIVE RADIO NETWORKS

Cognitive radio is a flexible and intelligent wireless system that is aware of its surrounding environment and changes its transmission or reception parameters to communicate efficiently avoiding interference with the primary or secondary users. Cognitive radio technology also enables implementation of adaptive mechanisms to yield more intelligent decisions. The secondary users will benefit from this cognitive radio to utilize the licensed band of the primary system as long as the licensee's operation is not compromised. Compared to ad hoc wireless network, cognitive radio ad hoc networks are subject to higher levels of interference since two classes of users are concurrently utilizing (or attempt to utilize) the communication medium. Therefore, proper interference management techniques considering the requirements and features of cognitive radio networks have to be designed. Consequently, determining the interference of the secondary users, that dynamically appear/disappear and may have diverse transmission ranges, on primary users is challenging. Providing communication among cognitive radio users in the presence of primary user communication is also challenging.

In a cognitive radio system, a secondary link is activated along with the primary link in a way that it does not disrupt the primary link. There have been three essential approaches for the cognitive transmission in the literature: the interweave, the underlay and the overlay approaches [2, 50]. In the underlay approach, the cognitive radio transmits in a manner that its interference at the primary receivers is negligible. In the overlay approach the cognitive radio imposes non-negligible interference at the primary receiver but it makes up the performance degradation in the primary radio with the help of its non-causal access to the primary users data. The interweave technique is based on the idea of opportunistic communication. There exist temporal spectrum gaps (opportunities) which are also called as spectrum holes that are not in use by the primary owners and consequently can be used for secondary communication. Therefore the task for spectrum sensing is to detect whether there is primary user or not. On the other hand, for a more sophisticated cognitive radio such as hybrid overlay/underlay cognitive radio [51, 52], secondary user can also utilize the gray spectrum (occupied by primary use), and it is required to limit the power of secondary user to avoid harmful interference to primary user. Specifically, after the transmission, the power of the secondary user inflicted on primary user should be below the primary user's interference tolerance level. Hence, for such an approach, it is also necessary to find more information related to the primary user, such as the power of the primary user, the distance between the secondary user and primary user (or location of primary user) besides just the existence of the primary user. As a direct result, the concern becomes not only about detection of a primary user but also detection of power level and location of the primary user. Such information, i.e. transmission power and locations of the primary users, are two key resources that determine spectrum opportunities for cognitive radio users. Consequently, it becomes beneficial to find appropriate means to estimate primary user's location such that the primary network is secured from excessive cognitive radio interference while concurrently making sure that the quality of service within the cognitive radio network is assured. Having such information allows cognitive radio users to change their transmission ranges accordingly to continue their current communication session without affecting primary users. To achieve this objective, Range Adaptive Cognitive Radio Networks (RAC) is proposed by utilizing an adaptive transmission range scheme in this chapter. RAC mechanism is based on self-adjusting variable transmission range of secondary users to keep communication link alive or to find an alternative path that circumvents the primary user activity.

For cognitive radio networks, there has been an interest in the recent years for determining an optimal transmission range which is also called as optimum power interchangeably for a fixed number of secondary nodes distributed over an operating area [53, 54, 55, 56, 57, 58, 59, 60, 61] to manage the interference problem. Wang and Zhu [53] studied the power control of transmitter in cognitive radio system and employ game theory for modeling. In [54], authors considered the distributed power control problem in a CR network which shares the primary user channel while trying to guarantee the QoS requirements for both the primary and secondary user simultaneously. In [55], the authors proposed an opportunistic power control strategy for the cognitive user, which they proved to be optimal in the sense that it maximizes the achievable rate of cognitive user while guaranteeing the outage probability of the primary user not to be degraded. All of these mentioned studies tries to find and allocate an optimal range (power) and assigns it statically for a given scenario. Neither of them adjusts the transmission range adaptively during a communication session. However, adaptive allocation of transmission range (power) has been shown to be an efficient and effective means of improving the performance and capacity of wireless networks [62, 63, 64]. Naturally, as an attractive idea, there is also an interest on using adaptive transmission range in cognitive radio networks [65, 66, 67, 68, 69, 70]. Having said that, to the best of my knowledge, RAC is the first scheme that incorporates adaptive transmission range mechanism into the cognitive radio technology. In [66], the constrained stochastic games are adopted and extended to exploit the optimal policies for the dynamic power management problem in cognitive radio networks by considering the variations from both the channel gain and the primary traffic. The dynamic environments occurred from the channel variations and the uncertain spectrum holes is modeled as the ergodic Markov decision process. Constraints for allowable interferences is applied in order to preserve the communication quality among the primary and the secondary users. With the satisfaction of the defined constraints, the constrained Nash equilibrium suggests an optimal solution to the dynamic power assignment according to the cognitive radio users' current state within the cognitive radio network. In [67], a distributed power control algorithm for cognitive radios is proposed. Authors assume that the secondary user can decode part of the feedback channel of the primary user. Decoded part is related to the power control command, which is sent by the primary receiver to the primary transmitter. Power adjustment is done in every predetermined time slot . The secondary transmitter updates its transmission power according to a history window of feedback commands of the primary system which are sent from primary receiver to its transmitter. The results presented show that cognitive radio users slightly interfere with the primary system. In [68], authors employ both adaptive and fixed transmit power control to the cognitive radio transmission such that the interference to the primary users is limited. For analytical modeling of cognitive radio transmission, authors derive a closed-form expression of the detection probability for the energy detection with selective combining in a Rayleigh fading channel. By using mentioned analytical model, the maximum constant output SNR at receiver side cognitive radio subject to the interference constraint is obtained. The transmit power of the cognitive radio transmitter is adjusted in each fading block to maintain a constant output SNR at the cognitive radio receiver. Authors assume that cognitive radio users have multiple antennas to obtain the distribution of the interference. They also assume that cognitive radio users report their geolocation to a database. This database also has the geolocation of primary user receivers. According to this geolocation information, the interference constraint calculated on the basis of propagation models and stored as part of the regulatory information in the database.

In [69], an online power adaption algorithm which maximizes the valuation of each user considering the future reward and the dynamics of experienced environment is proposed. Authors introduce a valuation function for considering the time-varying property of dynamic environment. It represents the total amount of reward that a cognitive radio user can expect over the future. The algorithm contains mainly three parts: dynamic environment model, dynamic learning, and policy selection. To model the dynamic environment model, users are assumed to be the players of a game, and each user makes tradeoff by power adaption. Dynamic learning consists of two parts which are predicting and exploiting. To enable the efficiency of energy consumption, every user will select the optimal policy to maximize its valuation by using perfect prediction for a single user. Although, the authors claim that their approach has better performance, simulations are done only with 2 users and considering only one channel. Such an simulation environment does not reflect a practical cognitive radio network.

Durowoju et.al. model the cognitive radio network for mobile and immobile users and propose algorithms exploiting primary radio environment knowledge (spectrum use), called power control with primary protection via spectrum sensing [70]. Authors proposes distributed constrained power control and an improved version of mentioned algorithm named as generalized distributed power control algorithm. In that study, cognitive radio users are considered to be moving with some velocity within the cognitive radio network and are subject to fading variations, however primary users are modeled as stationary TV transmitters and receivers. The link gain evolution process models as a distance dependent shadow fading process where cognitive radios move with constant velocity. The mentioned study proposes a scale-up factor (2 dB) to drive up the SINR target in order to maintain the QoS within the cognitive radio network for non-stationary cases.

Like mentioned studies pointed out, using adaptive transmission ranges is suitable for cognitive radio networks as the topology changes quite often. RAC is shown be an effective solution in such a changing environment due to varying primary node activities by simulations. RAC scheme is explained in more detail in the next sections.

5.1 Network Model

In this chapter, a cognitive radio ad hoc network environment with primary and secondary nodes, where all nodes communicate with each other in their own networks, is considered. There is no communication (i.e., no cooperation) between primary and secondary networks. The network is modeled as a graph $G = (N, L)$ where N is a finite set of nodes, $N = \{x_1, x_2, \ldots, x_n\}$ and L is a finite set of unidirectional links, $L = \{(x_i, x_j)\} : 1 \leq j \leq n \; for \; x_i \in \Re^d$,
$1 \leq i \leq n$. If a node m is within the transmission range of node n, then n and m are assumed to be connected by an unidirectional links $l_{nm} \in L$, such that whenever n transmits a message, it will be received by m via l_{nm} and vice versa. A route or path from node s to node d is an alternating sequence of nodes and links, representing a continuous traversal from node s to node d. Each node n has a wireless optimal transmitter range R_{opt} that is used in normal operation and is allowed to use different transmission ranges R_n independently from other nodes to communicate with other nodes in their neighborhood, $R_{min} < R_n < R_{max}$, to retain the communication path if needed.

5.2 Details of the Implementation of the RAC

In the proposed adaptive range scheme, a modified version of AODV adapted to cognitive radio networks [19] is used as routing algorithm. In addition to the inherited characteristics of used AODV protocol, each node n in the network has a neighbor node table, which is constructed using beacon messages to its neighbors once in every time quantum. If the spectrum sensing algorithm uses hello messages, those

Algorithm 5: Range Adaptive Cognitive Radio for node n_i

begin
    if *PU detected* **then**
        if *PU distance calculated* **then**
            adjust transmission range R_{best} not causing harmful interference to the PU;
        else
            while *interference to primary user* $> T_i$ **do**
                reduce the transmission range by ΔR
            end
        end
    else
        adjust transmission range R_{opt};
    end
    if *PU activity interrupted current communication session* **then**
        multicast RREQ plus the first packet in the queue to neighbors that are far from the PU;
    end

can be used for this specific purpose and there will no need to use additional beacon messages in the proposed scheme. Also if there is an ongoing communication session overhearing nodes uses the information. In the neighbor table, a distance metric is stored for every neighbor locally. Each node receiving the beacon, determines a distance metric to a neighboring node based on measuring the received signal strength indicator (RSSI), Time of Arrival (ToA), and Angle of Arrival (AoA) of the received beacon messages [71, 72, 73].

To clarify, the example cognitive radio network shown in Fig. 5.1 can be considered. In this network, node *S* has some data to send to node *D* and therefore needs to find path to destination *D*. As stated above, a modified version of AODV adapted to cognitive radio networks [19] is employed. The protocol starts by sending out a broadcast Route Request (RREQ) message seeking destination *D*. The destination node *D* knows the spectrum opportunity distribution of all nodes on the path when receiving RREQ message, and assigns a frequency band to its cognitive radio transceiver. It then, sends back a Route Reply (RREP) to the source node, encapsulating the assigned band. Intermediate node assigns frequency band with the help of the band choices extracted from the RREP, and the spectrum hole (spectrum opportunity) information from previous RREQ. Then the node establishes path to the destination via its cognitive

Algorithm 6: RAC:Local Repair for node n_i

```
begin
    if primary user detection then
        use RAC to adapt transmission range;
    if active path information packet received then
        store active path nodes information;
        decide which nodes on the path are neighbor node;
    if RREQ+packet arrives for a specific destination D then
        check neighbor table and active path information;
        decide which nodes to send;
        multicast RREQ+packet to those;
```

radio and generates new RREP message to send back to the source. Once the path is constructed, communication session continues normally. Upon the start of the communication process, every node n in the active path locally broadcasts the active route information in the beacon messages to its neighbors using the neighbor table. Receiving this path information, neighboring nodes control their own neighbor table and decide which nodes in the active path are in their neighbor table. Whenever a primary node activity is sensed by the cognitive radio engine (Fig. 5.2), every node detecting the primary user activity in the active path, tries to determine the distance of the primary user and according to the determined value, it adapts its transmission range that restricts the interference to the primary user below a certain interference threshold for node i, T_i. As can be seen in Algorithm 5. If the node density is high enough, the best transmission range that enables the retaining the active path without causing any harmful interference to primary node is selected by checking the distance values of the neighbor table. If there is no such value that retains the active path without interfering the primary user, all nodes in the active path adapt their transmission ranges to their maximum range which is not causing any harmful interference to the primary user (Fig. 5.3). After this adaptation, nodes that detected the primary user activity in the active path, multicast received packets of the ongoing communication session to its available neighbors according to the neighbor table along with a route request message to the destination node D. As a consequence, the new path is constructed with only local update upon the first route reply message received. Algorithm is given in Algorithm 6. If this is not possible, a route error message is sent to the source node. Afterwards, a re-routing from node S to node D is initiated.

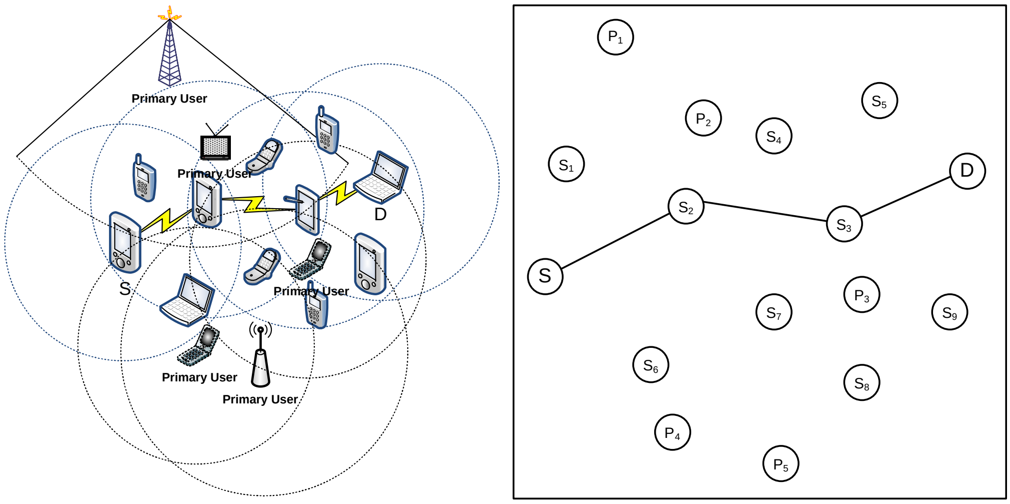


Figure 5.1: An illustration of a CR ad hoc network and its 2D mapping on the right, node *S* communicating with node *D*.

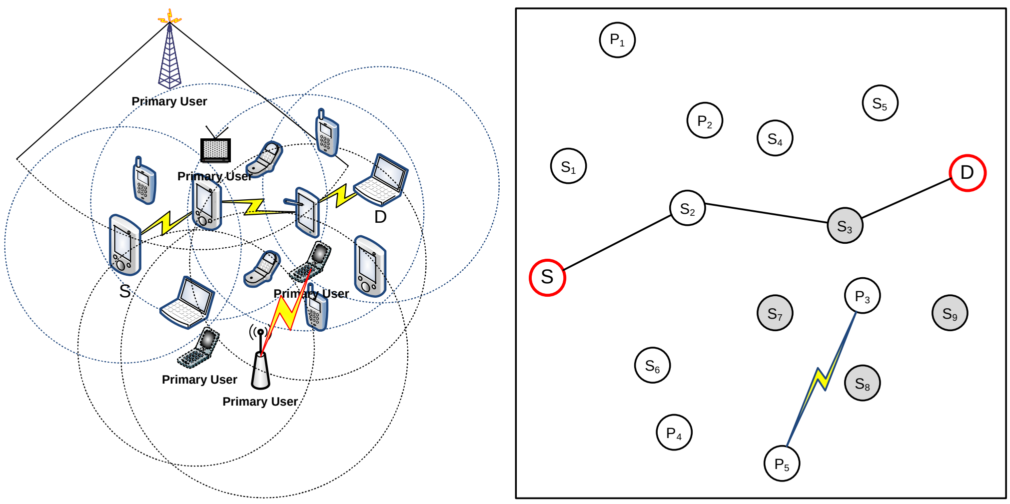


Figure 5.2: A primary user starts communication (the secondary nodes in the range of the primary users are shaded in gray.

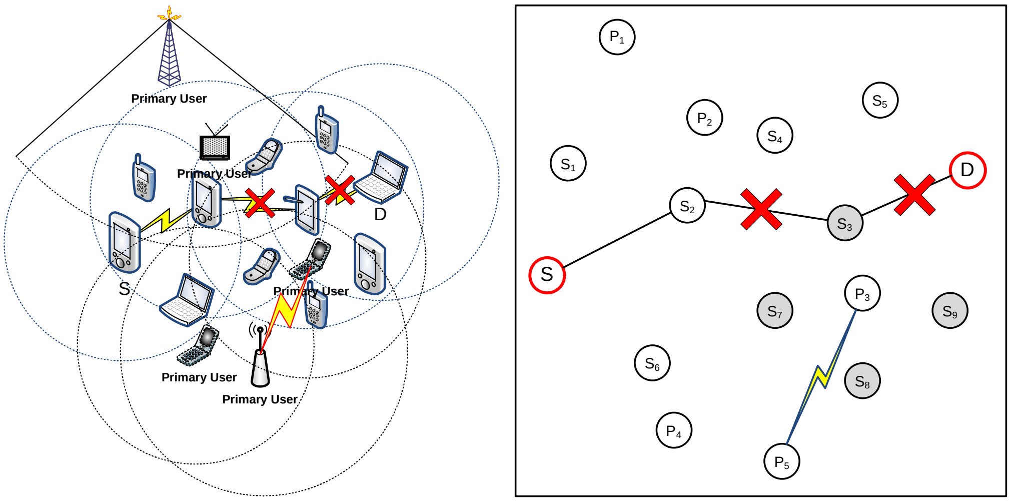


Figure 5.3: Due to primary node activity, secondary nodes in range leave the spectrum immediately.

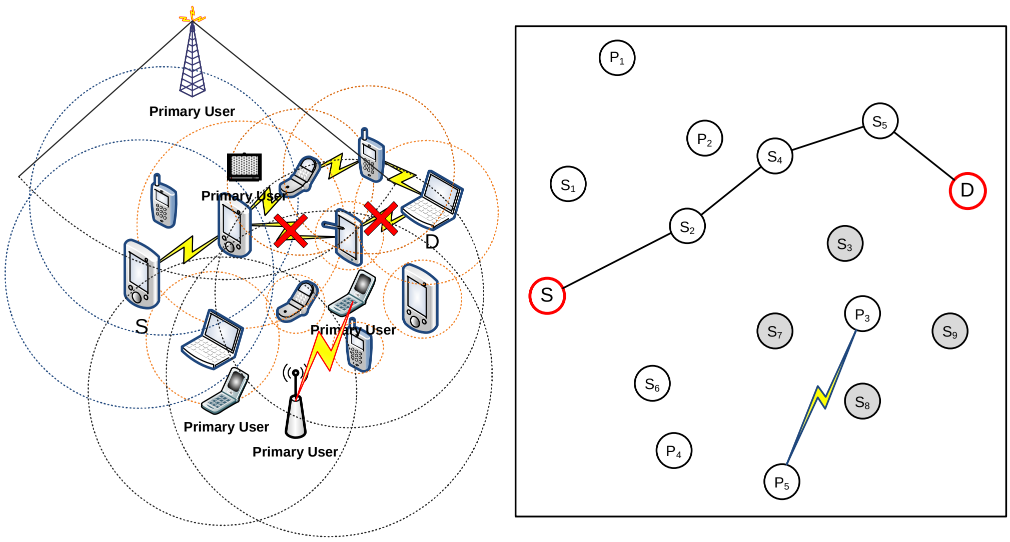


Figure 5.4: Re-route with adaptive range and local repair using range adaptivity.

5.3 Simulation and Performance Analysis of RAC

The characteristics of the RAC are explored under a number of different scenarios. The robustness of the RAC is investigated for various numbers of both primary and secondary nodes, stressing the impact of adaptive transmission range on the throughput performance. The simulations are run for networks of sizes 10 to 100 secondary nodes and 20 to 100 primary nodes. It is shown that since the node density has a great importance on the performance of the RAC for retaining the path and for the success of the local repair, the RAC performs high throughput for dense networks. However, after a certain threshold throughput starts to decrease due to the congestion. For example the peak average throughput of the RAC with 20 primary node is reached when 60 primary nodes are around. A sharp decrease after 60 nodes indicates the practical limit for the trade of between the number of primary and secondary users. (Fig. 5.5) As expected, average throughput is inversely dependent on the number of primary nodes as seen in Fig. 5.6.

As noted earlier, SORP [19], a modified version of AODV and a recently proposed spectrum-tree based on demand routing STOD-RP [24] are used for comparisons. Throughput and end-to-end delay comparisons have been evaluated between SORP, STOD-RP and RAC to show that RAC can well fit the multi-flow multi-channel environment and effectively exploit the potential large communication capacity in CR Networks. In the simulations, the rate of flows is varied from 100 Kbps to 1800 Kbps. The nodes are randomly placed in the area, and 8 flows having the same traffic generation rate are initiated. When the traffic load is low, all three schemes have more or less the same performance. As the flow rate increase, the throughput of SORP increases slowly towards the limit of the established path. Also in SORP, nodes become disconnected due to primary user activity, and no packets are forwarded. STOD-RP performs better than SORP since STOD-RP also employs a route recovery algorithm. As the traffic load becomes higher, the performance improvement of the RAC over the other two schemes becomes more significant due to path retaining and local repair using adaptive transmission range. In a dynamic environment, which means the network topology varies frequently, the RAC adapts nodes transmission

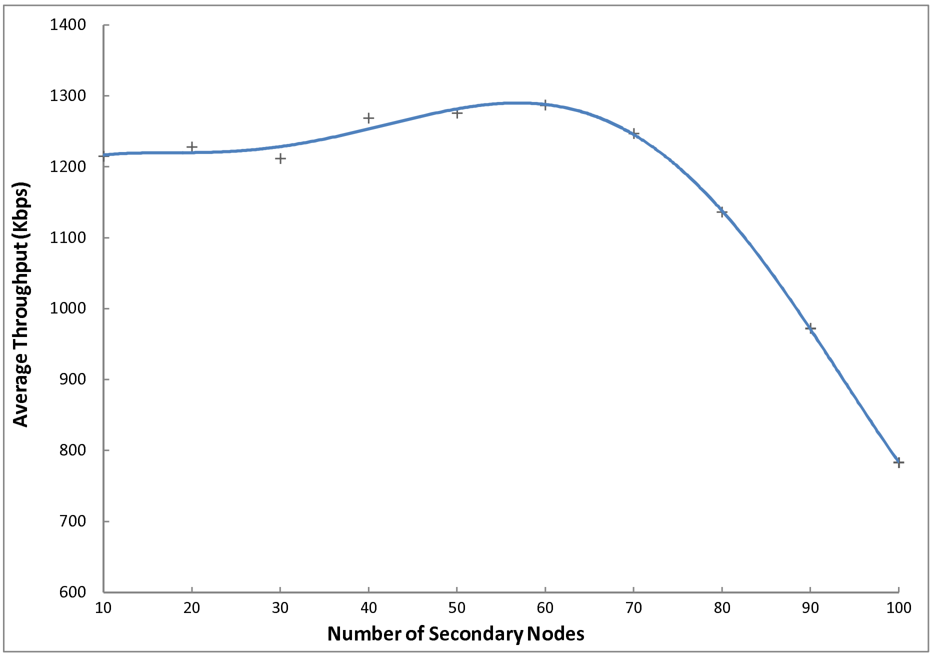


Figure 5.5: Average throughput of the RAC with 20 primary nodes in the network.

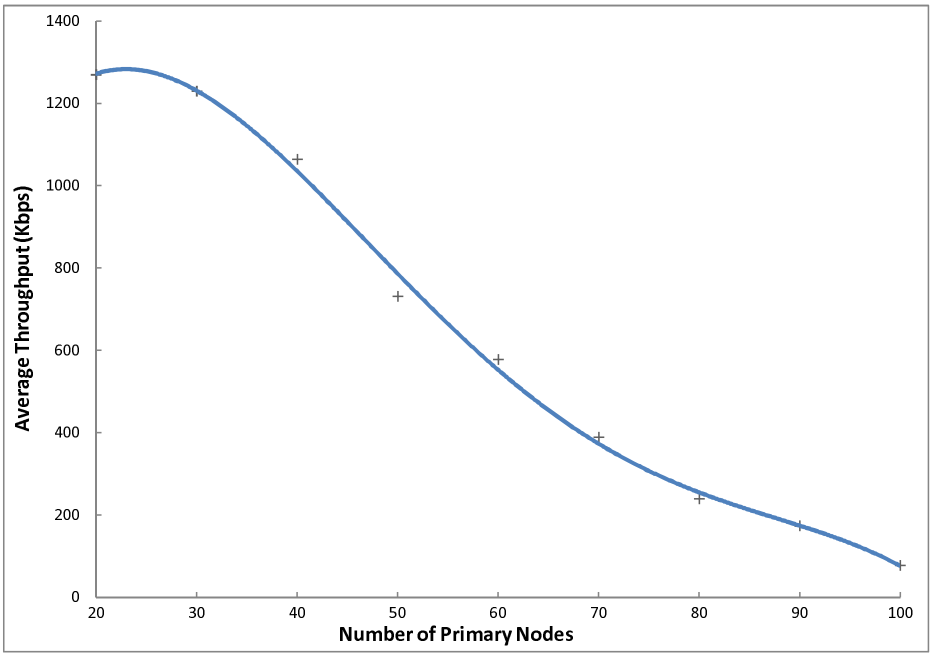


Figure 5.6: Average throughput of the RAC with 50 secondary nodes in the network.

range to retain the secondary nodes communication path or performs a local repair when the distance to the destination is not reachable without harmful interference to the primary user. Therefore, the established route in the RAC is better than the route built in the other two schemes in a frequently varying environment. The result is illustrated in Fig. 5.7.

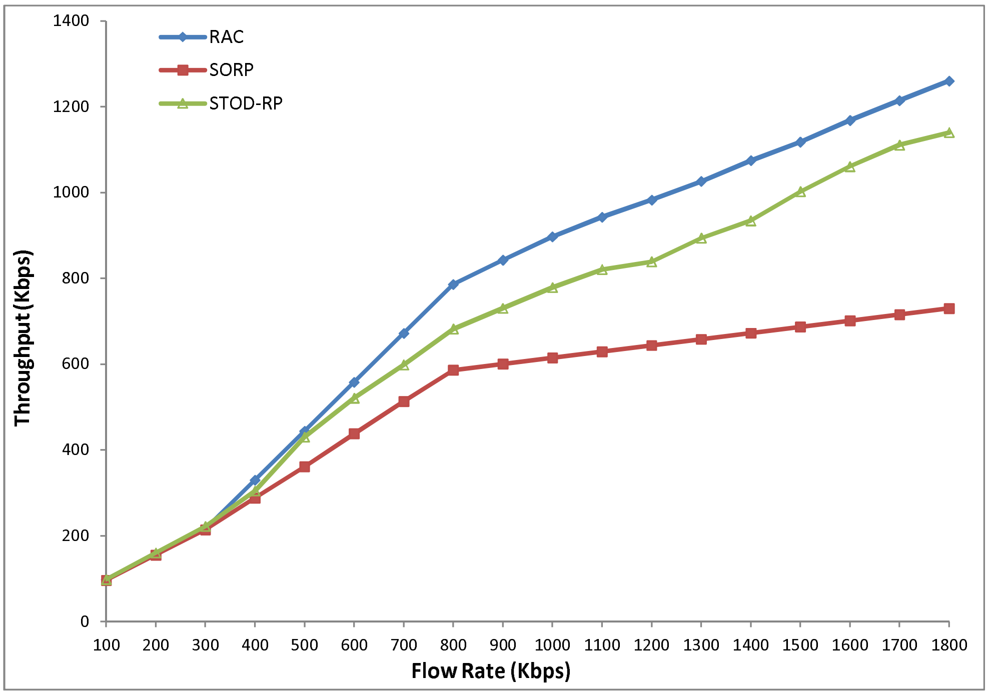


Figure 5.7: Throughput when two hosts, *S* and *D*, communicate.

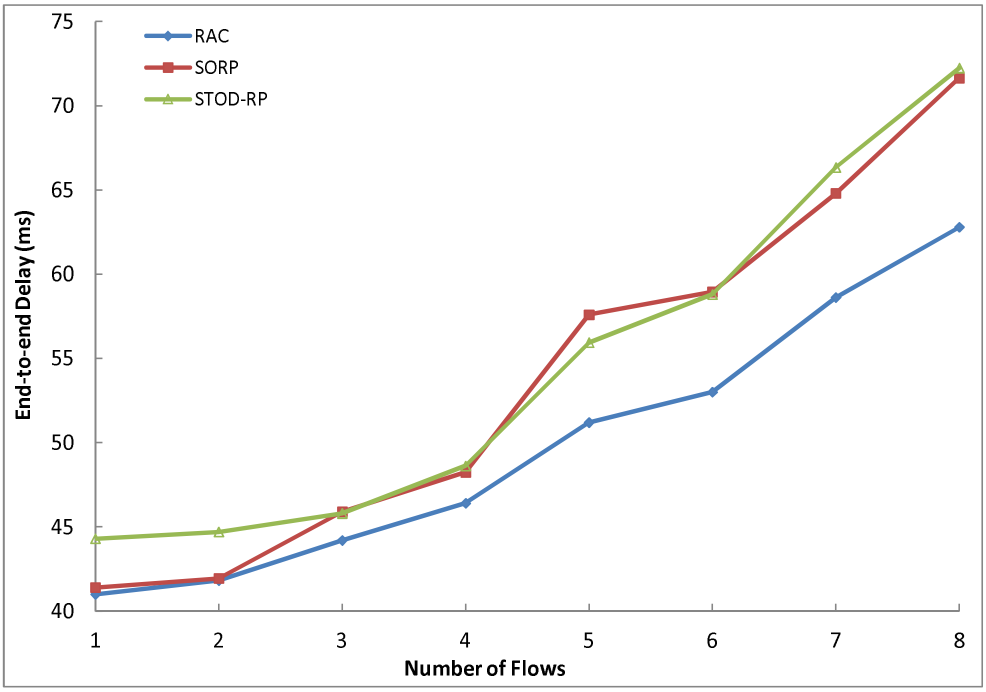


Figure 5.8: Average end-to-end delay performance vs. number of flows.

The end-to-end delay performance of the RAC with other schemes is also compared. The number of intersecting flows is adjusted from 1 to 8 to evaluate the performances on intersecting flows. The simulation result is shown in Fig. 5.8. When the number of flows increases, the RAC seeks a balance between assigning new frequency bands to allow simultaneous transmission and accommodating some nodes on one band to avoid switching delay. Also the re-route establishment time is lower in range adaptivity than the others since those techniques have to reconstruct a path from source to destination upon a primary user activity detection. Consequently, the RAC achieves an overall optimal delay, than the other two as the number of intersecting flows grows as shown in Fig. 5.8.

5.4 Concluding Remarks

Range adaptivity is proposed to enhance throughput of cognitive radio ad hoc networks. RAC is an autonomous distributed adaptive transmission range control scheme for cognitive radio networks that simultaneously considers the QoS requirements of primary and secondary users. RAC is based on self-adjusting variable transmission range of secondary users to find an alternative path to keep communication link alive. It is a simple yet an efficient approach to utilize throughput and reduce end-to-end delay. Simulative performance analysis indicates that RAC serves as a proof-of-concept and shows a possible direction to improve the performance of routing protocols for cognitive radio ad hoc networks.

6. SELF ADAPTIVE ROUTING FOR DYNAMIC SPECTRUM ACCESS IN COGNITIVE RADIO NETWORKS

In this chapter, a novel self adaptive routing algorithm, SAR, which is designed for range adaptive cognitive radio networks for efficient data transportation in CR networks by making use of transmission range adaptivity dynamically, link modeling and interference avoiding, is proposed. Although link modeling, interference avoiding and different transmission ranges with relaying methods have been previously adapted separately, to the best of my knowledge, SAR is the first routing technique that incorporates all of them into a single routing framework for cognitive radio networks. The range adaptivity mechanism is based on self-adjusting variable transmission range of secondary users dynamically to find an alternative path to keep communication link alive without interfering the primary user. When a new route cannot be constructed by range adaptivity, band switch operation takes the turn. If band switch delay is found not feasible or no available SOPs exist in the other bands, a brand new path is constructed from scratch.

Both spectrum usage and interference metrics are incorporated into the range adaptive cognitive radio network. SAR takes the advantage of capturing any spatial and/or temporal locality of link disconnection, and interference levels and leveraging both for optimal route selection for cognitive radio networks.

6.1 The System Model

In the network architecture being considered, similar to previous chapters, a number of primary networks coexist and may overlap with the secondary network. Routing in cognitive radio networks requires both spectrum quality and spectrum availability issues to be addressed. The proposed metrics are derived considering both as described in Chapter 3. In this section, the network architecture is described by focusing on the node and channel aspects of the network in detail.

6.1.1 Node Architecture

In the proposed model, each secondary node is equipped with a single cognitive radio transceiver. It is assumed that a secondary node can tune its radio transceiver to any of the allowed channels in the licensed (primary) band. There is an underlying channel coordination mechanism at the link layer that allows neighboring nodes to engage in pairwise communication as previously addressed in [74, 75]. No prior assumptions are made on the number, location, transmission standard or protocol that are followed by any primary user. The outcome of the sensing algorithm running at the physical layer is being utilized to obtain necessary information in order to constitute routing metrics. However, the scope of this study is limited to the routing for cognitive radio networks.

6.1.2 Channel Structure

The licensed band comprises of a number of channels that are allowed to be used by cognitive radios. Each channel has a bandwidth that are known in advance. As mentioned before the primary user activity is modeled as a two stage ON-OFF (busy-idle) random process. Since cognitive radio nodes preserve their spectrum opportunities (SOPs) locally and SOPs change temporally and spatially, spectrum availability distribution might be quite different from node to node. Spectrum availability cost is used to assess available channel list in the proposed technique. Whenever sensing algorithm sends channel availability information the cost metrics are recalculated and cost of a available channel is updated. Cognitive radio nodes utilize spectrum availability cost list to establish links to construct routes.

6.1.3 SOP Discovery and Sensing

A SOP in a channel can only be discovered by sensing. It is assumed that sensing algorithm provides instantaneous channel availability information periodically and the cognitive radio users can reliably detect the presence of a primary user. Recent research has spent considerable effort on the accuracy of sensing. Some of the studies propose cooperation techniques in which one of the users acts as a relay for the others, leading to a significant decrease in detection time and an increase in overall agility [76, 34]. However, in order to characterize an imperfect sensing performance, the probabilities of miss detection and false alarm have also been considered in simulations. Both miss detection and false alarm rely on the length of the course of sensing. During the course of sensing, especially for the commonly used energy detection techniques, the adjacent CR users also must be silenced. Thus, path latency is increased while throughput is decreased considerably since CR users along the packet forwarding path are unable to transmit owing to the enforcement of the silence zone. Thus, a tradeoff between sensing capability and achievable throughput as well as latency exists depending on the sensing algorithm used. The probabilities of miss detection and false alarm along with sensing time can be altered to provide a perfect sensing knowledge such as in DORP [18], STOD-RP [24] and SEARCH [26]. Note that the proposed model is designed to work for both perfect and imperfect sensing knowledge. The proposed spectrum and interference aware self adaptive routing technique is described in detail below.

6.2 The Routing Algorithm

In this chapter, similar to previous chapters, a cognitive radio ad hoc network environment with primary and secondary nodes, where all nodes communicate with each other in their own networks, is considered. There is no communication, i.e., no cooperation, between primary and secondary networks. The network is modeled as a graph comprising a finite set of nodes and a finite set of unidirectional links. If a node m is within the transmission range of node n, then n and m are assumed to be connected by an unidirectional link. A route or path from node s to node d is an alternating sequence of nodes and links, representing a continuous traversal from node s to node d. Each node n has a wireless optimal transmitter range R_{opt} that is used during normal operation and is allowed to use different transmission ranges, R_n, independently from other nodes to communicate with other nodes in their neighborhood, subject to $R_{min} < R_n < R_{max}$, to retain the communication path if needed.

The successful operation of the cognitive radio network will be disturbed, if a primary user activity detected due to their priority in spectrum access, and the operations of primary users must not be affected by any of the unlicensed users. Regardless of the used protocol, frequent interruption in a selected route would definitely degrade the performance of the communication for the secondary users. Secondary users may agree upon a reduced performance within the scope of expected QoS.

Therefore the motivation is to design a routing technique that provides QoS guarantee which will allow a path to be retained during a data communication session along that path between secondary nodes when it is feasible to retain complete path and communication session. SAR: Self Adaptive Routing for Dynamic Spectrum Access in Cognitive Radio Networks is proposed to achieve this objective by utilizing RAC: an adaptive transmission range scheme [77] and incorporating essential, performance boosting routing metrics for optimal path selection.

6.2.1 Design Essentials

The SAR is aimed at finding the optimal route at the beginning of the communication session and retaining that path or to perform a local repair to keep communication link alive by self-adjusting transmission range of secondary users locally upon detection of a primary user activity. The transmission range optimization procedure is implemented in the CR engine in the SAR in a distributed manner. In every node of the secondary network, combined routing metric values are kept in a table which includes only local neighbors. The use of local data would also provide and support scalability of the SAR. It is assumed that a sufficient number of secondary users are available within the network, along with a number of primary users. Therefore, the general claim about transmission range, that is, low transmission range would not provide a proper connectivity among users to ensure communication would not be true for this case. Providing communication among secondary users in the presence of primary user communication proposes a totally different environment and trying to keep connection even with a reduced range improves the overall network performance for the secondary users when possible. On the other hand, if the transmission range is higher than the optimum value, it will ensure connectivity but will increase the probability of encountering a primary user in the transmission range, cause harmful interference to more primary users, increase collision and congestion of control packets. Therefore, although increasing the range of transmission is a possibility R_{max} value is kept as R_{opt}.

The proposed routing technique is inspired from a well known routing protocol AODV [78] adapted to CR networks [19]. In addition to the inherited characteristics of AODV protocol, each node n in the network has a neighbor node table, which is constructed using beacon messages to its neighbors once in every time quantum.

Note that, if the spectrum sensing algorithm uses beacons, there is no need to use additional beacon messages for the proposed scheme. Also if there is an ongoing communication session, overhearing nodes use the information. In the neighbor table, a distance metric is stored for every neighbor locally. Each node receiving the beacon, determines a distance metric to a neighboring node based on measuring the Received Signal Strength Indicator (RSSI), Time of Arrival (ToA), and Angle of Arrival (AoA) of the received beacon messages. Calculation of the distance metric is kept out of the scope of this article [71, 72].

6.2.2 Routing via Range Adaptivity

A typical scenario is depicted in Fig. 5.1. In the given network, node *S* sends data to node *D* and therefore needs to find path to destination *D*. The protocol starts by sending out a broadcast Route Request (RREQ) message on each available channel seeking destination *D* as it was for AODV. A RREQ also contains a metric field. Upon receiving the RREQ packet intermediate nodes create a Reverse Route that points towards the source node. If the RREQ packet is a duplicate, it is simply discarded in the original AODV protocol. If the proposed metric is used with the AODV, this approach does not work, since it does not allow selecting the path with the lowest metric value. Therefore the forwarding behavior of the intermediate nodes is modified for the SAR. In the SAR, intermediate nodes forward the initial Route Request (RREQ) packet, and establish the corresponding Reverse Route. Moreover, nodes also forward any subsequently received RREQ packets, if they have a lower routing metric value such a forwarding operation would be followed by an update in the Reverse Route accordingly. The destination node *D* keeps the spectrum opportunity (white hole) distribution and the total cost of all nodes on the path when receiving RREQ message, and assigns a frequency band to its cognitive radio transceiver with respect to these values. It then, sends back a Route Reply (RREP) to the source node, encapsulating the assigned band. Intermediate node assigns frequency band with the help of the band choices extracted from the RREP, and the spectrum opportunity information from previous RREQ. Then the node establishes path to the destination via its cognitive radio and generates new RREP message to send back to the source.

Once the path is constructed, communication session continues normally. Upon the start of the communication process, every node *n* in the active path locally broadcasts the active route information in the beacon messages to its neighbors using the neighbor table. Receiving this path information, neighboring nodes check their own neighbor table and decide which nodes in the active path are in their neighbor table. Whenever a primary node activity is sensed by the cognitive radio engine, every node detecting the primary user activity in the active path, tries to determine the distance of the primary user and according to the determined value, it adapts its transmission range that restricts the interference to the primary user below a certain interference threshold for node i, T_i (Fig. 5.3). The designed algorithm to make the decision is given in Algorithm 5. Assuming that there is a sufficient number of secondary nodes, the best transmission range that enables the retaining the active path without causing any harmful interference to primary node would be selected by checking the distance values of the neighbor table. If there is no such value that retains the active path without interfering the primary user, all nodes in the active path adapt their transmission ranges to their maximum range which is not causing any harmful interference to the primary user (Fig. 5.4). After this adaptation, nodes that detected the primary user activity in the active path, multicast received packets of the ongoing communication session to its available neighbors according to the neighbor table along with a route request message to the destination node *D*. As a consequence the new path is constructed with only local update upon the first route reply message received. The local repairment Algorithm is given in Algorithm 6. If this is not possible to establish a route, a route error message is sent to the source node which yields a re-routing from node *S* to node *D*.

6.2.3 Route Adaptation and Route Preservation (Local Repair)

The selection of links comprising a path might be optimal at the time of establishment, but this might change drastically during the lifetime of a path. Due to the classic ad hoc network problems and/or characteristics of CR technology like primary user activity it is necessary to have a maintenance operation in the routing protocol, where each node has to corroborate the area it belongs to, and update information for the mobility factor, interference and spectrum availability. Accordingly, there is need for a mechanism that continuously maintains and optimizes an established route. Therefore, route adaptation is incorporated to the SAR. The route adaptation is implemented in a distributed manner at each node locally; as a consequence, it does not incur any routing overhead.

The route adaptation mechanism simply controls the combined routing metric of every active link periodically to determine if it is over a given threshold. If that is the case, the CR node will switch to a less loaded link or perform a spectrum switching that is shared with the next hop, if such case is available and feasible. To avoid instabilities and constant switching, a hysteresis function is applied. The route adaptation mechanism should not be confused with local repair feature, which allows a route discovery mechanism to be initiated by an intermediary node in case of a link failure. Route preservation (local repair) can be done by: (a) jumping the broken node if the next-next hop in the path is reachable; (b) choosing another reachable node(s), which is far from the primary user, to be the next hop which is reachable by the previous node and the next node in the path, (c) by local range adaptivity (Algorithm 6). The SAR is able to quickly repair link breaks in active routes whenever they occur.

6.3 Simulation and Performance Analysis of SAR

Through simulations implemented in ns2 [79], the performance and functional correctness of the SAR and its relative performance compared to that of DORP [18], STOD-RP [24] and SEARCH [26] are evaluated. Unless otherwise noted, simulations are run with the following parameters. Two-ray ground propagation model is used at the radio layer. The bit rate for each channel is 2Mbps. Variable number of mobile nodes up to 100 moving in a rectangular area 1800 m x 1800 m in dimension is modeled. Each node picks a random spot in the rectangle and moves there with a speed uniformly distributed between 0 – 20 m/s. Upon reaching this point, the node picks a new destination and repeats the process. As mentioned before the primary users' activities are modeled by using the exponential ON-OFF process. The coverage range of the primary user on its operation channel is 250m. These parameters are set to the given values since they are similar to the default values used in previous study of various protocols. Thus a comparison among the protocols can be done. During the simulation the following default communication pattern is used. Each source node generates and transmits constant bit rate (CBR) traffic and each message is 1KB in length. The transmission interval for each node is set to 100ms. A Voice-over-IP (VoIP) traffic is also injected into the network to make a more realistic scenario. A total of six VoIP CR users are randomly distributed over $8 - 128$Kbit/s with random arrival rates (including packetization intervals according to the codec G.711, G.726 and G.729 recommendations). 50 experiments are performed in random multi-hop network topologies, for each different parameter settings.

The characteristics of the SAR are explored under a number of different scenarios. The robustness of the SAR is investigated for various numbers of both primary and secondary nodes, stressing the impact of combined metric and adaptive transmission range usage on the overall performance. The simulations are run for networks of sizes 10 to 100 secondary nodes and 10 to 100 primary nodes. It is shown that since the node density has a great importance on the performance of the SAR for retaining the path and for the success of the local repair, the SAR performs high throughput for dense networks. However, after a certain threshold throughput starts to decrease due to the congestion. A sharp decrease indicates the practical limit for the tradeoff between the number of primary and secondary users. Also as expected, average throughput is inversely dependent on the number of primary nodes as seen in Fig. 6.1. As noted earlier, DORP [18],a modified version of AODV, and spectrum-tree based on demand routing STOD-RP [24] and recently proposed a geographic forwarding based SpEctrum Aware Routing protocol for Cognitive ad-Hoc networks SEARCH [26] are used for comparisons. Packet delivery ratio, throughput and end-to-end delay comparisons have been evaluated between DORP, STOD-RP, SEARCH and SAR to show that the SAR can well fit the multi-flow multi-channel environment and effectively exploit the potential large communication capacity in CR Networks. In the simulations, the rate of flows is varied from 100 Kbps to 1800 Kbps along with the injected VoIP traffic. The nodes are randomly placed in the area, and 8 flows having the same traffic generation rate are initiated with VoIP traffic. Packet delivery ratio is considered firstly. Fig. 6.2 illustrates how packet delivery ratio varies with increasing flow rate. The measurements of the packet delivery ratio over all traffic flows are averaged and plotted for each protocol. Contrary to the other protocols, SAR has a smooth trend especially for lower flow rates. When flow rates increases,

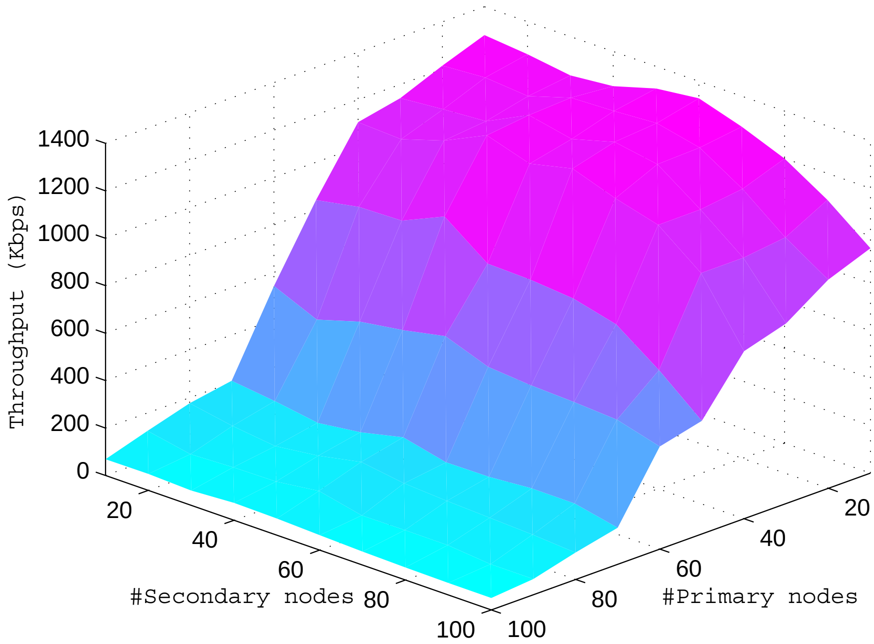


Figure 6.1: Average throughput of SAR as the number of primary and secondary nodes changes in the network.

other protocols suffer from the congestion and unable to deliver more packets. As seen clearly the proposed the SAR technique significantly improves the packet delivery ratio as the flow rate increases. The SAR has a better packet delivery ratio because of used metrics and the route preservation and adaptation scheme.

As another performance criterion, throughput analysis is conducted thoroughly (Fig. 6.3). When the traffic load is low i.e. less than 400kbps, all schemes performs with similar aggregate throughput. As the flow rate increase, the throughput of DORP increases slowly towards the limit of the established path. Also in DORP, nodes become disconnected due to primary user activity, and no packets are forwarded. STOD-RP and SEARCH perform better than DORP since STOD-RP employs a route recovery algorithm and SEACRH has a route maintenance algorithm as well as SAR. As the traffic load increase, the performance improvement of the SAR over the other schemes becomes more significant due to used routing decision metric and path retaining along with local repair using adaptive transmission range. In a dynamic environment (i.e., the network topology changes frequently), SAR adapts nodes transmission range to retain the secondary nodes communication path or performs a local repair when the distance to the destination is not reachable without harmful

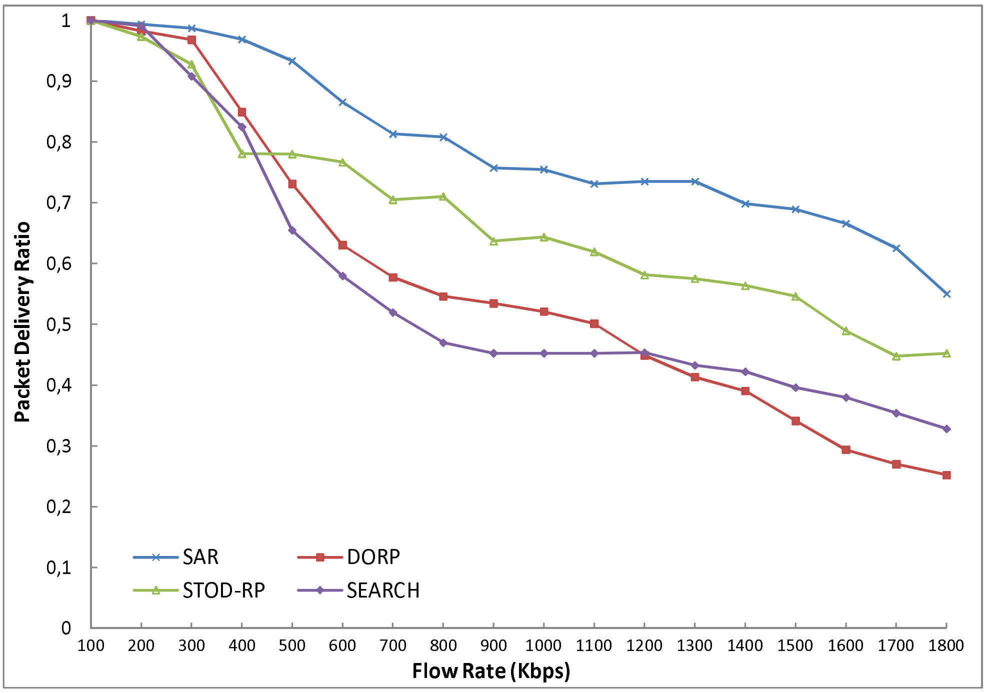


Figure 6.2: The packet delivery ratio as the flow rate increases.

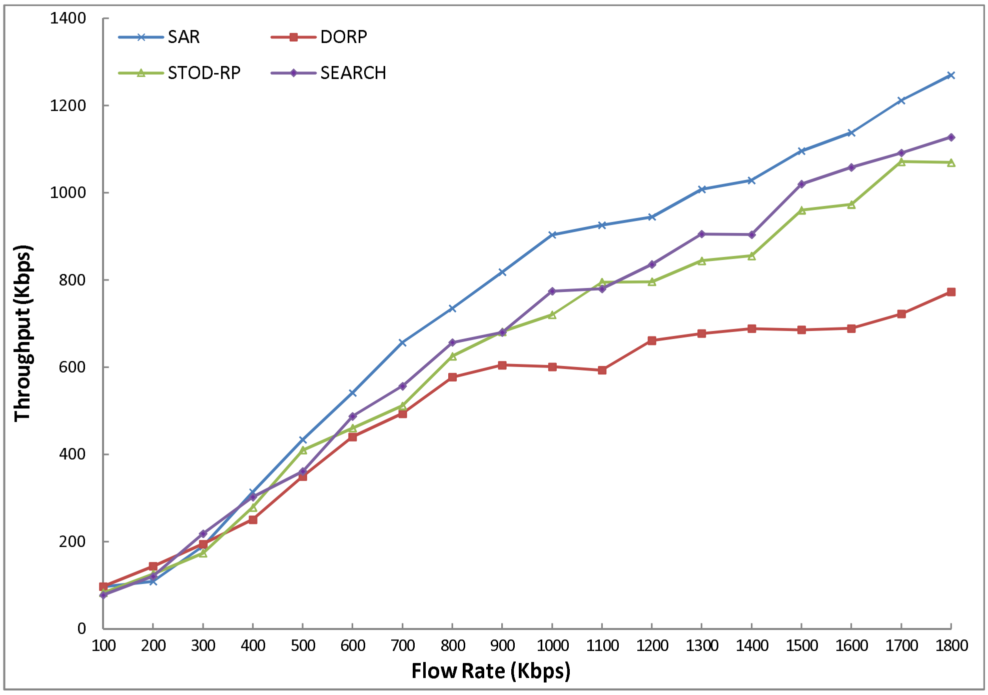


Figure 6.3: Throughput when two hosts, *S* and *D* communicate.

interference to the primary user. Also during the communication session, SAR performs route adaptation when feasible. Therefore, the established route in the SAR is better than the route built in the other schemes in a frequently varying environment. The number of available channels degraded to 16 to track the performance change of SAR. As seen in Fig. 6.4, SAR still performs good compared to the other schemes.

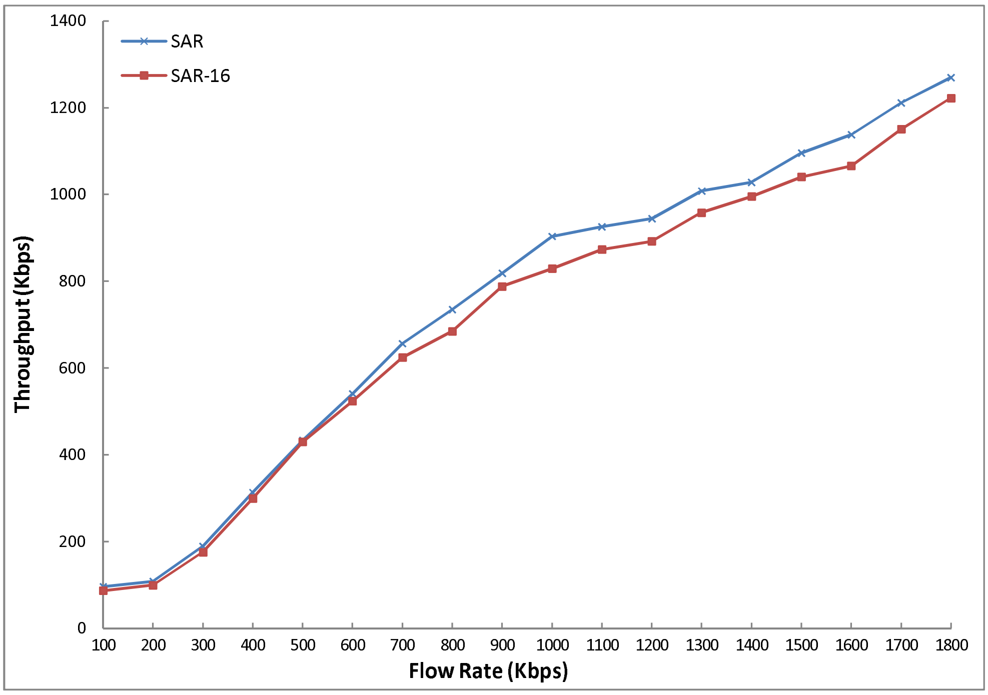


Figure 6.4: Throughput with 16 and 64 available channels.

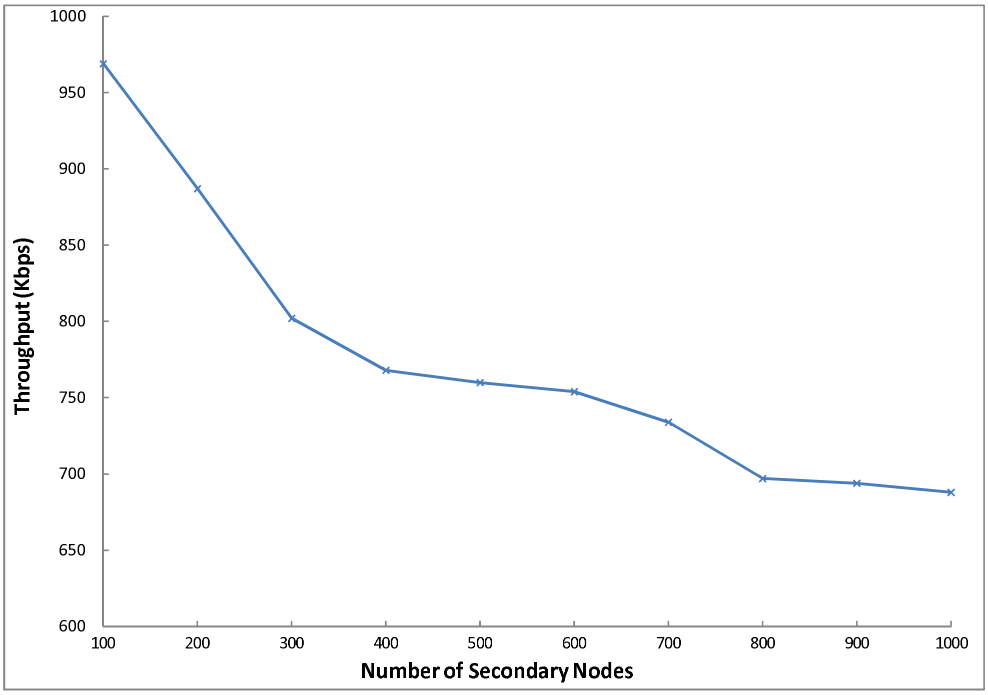


Figure 6.5: SAR's throughput with changing secondary node's density.

However, as the flow rate increases SAR has some performance degradation since there is not enough number of available channels to perform spectrum handoff.

As done for the UNITED technique, the impact of the number of secondary nodes has been researched for the given area, number of primary nodes, primary traffic and secondary traffic. The result of a number of runs of simulations is given in Fig. 6.5. As

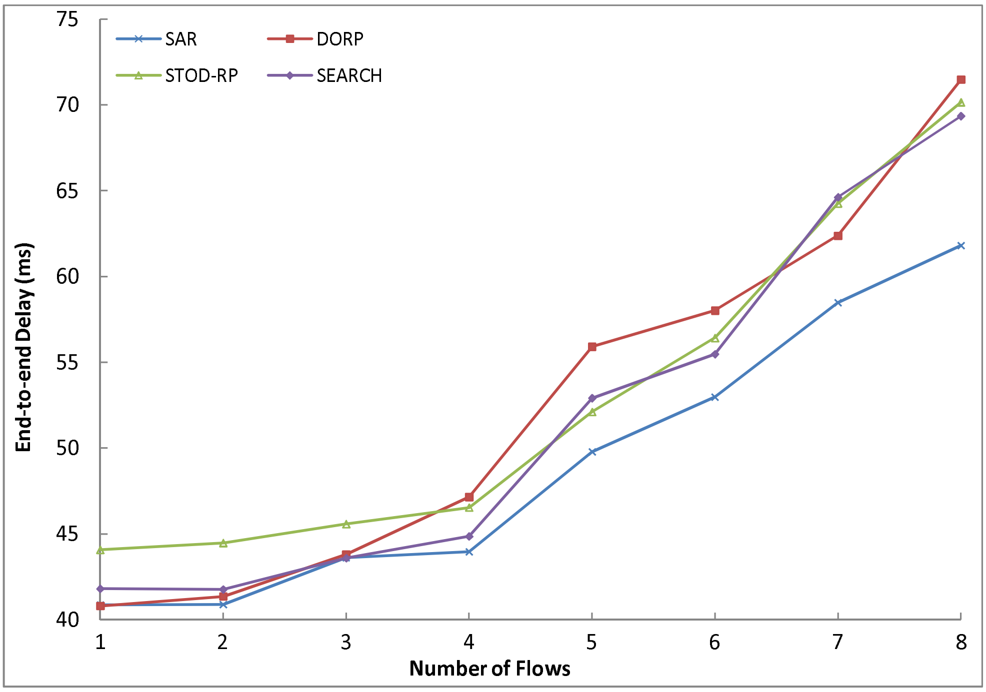


Figure 6.6: Average end-to-end delay performance vs. number of flows.

Table 6.1: Jitter Values for SAR

Number of Flows	1	2	3	4	5	6	7	8
$Jitter_{mean}$ (ms)	1.58	1.63	1.71	1.75	1.74	1.78	1.89	2.12
Maximum-Minimum (ms)	5.53	5.86	6.70	6.82	6.80	6.83	7.21	7.86

expected the overall performance decreases with the increasing numbers of secondary nodes. The performance drops between 100 and 300 secondary nodes. It is roughly over 750Kbps at 400 secondary nodes and stays at 750Kpbs level till 700 secondary nodes. After a small performance loss between 700 and 800 secondary nodes it becomes 700Kpbs level and remains the same till 1000 secondary nodes. Although a degradation exist, 30% performance loss in throughput for 900% increase in the number of secondary nodes is a promising performance.

The end-to-end delay performance of the SAR with other schemes is also compared. The number of intersecting flows is adjusted from 1 to 8 to evaluate the performances on intersecting flows. The simulation result is illustrated in Fig. 6.6. When the number of flows increases, the SAR seeks a balance between assigning new frequency bands to allow simultaneous transmission and accommodating some nodes on one band to avoid switching delay. Also the re-route establishment time is lower in range adaptivity than the others since those techniques have to reconstruct a path from source to destination upon primary user activity detection. Also, since SAR employs a route adaptation

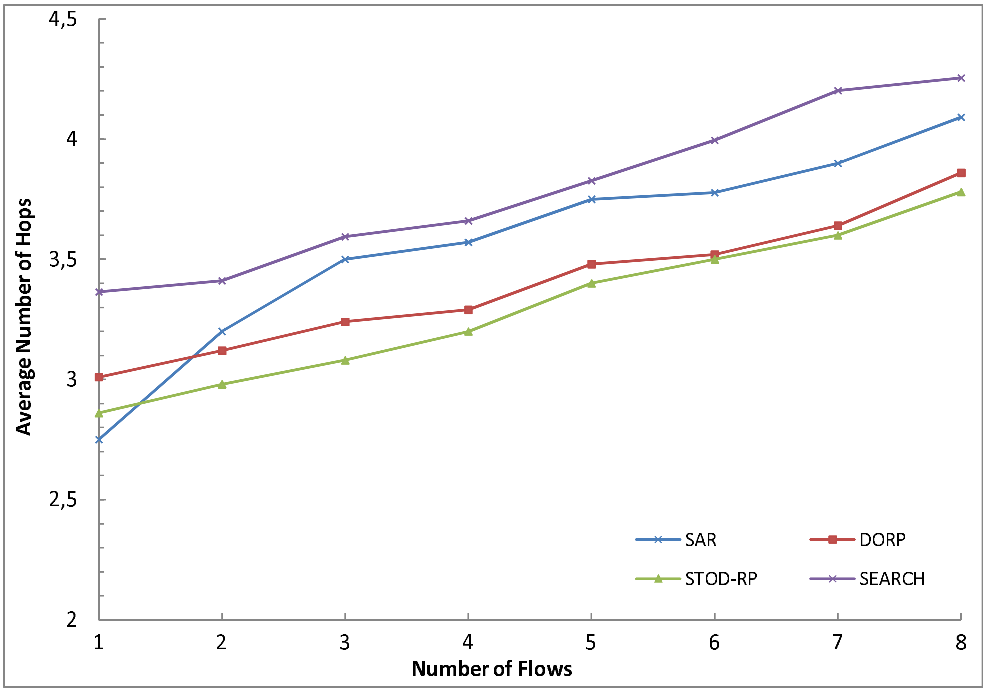


Figure 6.7: Average number of hops vs. number of flows.

mechanism to use better channels or links according to the combined metric, SAR has the advantage of routing the traffic on better and stable routes. Consequently, the SAR achieves an overall optimal delay than the other schemes as the number of intersecting flows increases as shown in Fig. 6.6. Average number of hops as the number of flows increased is provided in Fig. 6.7 to make efficient comparison of end-to-end delay performance.

Speech quality with VoIP is primarily impaired by packet loss, total end-to-end delay and the jitter. As a result, it is also important to assess the jitter on the cognitive radio network in order to determine the performance. The jitter values for SAR are measured and reported in Table 6.1. Jitter is typically less than 2ms. When the injected traffic load is high, of course there is more collision and interference, besides finding an spectrum opportunity gets difficult, which increase packet loss rate, packet delay and jitter. Measured jitter reveals the fact that using SAR technique yields better call quality than the acceptable call quality for VoIP applications.

To assess the effectiveness of the SAR, also the normalized routing overhead has been used as a performance metric. Normalized routing overhead can be defined as the total number of control ($N_{control}$) and data packets sent (N_{data}) normalized by the total number of packets successfully delivered in the CR network, also considering

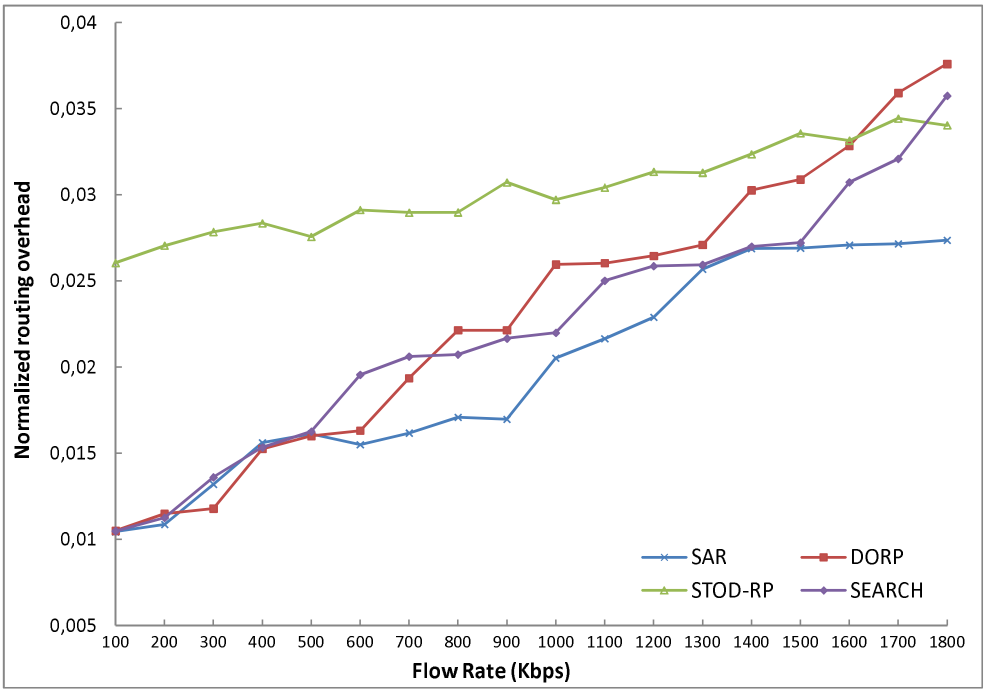


Figure 6.8: Normalized routing overhead as the flow rate increases.

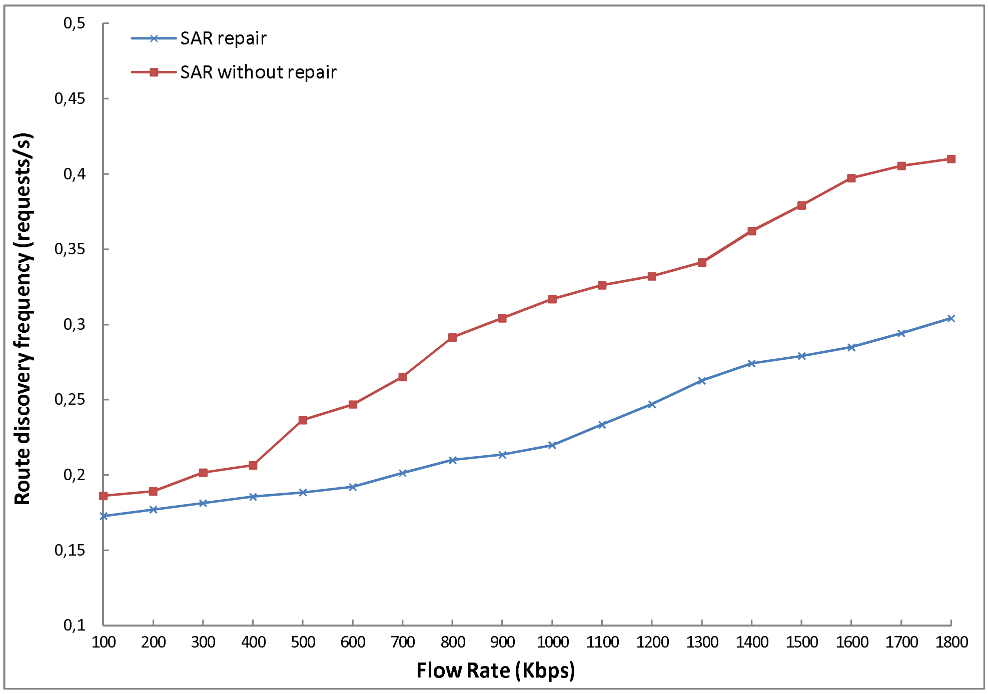


Figure 6.9: The route discovery frequency for SAR technique.

the number of flows. The normalized routing overhead of the SAR is illustrated in Fig. 6.8. The overhead remain fair when the flow rate increases and tend to remain steady. The performance of the recovery adaptation is also evaluated for SAR and plotted in Fig. 6.9. The number of generated RREQ messages signaling the need for a fresh route formation is plotted against increasing flow rate. When the route

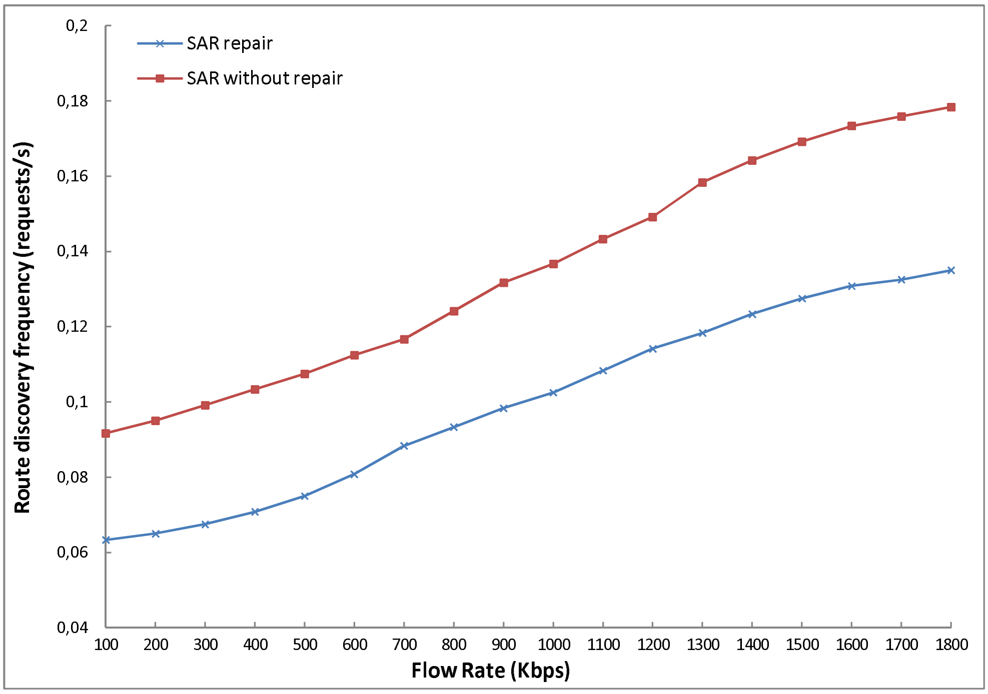


Figure 6.10: Mobility induced fresh routing requests.

adaptation mechanism is turned off, the resulting link failure results in the need of a fresh route formation from the source. These failures consists of both mobility and lack of spectrum availability. When route adaptation mechanism is employed, SAR tries to fix link breakages by local repair and tries to adapt the link changes relying on the cost metric by route adaptation. It is observed that this adaptation keeps the route connected through the relatively primary user free regions, leading to much fewer route outages. Fig. 6.10 illustrates the mobility induced fresh routing requests. As can be seen, when recovery adaptation is employed, SAR also manages to adapt itself to the mobility induced route breakages.

6.4 Concluding Remarks

In order to meet the requirements of self adaptivity, Self Adaptive Routing (SAR) is proposed as an efficient and easy to implement routing protocol for dynamic spectrum access in CR ad hoc networks. SAR uses the autonomous distributed adaptive transmission range control scheme for cognitive radio networks and utilizes proposed novel combined metric for routing. Accordingly, SAR is the first routing technique that incorporates link modeling, interference avoiding and adaptive transmission range into a single routing framework. Route adaptation and route preservation methods are also implemented to continuously maintain and optimize an established route and to repair the route when it is defective. SAR is reflexive to the primary activity and tries to minimize the effect over the cognitive radio ad hoc network as well as no or minimum interference is caused to the primaries during their activity.

7. CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

In this thesis, routing techniques for dynamic spectrum access in cognitive radio ad hoc networks is explored. First of all, existing routing algorithms are deeply investigated and classified according to their spectrum access methodologies and shortcomings of these algorithms are pointed out. Novel routing metrics specific to cognitive radio networks are introduced. The spectrum usage characteristics, and the interference created by existing flows in the network both from the primary and secondary users are taken into account to define introduced novel routing metrics.

In Chapter 4, a novel algorithm, United Nodes (UNITED), is proposed for maximizing the network throughput and minimizing the end-to-end delay. The UNITED operates autonomously in a distributed manner at every node. Initially, nodes organize themselves into several clusters by the clustering algorithm that is based on location, communication efficiency, network connectivity and spectrum availability. Following completion of cluster formation, routing is done according to the introduced spectrum usage and interference metrics. Clusters adapt themselves dynamically with respect to spectrum availability, and the high mobility of the nodes. Next, RAC: Range Adaptive Cognitive Radio Networks is proposed to enhance throughput of these networks. The RAC is an autonomous distributed adaptive transmission range control scheme for cognitive radio networks that simultaneously considers the QoS requirements of primary and secondary users. It is a simple yet an efficient approach to utilize throughput by dynamically changing transmission range when needed. The key feature of the proposed strategy is that, a cognitive user can maximize its achievable throughput and minimize end-to-end delay without interfering any primary user by dynamically changing its transmission range.

In Chapter 6, a novel self adaptive routing algorithm, SAR, which is designed for range adaptive cognitive radio networks for efficient data transportation in cognitive radio networks by making use of transmission range adaptivity dynamically, link modeling and interference avoiding, is proposed. Considering previously proposed algorithms, only a few of them have an adaptive re-routing mechanism. However, detailed experiments indicate that their performances are poor and they suffer from high computational complexities. In order to meet the requirements of self adaptivity, Self Adaptive Routing (SAR) is proposed as an efficient and easy to implement routing technique for dynamic spectrum access in CR networks. SAR uses an autonomous distributed adaptive transmission range control scheme for cognitive radio networks and utilizes a novel combined metric for routing. To the best of my knowledge, the proposed metric is the only one that incorporates in spectrum usage and interference characteristics to simultaneously consider the QoS requirements of both primary and secondary users. As a consequence, the proposed technique routes the traffic across paths with better spectrum availability and reduced interference via the novel routing metric.

Through a set of extensive experiments using ns2, it has been shown that proposed techniques achieves significant improvement on the throughput and end-to-end delay compared to existing protocols. It has been proven empirically that proposed outperforms other routing algorithms in terms of adaptability and efficiency.

7.2 Future Work

As a research direction, I pursue my research on estimation of spectrum usage in multiple dimensions such as time, frequency and space, identifying opportunities in these dimensions and developing algorithms for statistical prediction, analyzing the impact of the ratio of spectrum availability and cooperation with primary network. Proposed techniques can be further enhanced by incorporating a learning based approach that identifies the type of the primary user, its duty cycle, times of operation, and traffic generation characteristics.

Another aspect of future work may consists of using different traffic models and extending proposed techniques to the transport layer.

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