[UCI]I804:24011-200000266262

August 2017

Master's Degree Thesis

Energy-Efficient Multipath Routing in Cognitive Radio Ad hoc Networks

Graduate School of Chosun University

Department of Computer Engineering

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인지 무선 애드혹 네트워크에서의 에너지 효율적인 다중 경로 라우팅

August 25, 2017

Graduate School of Chosun University

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Advisor: Prof. Sangman Moh, Ph.D.

A thesis submitted in partial fulfillment of the requirements for a Master's degree

April 2017

Graduate School of Chosun University

Department of Computer Engineering

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싱그 키쇼르의 석사학위논문을 인준함

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2017년 5월

조선대학교 대학원

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ABSTRACT

Energy-Efficient Multipath Routing in Cognitive Radio Ad hoc Networks

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Cognitive radio technology has emerged as a promising solution to the inefficient spectrum utilization issue that has had troubled the academia, industry, research and regulatory bodies for a long period of time. Routing in cognitive radio ad hoc networks (CRAHNs) is a challenging research topic primarily because of dynamic topology, intermittent connectivity, spectrum heterogeneity, and energy constraints. As a result, factors such as link stability, path lifetime, energy consumption, and adaptability to dynamic network scenarios are always questionable. More importantly, the implementation of an integrated approach to select the best route and the channel for the entire process is the crux of the whole routing process. Several routing protocols have been proposed so far in an attempt to best fit the requirements of cognitive environment. Nevertheless, they fail to cover up indispensable domains of these networks and, eventually, end up stressing on one of the aspects more than any other leading to some serious setbacks in the protocols themselves. In this thesis, an energy-efficient and robust multipath routing (ERMR) protocol is proposed by taking into account prominent design aspects of CRAHNs. The proposed ERMR uses the energy-efficient path to perform data transmission through the

most stable channel evaluated in terms of the access duration which compliments to improving the longevity of the routing path. The residual energy of the node acts as selection criteria for the next hope node whereas the stability of the channel is taken into account for determining the complete link. The protocol is expected to prolong the lifetime of the network by preventing improvident energy consumption resulting mainly from route breakages, frequent route discoveries, subsequent route set up the process and the channel switching process. The simulation results prove that the proposed ERMR outperforms the conventional in terms of average network throughput, packet delivery ratio, average energy consumption per bit, and average end-to-end delay in both scenarios of varying traffic and node density.

한 글 요 약

인지 무선 애드혹 네트워크에서의 에너지 효율적인 다중 경로 라우팅

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인지 무선 기술은 낮은 스펙트럼 이용률 문제에 대한 새로운 해결책으로 부상하고 있다. 인지 무선 애드혹 네트워크(CRAHN)에서의 라우팅은 동적 토폴로지, 간헐적 연결성, 스펙트럼 이질성, 에너지 제약 등으로 인해 도전적인 연구 주제이다. 따라서 링크 안정성, 경로 수명, 에너지 소모, 동적 네트워크 상황에 대한 적응성 등과 같은 요소가 매우 중요하며, 최적의 경로와 채널을 선택하는 통합적 접근과 구현이 적극 고려되어야 한다. 그 동안 여러 라우팅 프로토콜들이 인지 무선 환경에 맞도록 제안되었지만, 상기의 다양한 요소들을 체계적으로 고려하지 못하는 문제를 안고 있다. 본 연구에서는 CRAHN 의 중요한 설계 요소들을 고려함으로써 에너지 효율성이 높고 동적 환경에 견고한 라우팅 프로토콜(ERMR)을 설계한다. 가장 안정성이 우수한 채널을 사용하고 잔여 에너지가 많은 노드를 통해 경로를 설정함으로써 에너지 효율성이 개선되고 경로의 수명 또한

길어진다. 경로 단절, 경로 발견, 채널 스위칭의 빈도가 대폭 감소하여 에너지 소모가 줄고 결과적으로 네트워크 수명이 연장되는 효과가 있다. 시뮬레이션 결과에 의하면, 제안한 ERMR 프로토콜은 네트워크 전송률, 패킷 전달률, 비트당 에너지 소모량, 종단간 지연시간 측면에서 기존의 프로토콜보다 우수한 성능을 갖는다.

I. INTRODUCTION

The unprecedented growth and development in the sphere of wireless communication and relevant applications has not only made spectrum a precious resource but also has flopped the concept of fixed spectrum assignment severely. The unlicensed bands, on one hand, are unexpectedly congested whereas a large portion of the licensed bands are severely underutilized. The licensed spectrum like UHF/VHF TV frequency bands are not used to their fullest but, on the contrary, the unlicensed bands mainly the industry, scientific and medical (ISM) is massively populated because of the free access[1]. This scary situation has led to the birth of Dynamic Spectrum Access (DSA) [2] which aims at making the best opportunistic use of unused spectrum called spectrum holes or spectrum opportunities and thus ensures that both licensed and unlicensed bands are evenly utilized. Cognitive Radio Networks, in this regard, have emerged as a promising and reliable remedy for improving spectrum utilization and resolving the spectrum issues which otherwise is prone to biased consumption. It, however, has opened up plethora of new issues at physical, medium access control and routing layers.

Cognitive radio technology has been exceedingly successful in realizing this urgency of wirelessly communicating world and leveraging the features of Cognitive capability and Reconfigurability [3] to meet their purpose. The former allows the cognitive radio to sense the surrounding radio environment and fetch the information like frequency, bandwidth, power, modulation technique, and communication technology while the later enables it to redefine its internal state and parameters based on the interactions with outside world and thus adapt to the observed environment. As a unit, the technology allows the devices to achieve opportunistic access to the portion of unused spectrum bands and adapt accordingly to ensure communication flow. Cognitive radio network basically is constituted by two types of users: Primary User (PU) and Secondary User (SU).

The primary users have prioritized possession over the licensed bands whereas the secondary users can use only the vacant channels, unused by primary users, and, more importantly, without interfering the ongoing communication of primary users [4]. Cognitive radio networks, in general, abide by a cognitive cycle consisting of: spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing as shown in Figure 1. During the spectrum sensing process, secondary users sense the radio environment observing each spectrum band to detect spectrum holes. The information thus obtained is circulated to other spectrum management functions as well as other protocol layers to make availability of information more easy. Once the set of channel free of primary users is detected, the spectrum decision module selects the best channel as per the channel selection policy. The decision algorithm requires the information about the behavior of the primary users to combat spectrum heterogeneity. In cases, when there is an arrival of primary user back into the channel, the secondary users utilizing the corresponding channel must vacate the channel immediately and should either hold on their ongoing communication until the departure of the primary user or switch to another vacant channel to continue their data communication. And, there may be occasions when more than one secondary users may contend for the same spectrum, in such scenarios there must be a provision of spectrum sharing mechanism that promises prevention of transmission collisions and efficient use of the medium usually in the form of medium acces control protocol. To sum up, the most attention seeking issue in cognitive networks is the uncertainty of spectrum availability resulting from the primary user activity and the challenge of accomplishing SU-SU communication without impeding PU transmission. And to achieve this, it demands flawless implementation of spectrum sensing, spectrum decision, spectrum mobility, and spectrum sharing mechanisms with realistic cognitive radio environment.

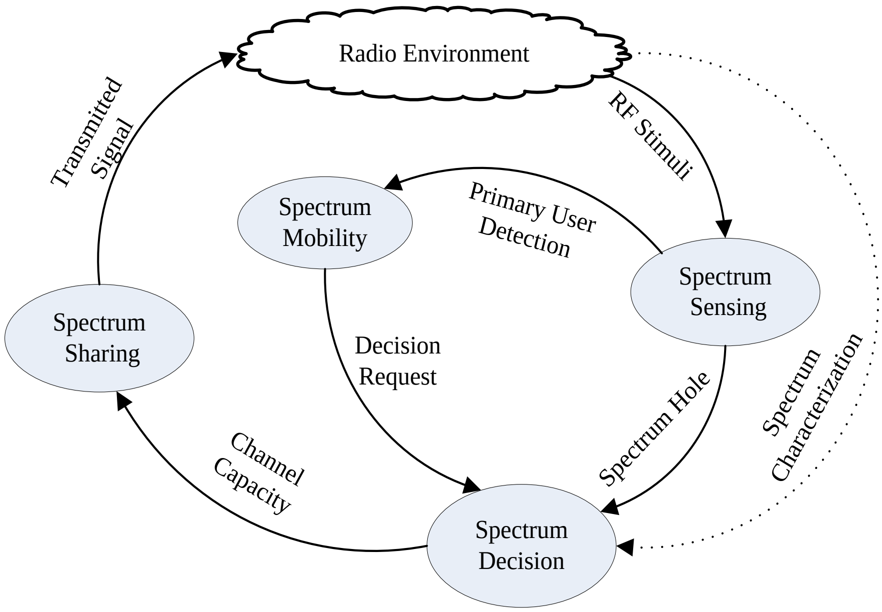

Figure 1. Basic cognitive cycle.

A. Cognitive Radio Ad hoc Network

Cognitive Radio Ad hoc Networks (CRAHNs) are infrastructure less form of cognitive networks. They are in fact the enhanced form of the conventional ad hoc networks, which are embedded with cognitive radio technology to ensure efficient and innocuous spectrum utilization [5]. The absence of a centralized network entity poses them number of challenges compared to their infrastructured counterparts. Without the network infrastructure, SUs need to cooperate and communicate among themselves in an ad hoc fashion to exchange network related information like network topology, spectrum opportunities, and the presence of PUs [6]. Figure 2 depicts a schematic of basic CRAHN system wherin the secondary users communicate with each other through vacant channels in in ad hoc fashion. Each secondary user is blessed with cognitive radio capabilities enabling them with decision making and action taking. And to be aware of the dynamics of the entire network resulting either due to their own actions or from the primary users, cooperation schemes turn out to be significant to exchange observed information. Along with this, distinguishing features like heterogeneity, dynamicity, self-configurability, scalability, limited energy, multi-hop architecture and others stand up as inevitable hurdles in realizing these networks. It really needs a great deal of research and relentless efforts to cope with such challenging environment.

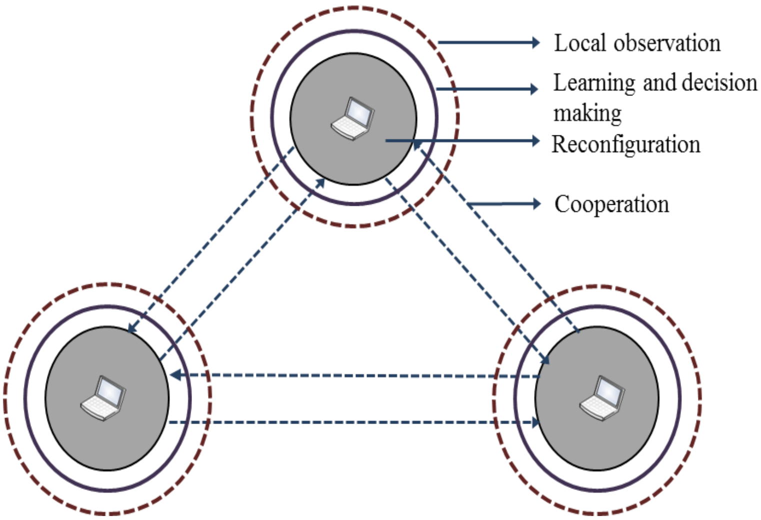

Figure 2. Cognitive radio ad hoc network.

Routing in CRAHNs remains as one of the most sought after topic for researchers worldwide. As mentioned above, working with CRAHN is not easy and things get even aggravated when it comes to routing. Since, CRAHNs have borrowed the attributes from both cognitive radio networks and ad hoc networks combined; the routing protocol, henceforth, designed must satisfy the requirements of both these networks [7]. Unpredictable mobility of nodes, variation of spectrum in time and space domains, energy constraints and PU activities simply add to the routing woes. A routing process in cognitive radio ad hoc networks, therefore, mush necessarily involve spectrum awareness, quality route set up and route maintenance procedure [8]. Often times, the sudden appearance of PU enforce the secondary user to vacate the current channel in use and at the same node mobility may lead to frequent route failures. Joint route and spectrum diversity is apparently the most dependable and effective approach to counteract these issues and provides efficient routing solutions for cognitive radio networks irrespective of their nature. It allows the SU to switch dynamically among multiple paths and/or multi-channel whenever the normal course of data routing is obstructed. The design of a routing protocol as such includes: selection of the optimal path with healthy relay nodes accompanied by selection of the most appropriate channel from the set of available channels for each link. It has to depend on the nature of routing protocol being designed to determine how these selections need to be made.

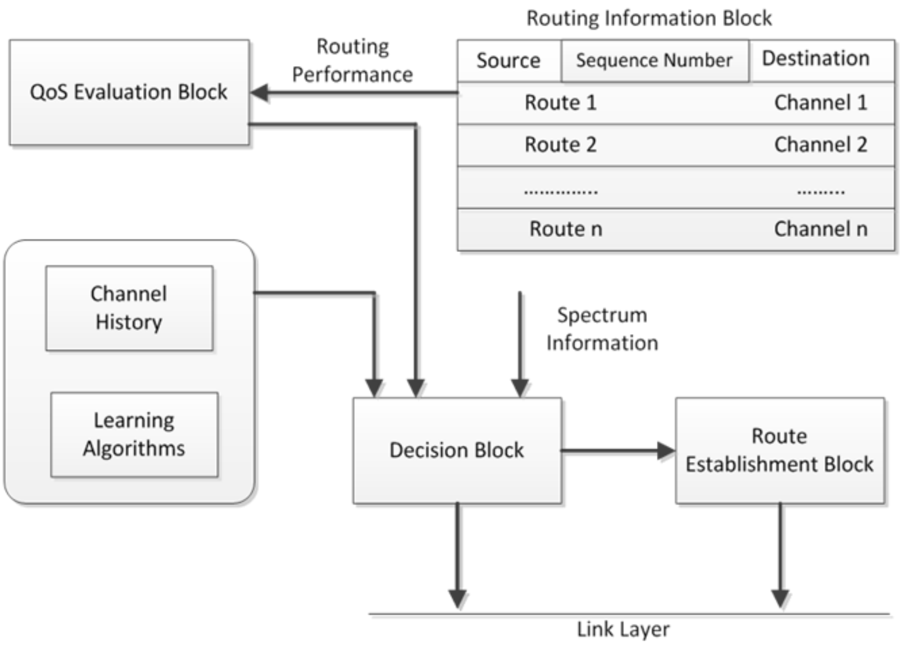

Figure 3. Routing framework in CRAHN.

A general routing framework in CRAHN is shown in Figure 3. Quite unlike the conventional ad hoc routing , routing tables here are extended to include channel information and other parameters if needed. The framework consists of a decision block that analyzes spectrum sensing inputs, channel information, and QoS aspects of routing path to make a final choice. The decision of shifting to an alternate path or switching to next vacant channel cannot be done in isolation, hence, the decision block must work in coordination with all other functional units. The QoS evaluation block evaluates the performance of current routing path and tries to match it to the requirements specified by the application layer. On the other hand, the major function of route establishment block is to specify whether the current route is good enough or there is a need for a new route. And finally, the learning block tends to keep the network aware of its environment to enable self learning and decision making.

An energy efficient routing scheme where data transmission is accomplished with minimum channel switching and rerouting and possibly before the appearance of PU is much needed for energy-constraint cognitive radio networks. In order to meet all these objectives, a lot of factors including the residual energy of each participating node, energy consumption along the path, stability of the channel selected, and back up path to counteract the sudden appearance of PU need to be considered. Single path routing do contribute to routing with energy efficient paths, but are non-responsive to route failure that are so frequent in dynamic networks of CRAHN type. Multipath routing, in this regard, provides a set of alternate paths to cope with mobility induced route failures. The dynamic switching of routing path can significantly reduce the frequency of route discovery process and contribute to saving of network resource that could have been wasted in setting up new routes. We, hereby, purpose an energy efficient multipath routing scheme that promises not only to conserve valuable energy with balanced energy consumption throughout the network but also ensures robustness of the path. We adopt the joint route and spectrum allocation approach to make sure that the heterogeneity does not degrade the performance of the CRAHN system.

B. Research Objective

Cognitive radio ad hoc networks have emerged to be promising technology in making the best use of the licensed spectrum in times when spectrum has been a valuable resource. It has, therefore, grabbing immense attention among the researches in both academia and industry. Routing procedure which forms a prominent aspect of such dynamic and energy constrained networks needs special attention. Most of the existing routing protocols are based on single routing metrics and somehow lag behind in addressing the nature of cognitive radio networks more precisely. At the same time, it is most important that the primary users activities are closely observed and subsequent decisions are made to avoid any kind of intervention to primary user communication. The protection of the primary user activites and the efficient use of the spectrum must be the first and foremost objective in any protocol designed for the cognitive radio ad hoc networks. We, therefore, aim at proposing a routing protocol with not only a focus on preserving energy for prolonged network life but also taking into consideration the concept of back up paths to combat mobility induced path failures and a channel selection policy to ensure that most stable channel is used. Thus, the protocol designed aims at prolonging the network lifetime of the cognitive networks ensuring efficient consumption of much needed energy, providing better adaptation, through multiple routing paths, to the changing network scenarios due to node mobility, and enhancing the longevity and existence of the route links by selecting the channel with highest availibiilty.

All in all, this thesis is an attempt to uncover the challenges underlying cognitive radio ad hoc networks, analyze them and , finally, design a routing protocol that possibly best fits the CRAHN environment. In this regard, the multi-hop multi-channel cognitive radio ad hoc network is exploited to come up with an on-demand routing protocol that is multi-metric, posseses dedicated common control channel, and joint node and spectrum selection algorithm.

C. Thesis Layout

The rest of the thesis is organized as follows: In the following chapter, several existing Routing protocols developed for CRAHNs are briefly reviewed while highlighting their stand outs. A qualitative comparison has been made in the same chapter to make the proposition more vivid. The proposed routing protocol is presented in chapter III where a detailed description to the routing procedure, including route discovery, route maintenance and primary user acitivity is done. In chapter IV, the performance of the proposed routing protocol is evaluated via computer simulation and compared with state-of-art routing protocol. Finally, it is concluded with possible future works in chapter V.

II. RELATED WORKS

A plethora of routing protocols have been poroposed and successfully developed to fit cognitive radio ad hoc networks. Different routing protocols have stressed on different factors with different networks models and aslo to fit different application. Some of the most relevant works in the field, with energy efficient routing mechanisms and multiple routes, are included herewith.

Ad hoc On-Demand Multipath Distance Vector (AOMDV) [9] is the fundamental of all multipath routing protocols in mobile ad hoc networks. This on-demand multipath routing protocol is an extension of AODV [10] routing protocol and succeeds in providing loop free and disjoint set of paths. The paths can be node disjoint or link disjoint as required and are selected based on the minimu hop count routing metric. It primarily modifies the exixting route request, route reply, and routing table in AODV routing protocol to suit multi-path purpose. The routes are sorted in order of their creation and are used alternatively, one route at a time, the next route stored in the routing table is used only when the preceeding route fails.

Low-Latency and Energy-Based Routing Protocol for Cognitive Radio Ad Hoc Networks (L2ER) is proposed in [11], which cumulatively considers energy and delay to select the optimal path for data transmission. This on-demand single path routing, extension of AODV routing protocol, uses joint route and spectrum selection to combat heterogeneity but fails to take into account channel availability probability and stability of the link. It , nevertheless, takes into account the residual energy of the node to select the next hop node and interference meausure to allocate spectrum.

Joint Path and Spectrum Diversity Based Routing Protocol (E-D2CARP) [12] exploits multi-path and multi-channel environment to circumvent PU affected regions and alleviate PU occupancy problem. Nevertheless, it does not guarantee energy efficient path as no energy metric is involved in route selection. The main objective here is to combat the PU occupancy. It uses "Expected Path Delay (EPD)" metric to make path selection which stresses on the path with minimum packet loss and lowest end-to end delay.

In [13], Beltagy et al. has proposed a multipath routing protocol with an objective of improving the reliability of transmission paths in cognitive radio networks. The "Route Closeness" metric has been introduced to select the paths that are not close to each other. The main goal of this routing design is to ensure that a PU could not interrupt all the selected non-close paths at the same time. However, the protocol fails to address the issue of spectrum diversity is not considered, which in itself is a distinguishing characteristic of CRAHNs. The protocol, thus, is not appropriate enough to be applied in highly dynamic CRAHNs.

In [14], a multipath routing protocol for cognitive radio ad hoc networks is proposed which aims at discovering resilient multiple paths in a single route discovery phase to enhance bandwidth utilization. The protocol stresses only on the robustness of the path, hence, selects the most stable path from source to destination. There is no consideration to the energy aspect of cognitive routing which is so crucial. It exploits the features of Multipath AODV (MAODV) route discovery mechanisms with necessary modifications to fit into cognitive radio environment.

In [15], energy efficient QoS (Quality of Service) routing protocol has been proposed based on the inherent features of dynamic source routing (DSR) [16]. The routing path is chosen on the basis of the residual energy, only the nodes with energy greater than the threshold value are considered appropriate for the process, and the channels are assigned on time division basis. The major problem with this approach is its failure even in medium and large networks because of source routing in DSR, thus, confined to small networks.

A minimum channel switch routing protocol is designed in [17], the main objective of which is to discover a routing path that guarantees minimum channel switching and prevent the energy loss coming out of undesired channel switching. It is developed on the basic principles of AODV routing and succeeds in minimizing interference issues. It, however, fails to take into account the nodal energy and dynamic nature of cognitive radio ad hoc networks.

Cognitive Ad-hoc On-demand Distance Vector (CAODV) routing [18] is one of the pioneer works in cognitive radio networks. It is a modification of the existing AODV protocol such that it applies joint path and channel selection with primary user activity avoidance. It is simply based on shortest path selection approach without giving a due to channel selection criteria and energy efficiency. Moreover, it has high tendency to routing overhead as the routing packets are broadcasted through all free channels.

Energy efficiency and spectrum stability are inevitable factors to be considered in the selection of routing path in CRAHN which are limited battery powered and extremely dynamic. A single routing metric usually lags behind in covering all the design aspects of routing in such complex networks and may fail to contribute to improved network performance. Simple inclusion of an energy routing metric does help in prolonging network life but cannot assure the reliability of selected path whereas introduction of multiple paths in the form of back up paths does help to mobility induced route failures but end up with improvident energy consumption. On the other hand, random selection of the channels simply adds to the despairs of both spatial and temporal spectrum heterogeneity. Most of the routing protocols fail to combine the metric based selection of channel with the route selection. The selection of channels on the basis of their characteristics not only contributes to improving the performance of the entire system but also leverages the multi-channel environment. A good routing protocol is, therefore, so much dependent upon good channel selection scheme [19]. A number of channel schemes like lowest interference impact on adjacent channels [20], channel availability probability [21], and contention-aware [22] among the secondary users have been thoroughly applied. In this regard, using the availability time of the channel as a selection criterion can help in enhancing the stability of the link and the path as a whole. The allocation of the channel with highest availability duration not only ensure route stability but at the same time lowers the frequency of channel switching which are much needed in multi-hop multi-channel networks. Furthermore, because CRAHNs are battery-powered and highly dynamic, energy efficiency and stability are the main factors to be considered in the selection of routing path in CRAHNs.

A. Design Issues of Routing in CRAHNs

Literally, routing refers to the process of finding the best path for successful delivery of data from source to destination. Unlike in fixed networks, routing in dynamic and heterogeneous networks is complicated in nature. It gets further complicated when the networks are multi-hop and multi-channel, which is the case in cognitive radio ad hoc networks. In CRAHNs, there are many inherent design issues of routing, which are summarized issue by issue as follows.

1. Dynamic Topology

Both SUs and PUs in CRAHNs are usually mobile. The unprecedented mobility accounts for the dynamic behavior of network topology. Whenever the participating nodes move out of the transmission ranges of each other, the route fails and communication cannot continue. Consequently, there is no guaranteed stability of any link or route between nodes and the probability of route breakage is comparatively high compared to infrastructure networks.

2. Spectrum Heterogeneity

The channels available to a node vary not only from time to time but also from node to node. Such spectrum heterogeneity usually results from PU activity and node mobility. Moreover, the information about the spectrum availability and occupancy need to be regularly updated and disseminated among all SUs. Consequently, routing is supposed to suffer frequent link failures and increased channel switching. Joint on-demand routing and spectrum assignment is the approach often used to combat spectrum heterogeneity issues and proves its worth remarkably.

3. Primary User Activity

Primary user are the major constituents of cognitive radio networks and , in fact, it is the primary user activity that make cognitive radio networks what it is. In any routing protocol design, it is important that the protection of primary user activy is guaranteed and also that the communication among them is not intervened in all conditions. Additionally, the accurate modeling of the primary users behavior plays a crucial role in making cognitive radio networks more realistic and precise. The arrival and departure procedure of primary users must be perfectly sensed and the resulting channels need to be opportunistically used without hamper the regular primary user communication.

4. Cross Layer Interaction

Even though routing is a network layer operation, it is incomplete without cooperative efforts from other communication layers. Spectrum sensing is primarily a PHY layer function while spectrum sharing is more of a link layer function. Likewise, the spectrum handoff process should collaborate with other communication protocols for information about channel parameters like interference level, path loss, channel error rate, link layer delay and holding time.

5. Common Control Channel

In absence of central network entity, SUs need a mechanism for exchanging network information about the neighboring nodes, PU activity and available channels. Due to spectrum heterogeneity, the concept of dedicated control channel can lead to resource overhead whereas broadcasting the same control message on all the available channels increases delay, energy wastage and network congestion. Thus, there is a lot of tradeoff in the implementation of common control channel.

B. Attributes of Efficient Routing Protocols for CRAHNs

Designing a routing protocol for CRAHNs is challenging. A large number of aspects need to be considered, but is not always possible to include all of them into a single place. Followed are the major attributes that an efficient routing protocol must hold to prove it vitality.

1. PU Awareness

The information about the location and the channel occupied by PU is of great help to SUs for making routing decisions. Such information is usually obtained by local observation and spectrum sensing, and helps SU to select the route with minimal interference of PU activity. The knowledge about primary users activites can be local or global kind in terms of their accessibility. Each secondary user must be aware of every primary user activity in its vicinity and it depends on the nature of system model how they obtain the information.

2. On-Demand Routing

In on-demand routing, the attempt to route discovery is initiated only when there is a data packet to be transmitted. Besides, this process does not need information of the entire network to be piggybacked in the control packets unike the source routing protocols. So it not only alleviates routing overhead but also minimizes energy consumption. Ad hoc on-demand distance vector (AODV) routing has been the most preferred scheme for routing in ad hoc networks in terms of energy consumption, loop-free operation and node participation.

3. Cooperative Scheme

In absence of central network entity, SUs have to cooperate between themselves in an ad hoc manner to exchange network information such as PUs' presence, neighboring nodes, and list of available channels. The information obtained through local observation and spectrum sensing helps in making routing decisions and reconfiguration.

4. Mutliple Metric Routing

Using multiple routing metrics (e.g., energy, hop count, and delay) and considering the spectral information in routing decision can make a routing path more efficient in terms of energy, stability, and network performances. The use of multiple metrics in selecting the routing path is always an added advantage and provides more robust, energy efficient route and more adaptable route.

5. Joint Path and Spectrum Diverstiy

The uncertain activities of primary users in both space and time domain are one of the reasons of performance degradation in CRAHNs. Thus, diversity techniques can help improving the performance and addressing the issue. In joint path and spectrum diversity approaches, multiple paths as well as multi-channel routes can be formed. As a consequence, an SU can dynamically switch among different paths and different channels for communication even under the influence of PU activity. Also, a fast and reliable route recovery mechanism can be provided against the route failure due to PU activity or node mobility.

6. Energy Harvesting

CRAHNs are energy constrained as they are operated by power limited batteries. But, with the increasing significance of such networks to to ensure balacnce spectrum usage, remedies to energy scarcity has to be addressed as well. One of the best solutions to this inevitable problem is designing the routing protocols that are appropriate for energy harvested networks. This helps to forget the issues of confined lifetime, upgrading the system performance.

C. Routing Metrics in CRAHNs

Routing metrics are the measures used by routing protocol to make routing decisions. Each routing protocol uses one or more routing metrics to determine the best path from source to destination. The routing metrics provide a basis for selection or rejection of a routing path [23]. Following are some of the state-of-art routing metrics for cognitive radio networks.

1. Hop Count

Hop count is numerically equal to the number of nodes a data packet has to pass through before reaching the destination. It is the simplest of routing metrics with no consideration to the channel quality. In principal, lower the number of hop count is, better the path is as it takes less time to reach the destination.

2. End-to-End Delay

End-to-end delay is basically the time a packet of data takes to reach the destination from the source. In CRAHNs, it depends on propagation delay, switching delay, backoff delay and queuing delay. Lower the overall delay is, better the considered route is.

3. Energy

In CRAHNs, there are two distinct measures for energy evaluation. Path energy refers to the total energy consumed in transmitting a packet of data from source to destination, including the energy incurred in transmission, reception and switching. However, a path cannot be considered efficient just because of minimal path energy because the residual energy of intermediate nodes needs to be considered.

4. Bandwidth

Bandwidth is the average rate of data transfer through the communication path, and the actual bandwidth is often termed as throughput. The routing path with higher bandwidth is preferred. Because, bandwidth is usually associated with channels allocated, it is more of channel selection alogorithms integrated with routing procedure.

5. Route Stability

The Route stability is generally defined in terms of the time duration that a route is completely available to an SU. Thus, the stability of a route is a function of the channel availability. In CRAHNs, however, it is highly unpredictable owing to node mobility and PU activity. Therefore, an effort to predict the primary user activities and/or evaluation of route availability is commendable.

6. Cumulative Metric

The combination of two or more routing metrics can also be used in making the routing decisions. The joint metric of end-to-end delay, hop count and transmit power is found in the literature. Such use of multiple metrics enables consideration of multiple factors simultaneously in evaluating routing paths, allows exploitation of different features of cognitive radio ad hoc networks and, thus, ensures more efficient paths.

D. Qualitative Comparison of Existing Routing Protocols

In this section, some of the most relevant routing protocols are subjected to qualitative comparision and subsequent insights to draw crucial inferences. The table below shows the study of various aspects of routing protocols as follows:

Table 1. Qulatitaive Comparison of Routing Protocols.

Protocol	Routing Path	Routing Metric	Channel Selection	Energy	CCC	Variant
AOMDV [9]	Multiple	Hop Count	Single channel	No	No	AODV
L2ER [11]	Single	Energy and Delay	Interference measure	Yes	Non-dedicated	AODV
E-D2CARP [12]	Multiple	Expected Path Delay	PU unoccupied	No	Non-dedicated	AODV
PMRC [13]	Multiple	Route Closeness	Single data channel	No	Dedicated	DSR
MRPC [14]	Multiple	Hop Count and Stability	Stability	No	Dedicated	AODV
EQR [15]	Single	Route Utility Factor	TDMA	Yes	Dedicated	DSR
MCSR [17]	Single	Number of Channel Switch	Common channel	No	Dedicated	AODV
CAODV [18]	Single	Shortest Path	Random	No	Non-dedicated	AODV

Different routing protocols as mentioned have their own uniqueness and operate in different ways. As seen from above, most of the protocols, except L2ER , EQR, MCSR, and CAODV are multipath routing protocols reflecting the need of multiple paths in cognitive radio ad networks. The main purpose is to negate the impact of possible route failure which is apparently high in general wireless ad hoc networks as well as in cognitive radio ad hoc networks. It simply provides much needed robustness and adaptability to the dynamic environment. Nevertheless, the idea of forming multi-path is apparently different in each case. AOMDV uses the notion of “advertised hop-counts” to form multiple paths with different hop counts. E-D2CARP exploits path and spectrum diversity to form various paths that posses different channel and nodes. PMRC forms routing paths that are far off from each other such that they are at minimal risk of primary users. The routes are formulated based on the overlapping areas, smaller the area better it is. In this regards, MRPC forms node disjoint paths by exploiting the feature of sequence number, it prohibits the repeated transmission of control packets with same sequence number to preserve loop freedom and disjointedness.

Each of the routing protocols has formulated its own routing metric to fulfill its own requirements thought it can be more or less effective when compared with another protocol. AOMDV is a shortest path routing protocol which uses hop count as a routing metric. It is a single channel routing protocol where control and data packets are propogated through the same channel. L2ER, on the other hand, has a cumulative routing metric that tends to select the optimal path with minimum energy consumption and end-to-end delay combined. in order to assign a channel for a link, it evaluates the channels based on the interference values due to primary uers. The channel with minimum interference is, finally, assigned as preferred channel. Whereas, E-D2CARP evaluates probability of packet loss and link delay in its routing procedure via its routing metric called Expected Path Delay (EPD). It uses same channel ,free fromo primary user, for both control and data packets. All the licensed channels are regularly sensed to keep track of their states. PMRC makes sure that the selected routes are not close enough to be interrupted by an active mobile PU. Route Closeness, in terms of the overlapping areas, is the measure of the proximity of the routing paths in this protocol. This protocol has two channels in total: one as common control channel and other as a data channel.MRPC based on MAODV uses hop count to select the shortest routes while integrating channel selection policy for each link based on channel stability that selects the most stable channel. Likewise, EQR uses route utility defined as the ratio of residual energy to hop counts to evaluate energy efficient QoS path, whereas the channes are assigned based on time division multiple access technique (TDMA). The number of free timeslots between the two users has been termed as the bandwidth of the link and a meaure of Quality of Service (QoS). MCSR, on the other hand, selects the routing path that incurs minimum channel swithches with an aim of minimizing switching overhead in cognitive networks. Each nodes selects the channel which is common or available for majority of the neighboring nodes. And, CAODV as the original AODV is based on the principle of shortest path routing. The channel is selected randomly but only exception that it should not be the immediate adjacent channel to the current channel in use.

As mentioned earlier, energy is one of the major constraints in limited powered cognitive radio ad hoc networks. Several attempts have been made to include energy approaches even in routing protocols as in L2ER and EQR. But, unfortunately, they do suffer from some deficiencies, which prompts us to propose an energy efficient routing protocol.

III. SYSTEM MODEL

We consider a battery powered cognitive radio ad hoc network with *N* primary users and *M* secondary users, the number of secondary users is greater than the number of primary user in most cases. The number of licensed channel is assumed to be equal to the primary users itself such that each primary user has a particular channel assigned to it. The primary users hold undisputable licenses for specific spectrum portions and do not deviate from their assigned spectrum portions during their ON time: the time during which they occupy their channel. Secondary users are expected to utilize the licensed channels opportunistically whenever the primary users of corresponding channel are in OFF state: the time during which the primary users free their channel. Furthermore, they are supposed to exchange their network related information, encapsulated in the control packets, through dedicated common control channel. The secondary users are assumed to possess two radio transceivers for control packets and data packets transmission separately. It is also expected that secondary users can tune its radio transceiver to any of the vacant primary user channel if any. The number of channels free from primary users varies from one secondary user to another located differentluy and might change with the passage of time. Therefore, the secondary users are supposed to have decent spectrum sensing capability to find out the vacant channels not in use by the primary user and an ability to use those opportunistically until the arrival of primary user.

A good primary user activity modelling is equally important to make the environment more realistic and ensure that they have effective impact in there. Primary users are modeled by virtue of independent and identically distributed ON and OFF process with exponential distribution [24]. In ON state, the primary user is active and occupies its channel for T_{ON} period of time. During this period it performs its data transmission via that channel so the secondary users are not allowed to use the channel. On the contrary, in OFF state, the primary user is inactive so the secondary user can temporarily use the licensed channel until the PU gets into action. At the initial phase, we generate a sequence of binary numbers to denote whether the PU is active or not. It can be defined as:

$$P_t(n) = 1; \quad \text{If the primary user in active state}$$
$$= 0; \quad \text{Otherwise}$$

where n indicates the corresponding primary user and t represents time.

If, suppose, the ON and OFF periods of a primary are exponentially distributed with mean ON and OFF periods $\frac{1}{\alpha}$ and $\frac{1}{\mu}$ respectively as shown in Figure 1. Then, the probability of the primary user being in ON state in the next time period is given by:

$$P_{on} = \frac{\mu}{\mu+\alpha} \tag{1}$$

And, likewise the probability of being in OFF state is given by the following equation:

$$P_{off} = \frac{\alpha}{\mu+\alpha} \tag{2}$$

where is μ is the birth rate and α is the death rate of the process .

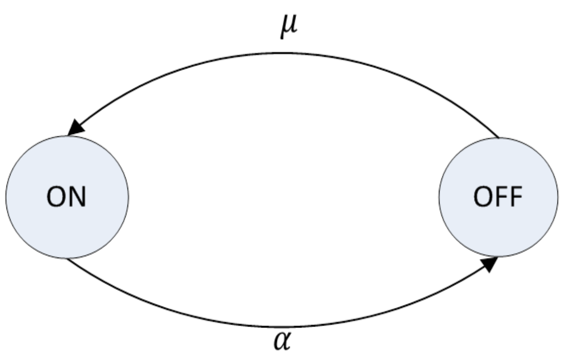

Figure 4. Alternating ON-OFF states.

The durations of ON and OFF states following an exponential distribution is given by:

$$P(x) = 1\text{-}e^{-\gamma x}$$

$$\Rightarrow x = \frac{-ln(1-P(x))}{\gamma} \qquad (3)$$

where x is the variable to be evaluated, and can be ON or OFF period whereas γ represents the corresponding mean period. If T_{ON} represents the ON period of a primary user then it is calculated as:

$$T_{ON} = \frac{-ln(1-P(on))}{\gamma_{on}} \qquad (4)$$

Similarly, the period of being inactive T_{OFF} is given by:

$$T_{OFF} = \frac{-ln(1-P(off))}{\gamma_{off}} \qquad (5)$$

IV. ENERGY-EFFICIENT MUITIPATH ROUTING PROTOCOL

The traditional routing path selection metric of shortest path is not applicable for cognitive radio ad hoc networks which are quite different nature to typical wireless ad hoc networks. We propose an energy efficient multipath on-demand routing protocol with improved robustness for cognitive radio ad hoc networks. It aims to integrate multiple facets of CRAHNs which basically are mobile ad hoc networks with cognitive radio technology. The concept of primary and back up path to counteract mobility induced route failures coupled with energy efficient approach to prolong the network life is the crux of the protocol. In its simplest form, it is an on-demand hop by hop routing protocol which discovers multiple paths between the specified sources and destinations identical to that of AOMDV. Unlike in the single path routing protocol where route discovery process has to start every time the path fails, here the process starts only when all the routes in the stack break down. The selection of next hop nodes on the basis of their residual energy not only reserve their energy for latter sessions but also ensures balanced energy consumption throughout the network. It is made sure that the paths taken into consideration are the most energy efficient paths based on energy consumed in transmission, reception, channel switching and idle listening combined. It is worth noting that the routing procedure, selection of routing path, is carried in collaboration with the channel selection. At each link, the selection of the next hop node is performed simultaneously with channel allocation to build a complete and efficient architecture for cognitive radio ad hoc network. The channel thus assigned is the most steady one in terms of access duration which is evaluated for each and every link. To sum up, the protocol is designed to exploit the benefits of node, channel and path diversity attributes in cognitive radio ad hoc networks. The protocol broadly consists of route discovery, and route maintenance phase as explained below.

A. Route Discovery

The process of route discovery allows the source to find the multiple routes between itself and the destination based on the routing metric evaluation. And, it is relatively different and costly approach when compared to the process in traditional ad hoc networks. The route discovery mechanism involves three major steps to get the process done.

1. Route Request

Principally, it is based on AOMDV routing algorithm for ad hoc networks with some modifications to adapt cognitive environment. As the protocol is an on-demand routing protocol, the source starts the route discovery process only when it has data to transmit. In this process, route request (RREQ) packets are broadcasted from the source towards destination forming multiple reverse paths at intermediate nodes. In the other end, multiple route reply (RREP) packets are made to traverse along the set reverse paths paving the way for forward transmissions. The multiple paths thus formed are loop-free and node disjoint. It uses the concept of ‘ advertised hop count’, flood based route discovery and regular route updates locally at each to ensure loop-freedom and path disjointedness. The basic structure of the RREQ packet is as follows.

S	D	SN	ACS	CAD	CA	RE	PC	HC	TO

S: Source D: Destination SN: Sequence Number ACS: Available Channel Set CAD: Channel Access Duration CA: Channel Assigned RE: Residual Energy PC: Path Cost HC: Hop Count TO: Timeout

Figure 5. RREQ packet structure.

And because it is a hop-by-hop routing process, a regular updating of RREQ fields is mandatory. Along with this, there is a routing table to be maintained at each participating node from the source to destination. The routing table should hold the following information to ease the route discovery and subsequent selection.

S	D	SN	AHC	Route List			
				next_hop1	last_hop1	path_cost1	channel1
				next_hop2	last_hop2	path_cost2	channel2
				next_hop3	last_hop3	path_cost3	channel3

S: Source D: Destination SN: Sequence Number AHC: Advertised Hop Count

Figure 6. Routing table structure.

Whenever, a source is to find the path for its data transmission, it broadcasts RREQ packet via common control channel after appending the necessary information including the available channel set, residual energy, hop count (zero), path cost, and other node information as indicated in the RREQ packet structure. The RREQ packet exists only for the time period defined in the Timeout field. When a neighboring node receives the RREQ packet, it first checks if its battery energy exceeds the threshold value and whether there are any common vacant channels between them. It is because in order to form a link between two nodes they should not only be within the transmission range of each other but also must possess at least one common vacant licensed channel between them. If either of the criteria is not met, the packet is instantly dropped. Otherwise, the intermediate node responds accordingly. In the response process, it first checks if it is the destination being looked for. If so, it replies with a unicast RREP packet, if not it rebroadcasts the RREQ packet into its surrounding. Before, it actually rebroadcasts RREQ packet, the routing table is updated with information like the last hop node, and hop count for reverse path and the channel assigned for that particular link. The channel assigned is the most stable channel available for that link owing to its highest availability time. Likewise, RREQ packet itself is also updated by appending node id, available channel set, residual energy, most stable channel, path cost and the hop count (residual energy, channel stability and hop count are increased by adding to their previous values). This process continues till the destination is reached, where the route decision and selection is made.

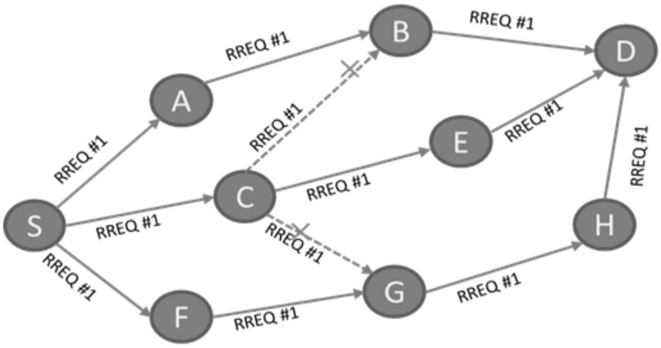

Figure 7. Multipath routing path discovery.

In order to enable multipath between the source and destination, the concept of sequence number is exploited which actually facilitates unique identification for a RREQ packet. To ensure that the routes are absolutely disjoint, the redundant RREQ packets with sequence number same as that of a RREQ packet that the node has already forwarded through it. Fig.4 shows the basic procedure of a route discovery process to find three disjoint routing paths. As seen from the figure, the process RREQ packet flow begins from the source S and ends at node D as destination. Each of the nodes makes sure that no RREQ packet is forwarded twice through it to avoid looping and maintain path disjointedness. As shown in the figure, the node B and G drop the RREQ packets with same sequence number **#1** as they have already forwarded a RREQ packet with same sequence number. This helps to keep up the concept of disjoint and loop free paths, which is crucial in multipath routing. The destination responds to only those RREQs received within the time set in the timer at the destination. All RREQs received after the time specified get dropped automatically. The route request process at an indermediate nodes can be summarized with the help of the flowing flow diagrams.

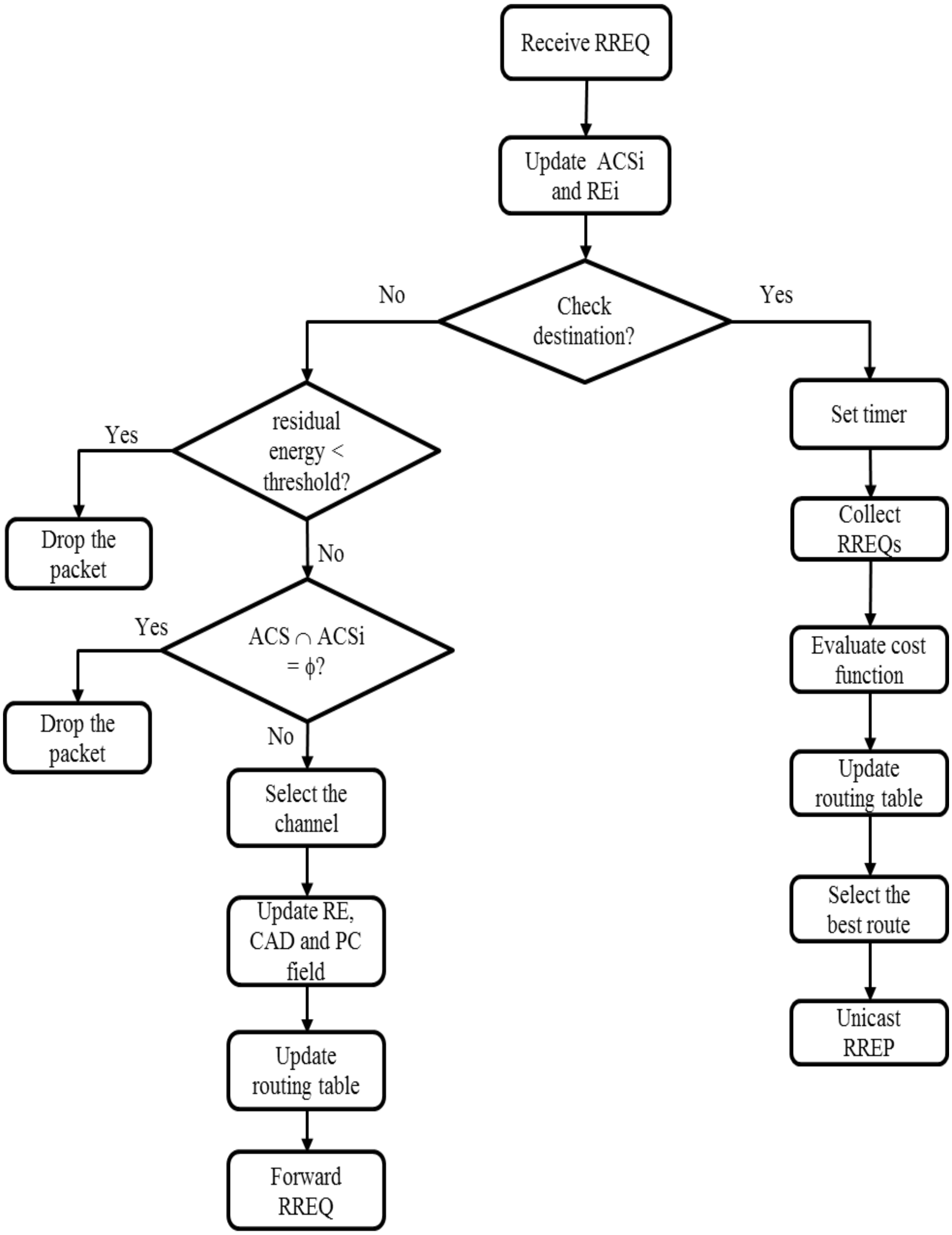

Figure 8. RREQ flow control at intermediate node.

2. Route Selection

At the destination, when RREQ packets from multiple path are received they need to be sorted in according to their energy efficiency and stability. This helps to categorize the paths as primary and backup or candidate paths. We use a cost function, a combination of energy and stability metric, to evaluate the order or category of the path. The path with highest cost function is preferred as the primary path and the rest are the used as backup paths in their respective orders. We propose the cost function as follows;

$$\textit{Cost Function (CF)} = a.E_{resp} + b.S_p \quad (6)$$

where '***a***' and '***b***' are weight factors such that '***a***' represents priority weight for the residual energy E_{resp} whereas '***b***' represents priority weight for the stability measure S_p of the entire path which actually represents the sum of spectral access times. The values of '***a***' and '***b***' are chosen as per the application. For instance, with application requiring energy rich nodes, the value is chosen as a>b. And if the longevity is more crucial then b>a under the condition a+b=1.

The residual energy of the path refers to the sum of residual energy of each node forming the path. And, it is given by the sum of the residual energy of all the nodes forming the path and is given by:

$$E_{resp} = \sum_{n=1}^{l} E_{resn} \quad (7)$$

where n is the number of nodes in the path including the source and destination and E_{resn} is the residual energy of each node. The residual energy of the node is the difference of initial energy of the node (E_{init}) and the total energy consumed by the node (E_{con}) during the routing process as indicated below.

$$E_{res} = E_{init} - E_{con} \quad (8)$$

The transmission of a packet from one node to the next relay node is an energy consuming process. Energy is not only consumed at the transmission, but also at the receiving side. And if the transmission and reception occur through different channel, a considerable amount of energy is involved in switching process. The energy incurred in switching is proportional to frequency difference between the channels [25]. Likewise, a dominant factor of radio energy gets consumed when the radio is listening to the channel to receive possible data. For often, idle listening cost is speculated to be 50-100% of the energy required for the receiving purpose. It is, therefore, we take into account all the aforementioned factors to gauge the energy, a node is likely to consume in successful transmission of data. If we neglect overhearing and assume data transmission to be completely along the path specified, the energy elapse can be calculated as

$$E_{con} = E_{tx} + E_{rx} + E_{swt} + E_{idle} \quad (9)$$

where E_{tx}, E_{rx}, E_{swt} and E_{idle} are represented as follows:

- E_{tx} is the transmission energy required for a packet of a data and is given by
  E_{tx} = **(1.65* packet size in bits)/ (2*10^6)** joules.
- E_{rx} is the energy required for receiving a packet of a data and is given by
  E_{rx} = **(1.15* packet size in bits)/ (2*10^6)** joules.
- E_{swt} is the energy consumed in case of channel switching and is given by
  $E_{swt} = P_{sw} * t_{sw} * |F_2 - F_1|$ joules

  where P_{sw}, the power dissipation for channel switching and t_{sw} is the time for channel switching for unit bandwidth. F_2 and F_1 are the frequencies of the channels switched to or from.
- E_{idle} is the energy loss while listening to channel and is given by
  $E_{idle} = 0.80 * E_{rx}$

As for the stability of the path, we take into account the time of the primary user being in OFF state in the next time period such that the corresponding channel can be used by the secondary users. In other words, it is the access duration available for secondary user communication. Higher the access duration more stable is the link. Hence, the stability can be measured as:

$$S_p = \sum_{n=1}^{l} T_{off} \qquad (10)$$

where n is the number of links in each path and T_{off} is the time period for which the channel is available to the secondary users associated with the link and follows from equation (5) .

We use this approach to evaluate the cost function for each path. Consequently, the path with maximum value for the cost function is taken as the primary path for data routing. In other words,

Primary Path (PP) = max (Cost Function)

The backup paths are also sorted in order of their cost function. The next path to be chosen for the data routing shall be the one with highest cost function, in case the primary path suffers route failure.

3. Route Reply

In CRAHNs, Route reply is the confirmation of the selected paths to the source. The destination node on receiving the RREQ copies forms the reverse paths similar to the way in intermediate nodes. It unicasts separate Route Reply (RREP) packets to each of the path discovered and sorted through the reverse path set up process. The basic structure of the RREP is depicted as below:

S	D	SN	HC	NH	CA	P-id	TO

S: Source D: Destination SN: Sequence Number HC: Hop Count NH: Next Hop CA: Channel Assigned P-id: Path ID TO: Timeout

Figure 9. RREP packet structure.

The main fields to be focused in RREP packet are Path-id, Channel assigned and Next hop which indicate the preference order of the selected paths, channel and the next hop node-id for the forward path. When an intermediate node receives a RREP packet, it sets up the forward path along the channel selected and then forwards a copy of route reply packet along the reverse path stored in its routing table and at the same time updates the hop count, channel assigned and next hop field of the route reply packet. Also, the routing table of the intermediate node is also updated with the information in RREP packet to set up the forward path. In case, if an intermediate secondary user node receives a duplicate of the RREP for the same destination pair , the packet is dropped except when it is for the new route discovery session. Thus, the routing table at the source node helps it to determine which path should be used in propagating data transmission. The route reply process at an intermediat node is depicted in the flow diagram in Figure 10.

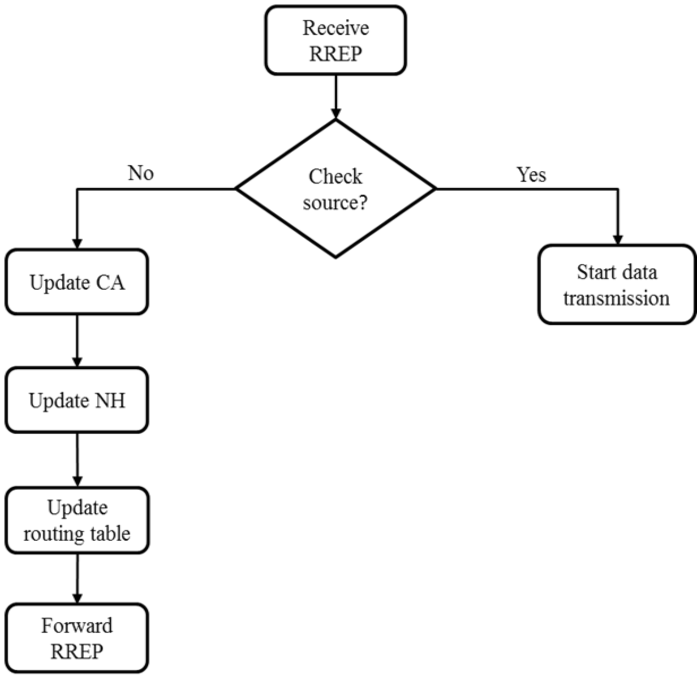

Figure 10. RREP flow control at intermediate node.

B. Route Maintenance

Route failures in CRAHNs occur primarily because of the sudden arrival of PU into the channel being used by SU pair and breakage of formed routes due to node mobility such that they get out of the transmission range of the neighboring nodes. These two failures are of different as far as their sources of origins are considered. Therefore, the routing protocol must be well enough to figure out the cause and provide solution accordingly each time route suffers intervention. In case where the channel being used is restored by corresponding primary user then the data transmission in that channel is subjected to halt. And, a new channel is explored to continue the transmission as mentioned in the channel selection procedure. And if the route failure occurs because of the dynamic behavior of any node, the routing path needs to be changed. The data routing should shift to the backup path. The failure of any route during the process is detected by periodic messages in the form of HELLO packets.

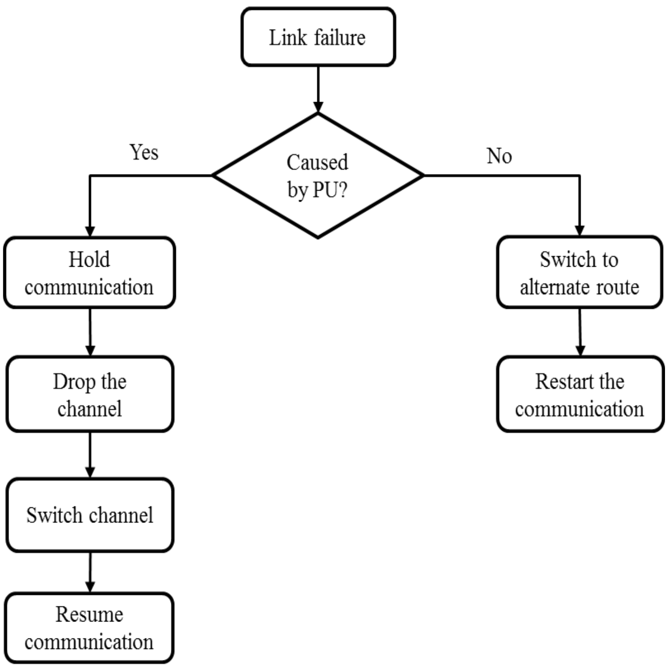

Figure 11. Route maintenance flow control.

V. PERFORMANCE EVALUATION

This chapter, describes the simulation environment, performance metrics, simulation results and comparison with one of the existing energy efficient routing protocols. The performance evaluation of the proposed routing protocol has been performed in NS-2.31 [26], a discrete time event simulator mostly used for networking protocol simulations. The protocol taken for comparison is "L2ER: Low-Latency and Energy-Based Routing Protocol for Cognitive Radio Ad Hoc Networks" an energy efficient routing protocol for cognitive radio ad hoc networks that tends to find the best path by avoiding the trade-off situation between energy and delay efficient routes. It is a single path on-demand routing protocol developed on the principles of AODV routing protocol to fit into cognitive radio environment. We choose it for comparison because of the fact that both are energy efficient routing protocols with multi-metric route evaluation approach. L2ER being a single path has its own restrictions under mobile environment. Also, there are significant differences in terms of the number of paths taken into account for each route discovery, channel selection strategies, and routing metric. The proposed protocol allows energy based multiple paths and channel availability based selection scheme to improve the network performance. This encourages us to evaluate their performance differences and analyze the possible reasons.

A. Simulation Environment

We consider a network area of 1000*1000 m^2 where a set of primary users and secondary users are randomly deployed. Also, we take into account 11 channels, in total, one of which is a dedicated common control channel and the rest are assigned as licensed channels for data communication, each of which assigned to separate primary user. The primary user activity is based on ON/OFF model where the ON and OFF times of the primary users are exponentially distributed with the mean factors. The PU during its ON state occupies the channel it is assigned for the calculated time and, conversely, frees the same channel during the OFF state. The transmission ranges of primary users are set to 150 m and are assumed to be completely static. The secondary users on the other hand have the transmission range of 250 m and are expected to move in random direction with a random speed within a range of 0-5 m/s and a pause time of 30 seconds. During the simulation run, all the routing control packets are designed to transmit through a control channel dedicated as common control channel which is shared by all the secondary users. And, the data transmission is accomplished through the data channel selected from the channel selection policy. The rest of the simulation parameters are listed in the Table 2 below.

Table 2. Simulation Parameters.

Parameter	Value
Simulator	NS-2.31
Network area	1000*1000
Number of primary users	10
Number of secondary users	10,15,20,25,30 (default),35,40,45
Number of licensed channels	10
PU modeling	ON/OFF model
Traffic type	CBR
Packet size	512 byte
Mobility	Random way point
Speed	0-5 m/s
Pause time	30 seconds
Number of sessions	4,6,8,10 (default),12,14,16
Initial energy	Randomly chosen (750-760 joules)
Transmission power	1.15 W
Reception power	1.0 W
Ideal power	0.8 W
Switching power	0.8 W
Stability weight	0.1,0.3,0.5(default),0.7,0.9
Simulation time	250 seconds

B. Performance Metrics

The following performance metrics are evaluated to measure the performance of the proposed routing protocol.

- *Average network throughput:* It refers to the total number of successfully received bits per second over the number of source-destination pairs.
- *Packet delivery ratio*: It is the ratio of the number of successfully delivered packets to the destinations over the number of packets sent from the sources. It can be regarded as a metric for routing path reliability.
- *Average energy consumption per bit:* It indicates the average amount of energy in joules consumed to reach a bit of data packet to the destination successfully.
- *Average end-to-end delay:* It is the average time a packet takes to reach its destination once generated from the source.

C. Simulation Results and Discussion

In this section, we evaluate the performance of the purposed routing protocol with NS-2 simulations and compare the results with L2ER routing protocols both of which are based on the energy efficient routing techniques. We perform extensive simulations under same and varying scenarios for multiple times. The results thus obtained are then averaged to consider the variations in results. The trace files obtained from the simulation are analyzed via AWK script files to obtain the numerical values for each of the performance metrics. We, basically, perform simulations under three different environments: by varying the number of active sessions, by varying the number of secondary users, and by varying the stability weight. And, in each case, average network throughput, packet delivery ratio, average energy consumption per bit and average end-to-end delay are evaluated as the distinguishing performance metrics.

1. Analysis by varying the number of sessions

In this case, the number of active sessions is increased from 4 to 16 with a step size of 2 and its impact on the network throughput, packet delivery ratio, average energy consumption per bit and average end-to-end delay is observed and analyzed. The secondary users are subjected to a random velocity between 0-5 m/s and the pause time is set to 30s while the number of secondary users fixed to 30. The main purpose in here is to evaluate the impact of different traffic scenarios on the performance of the routing protocols.

Figure 12 shows the average network throughput as a function of the number of active sessions. As seen from the figure itself, the throughput performance of both the routing protocols enhances with the increase in the number of sessions. This is because with the increasing pairs of source and destination more packets are successfully reaching their destinations with the specified time. Also, with smaller number of connections, the difference between the throughputs between the proposed protocol and the L2ER protocol is also small. Nevertheless, the proposed protocol is found to outperform the existing protocol significantly at higher number of sessions. At its best, the new protocol has a 25 percent higher throughput than its counterpart. The proposed protocol, with multiple paths, has a better tendency to combat the dynamic environment and the stress of routing that is expected to increase with the increase in the number of active sessions.

In Figure 13, it is noticed that the increases in the number of sessions has dual effect on the packet delivery ratio of the routing protocols taken into account. The pdr first increases with the increasing number of active sessions reaches at its peak value at 10 active sessions and, thereafter, experiences a drop owing to the congestion in the network. The proposed protocol depicts better packet delivery ratio by a healthy margin of 20 to 25 percent in all cases proving its robustness in cognitive radio ad hoc networks. The provision of backup paths to respond to route failures and availability of much stable channel are the factors contributing to improvement in the data delivery percentage.

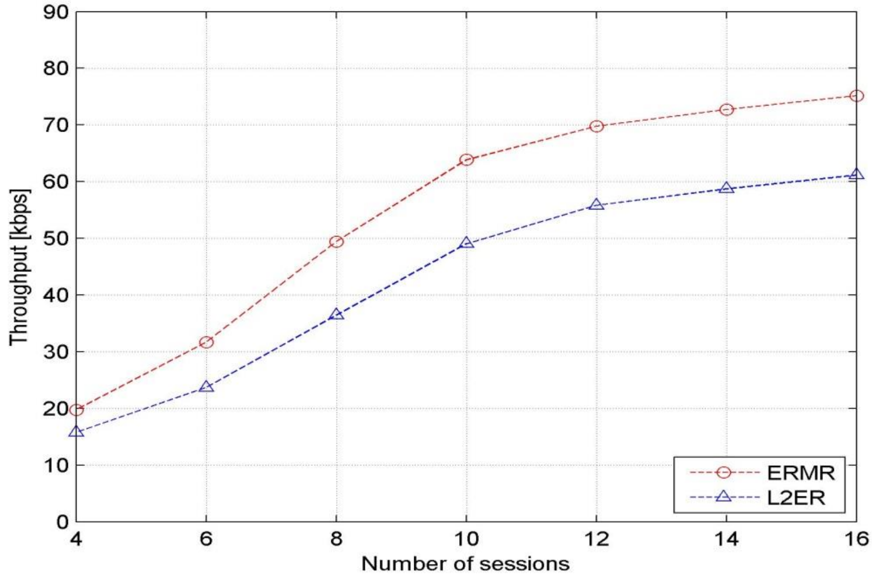

Figure 12. Network throughput vs. the number of sessions.

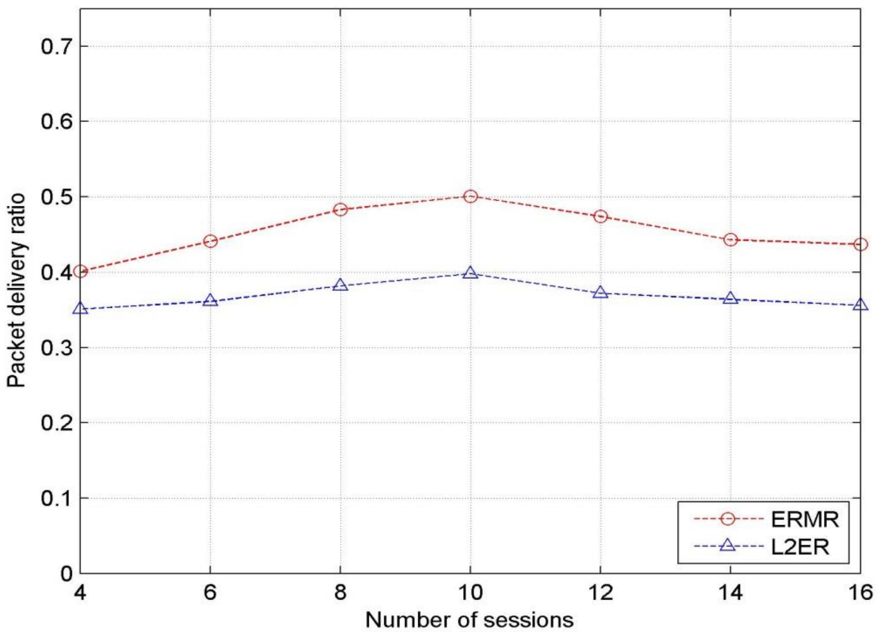

Figure 13. Packet delivery ratio vs. the number of sessions.

Figure 14 shows the average energy consumed per bit for its successful delivery to its destination. It is found that the energy consumption per bit sharply until the number of session is set to 10, thereafter, attaining almost steady consumption. In fact, the amount at which average energy consumed per secondary user increases with the additional sessions is considerably low compared to the number of packets reaching the destinations. This is what leads to the trend of the graph in the relevant figure. Furthermore, we find the proposed routing protocols exhibits uniformly low energy consumption throughout the process. Basically, both the routing protocols are energy efficient routing protocols designed for the cognitive radio ad hoc networks. But, L2ER in its original forms does not take into account the channel switching energy which is inevitable in multi-channel networks like the one discussed here. Also, a significant amount of energy can be saved for each route discovery process that takes place in mobile networks. Consequently, the notion of backup of path preserves this improvident energy consumption in finding new routing at every route failure. Likewise, a channel selection policy, in the proposed routing protocol, that ensures a stable channel for data communication avoids frequent channel switching and thus end up preserving much needed energy.

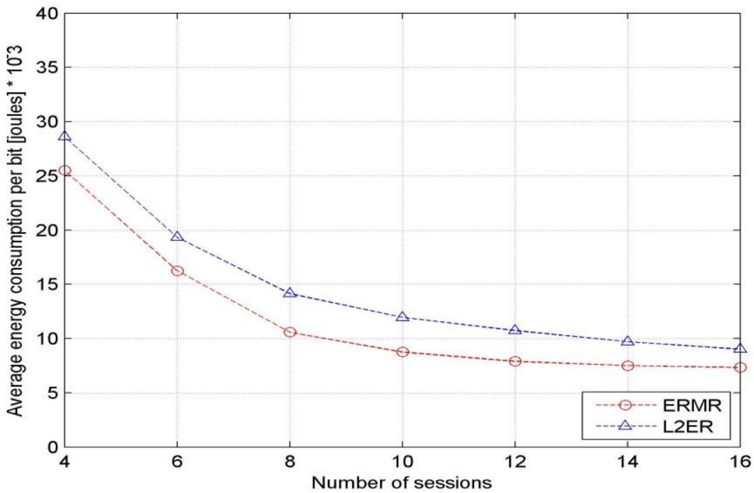

Figure 14. Energy consumption per bit vs. the number of sessions.

As seen from Figure 15, the average end-to-end delay, for both the cases, almost linearly increases with the increase in the number of sessions. And, it is also obvious, that the end-to-end of the proposed routing protocol is lower than the protocol compared with resulting from the better adaptability to the dynamic network and spectrum heterogeneity. The delay incurred in route discovery process, in single path routing, causes end-to-end latency to go higher. It is also the resilience to the mobility effects, in the proposed protocol, that accounts for lowered overall delay.

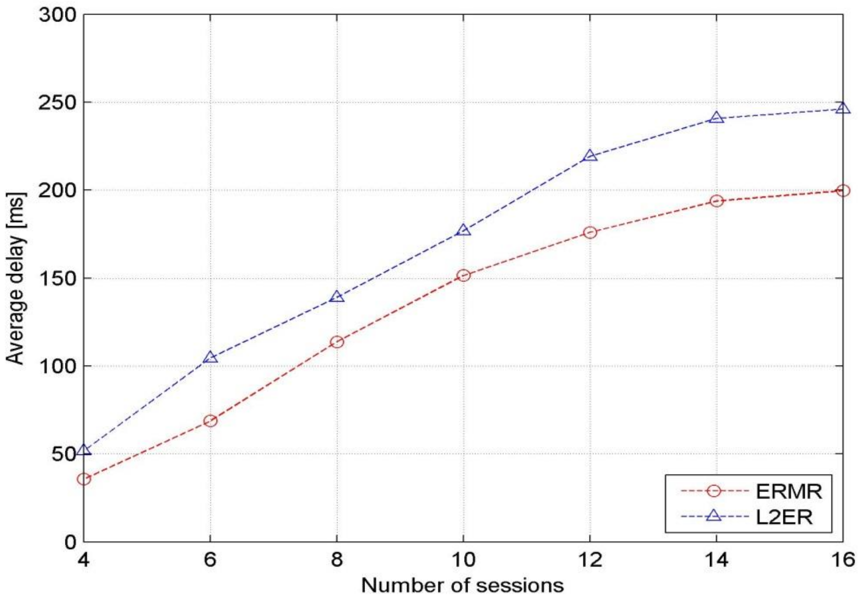

Figure 15. Average end-to-end delay vs. the number of sessions.

2. Analysis by varying node density

In this section, we vary the number of secondary users from 10 to 45 with a step size of 5 in a fixed network size and study its impact on network throughput, packet delivery ratio, energy consumption per bit and average end-to-delay as dependent variables along Y-axis. The number of active sessions in each case is fixed to 10 making the secondary user mobile with speed randomly choses between 0-5 m/s.

As shown in Figure 16, it is observed that the average throughput of both the routing protocols follows an identical trend with increasing number of secondary users. It increases quite noticeably in the first half to attain an almost steady state in the later phase. It is interesting to observe that the difference in the throughput measures of these routing protocols is increasing with the increase in the node density. At low node densities, the proposed routing protocol is found to outperform the existing protocol by around 15 percent and at higher densities the difference reaches to a significant 30 percent. It makes us to conclude that the proposed routing protocol for cognitive radio ad hoc networks has better adaptability and robustness to the increase of secondary users. And it is mainly because of its ability to negate the impact of possible route breakages in mobile networks and the minimal channel switching approach in the multi-channel environment.

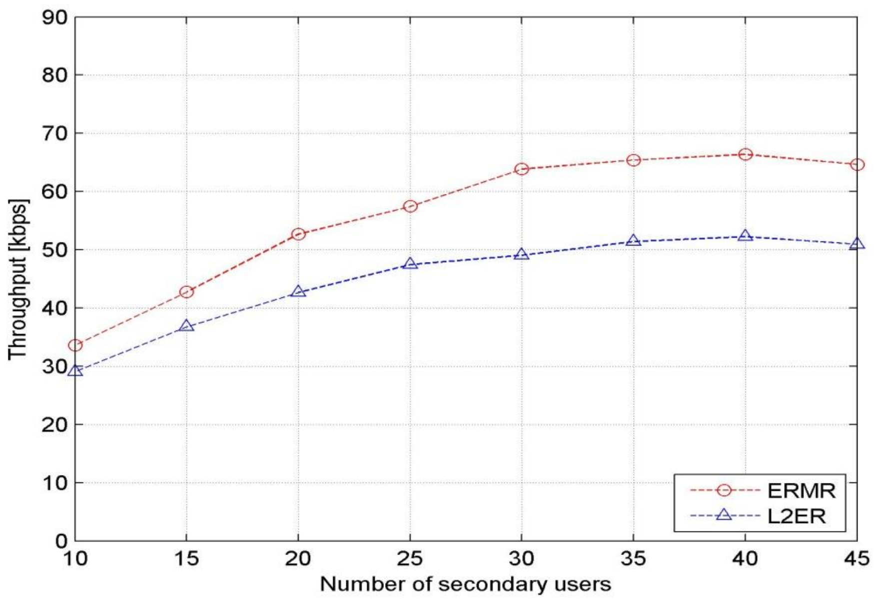

Figure 16. Network throughput vs. the number of SUs.

Figure 17 depicts the performance of packet delivery ratio of cognitive radio ad hoc network as a function of secondary user density. The trends are much similar to that of the throughput performances and are fairly reasonable. The graphs have gradual increase in the beginning, seemingly steady in the middle phase and slight drop in the end. As in the case of throughput performances, the differences in their delivery ratios is low at low densities and tends to widen up sharply with increasing node densities proving its better adjustment in the dynamic environment as mentioned earlier.

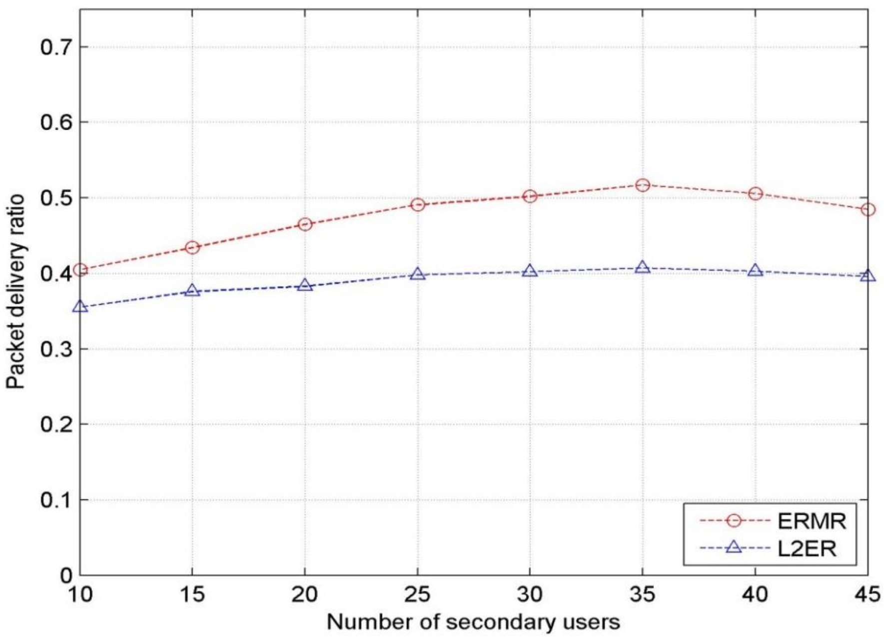

Figure 17. Packet delivery ratio vs. the number of SUs.

Figure 18 below shows the energy consumption per bit for the network with the variation in the number of secondary users. It reveals gradual decline in the energy consumption per bit in both the cases. This is because of the underlying fact that though the average energy consumed per node is on the rise in each case, the rate of increase of data packets reaching their respective destination is fairly higher than the rate at which energy is consumed at which node. Clearly, the proposed routing protocol proves its upper hand in saving much needed energy owing to its reduced route discovery processes, robustness and reduced channel switching.

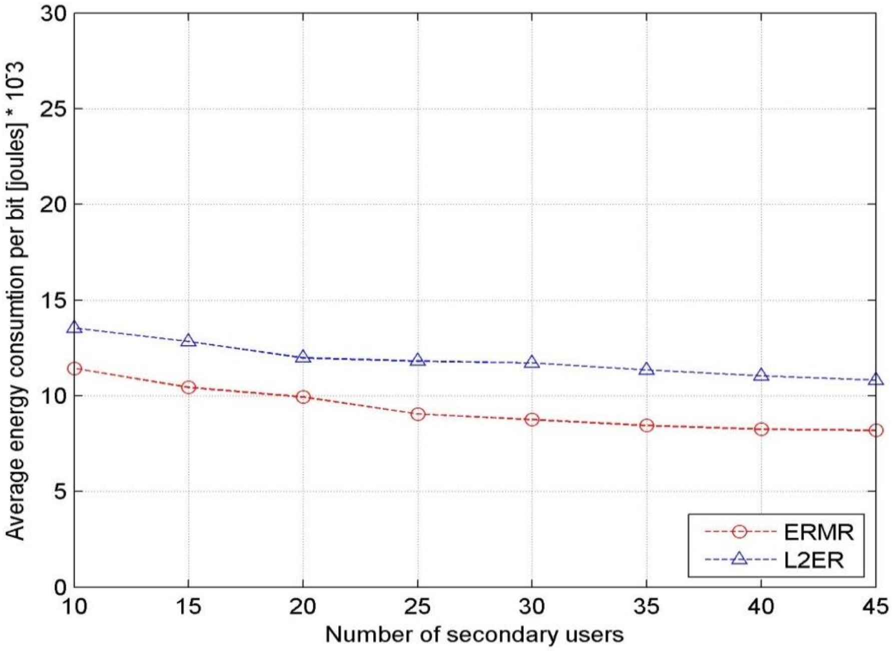

Figure 18. Energy consumption per bit vs. the number of SUs.

And, it is shown in Fig. 19 that, with the increase in the number of secondary users the average end-to-end delay suffers a rapid increase in both the cases. But, the proposed protocol has lower latency due to its better adaptability to the mobile network scenarios, fewer link failures always lower the delays involved in data transmission process, and lesser switching delays in the entire routing process itself.

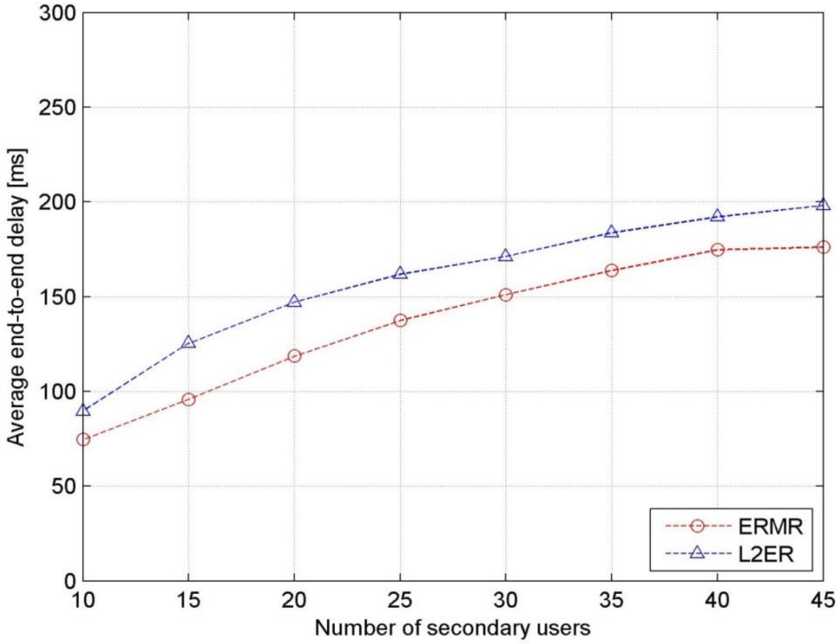

Figure 19. Average end-to-end delay vs. the number of SUs.

3. Analysis by varying weight factor

In this section, we vary the stability weight (b) used in equation (6) to observe the impact of variation of priority weights. The stability weight is varied from 0.1 to 0.9 with a step size of 0.2 in a fixed network size and ,thereafter, its impact on network throughput, packet delivery ratio, energy consumption and average end-to-delay as dependent variables along Y-axis. The number of active sessions in each case is fixed to 10 with 30 secondary users mobile with speed randomly chosen between 0-5 m/s.

Fig. 20 shows the variation of throughput as a function of stability weight. And as seen from the figure, the throughtput of the proposed protocol tends to increase with the increase in stability factor. Wheras the L2ER protocol shows no variation in is throughput performances as it is independent of this stability weight. But, in the proposed protocol, the increase in stability weight provides more stable links and hence the more stable routes contrary to the low stability weights. The more the stable routes better the performance of the network.

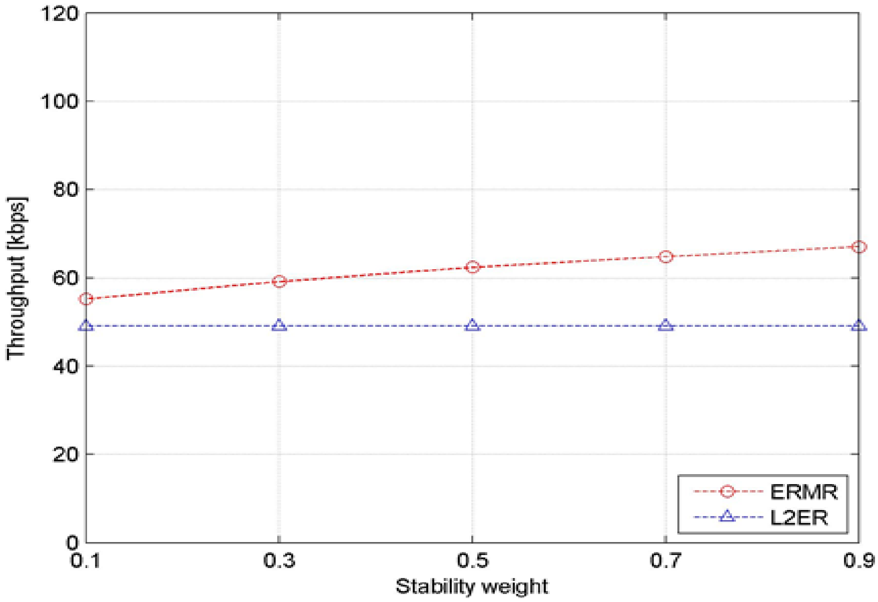

Figure 20. Network throughput vs. stability weight.

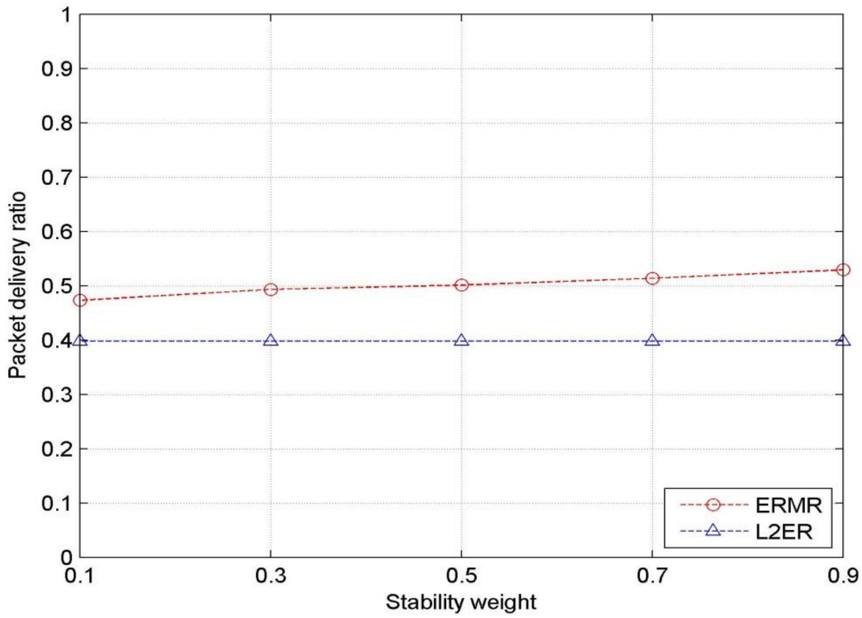

Figure 21. Packet delivery ratio vs. stability weight.

The impact of variation of stability weight on packet delivery ratio has been observed in Fig. 21. The increase in stability weight results in improved packet delivery ratio, though in small fraction, owing to stable links and ultimate routing path in the proposed routing protocol. L2ER protocol, however, reveals a steady performance being uninfluenced by the weight factors.

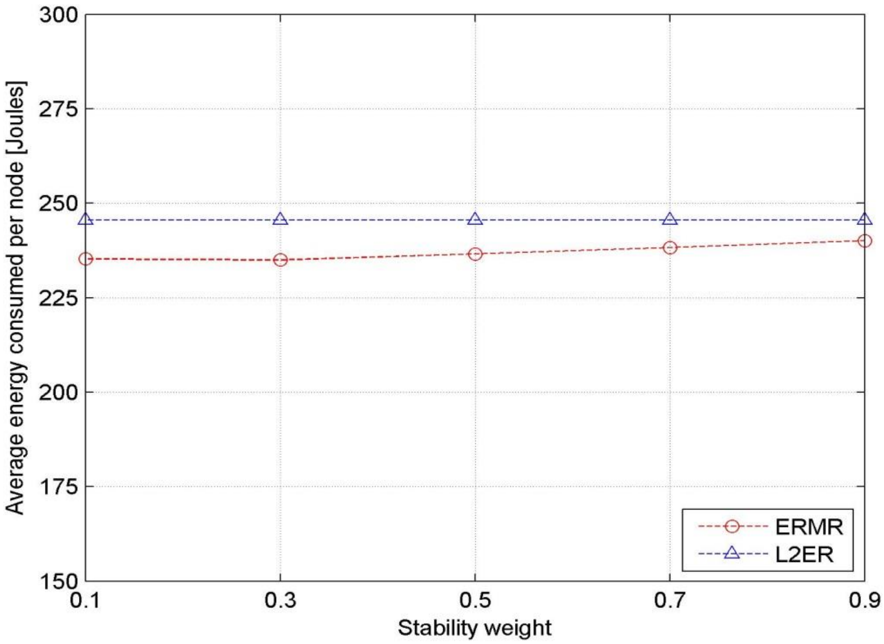

Figure 22. Energy consumed per node vs. stability weight.

The trend of energy consumption per node with respect to stability weight is shown in Fig. 22. With the increase in stability weight, there has been an increase in energy consumption, for the proposed protocol, due to fact that more and more packets are transmitted and received during the process. Nevertheless, the energy consumption in case of the proposed protocol is less that of L2ER, having constant energy consumption, throughout the process.

And, it is shown in Fig. 23 that, with the increase in stability weight the average end-to-end delay suffers a crucial decrease in case of proposed protocol.

The route selection with more stress on stability of the links and route lowers the link failures and thus lowers associated delay to reduce overall end-to-end delay.

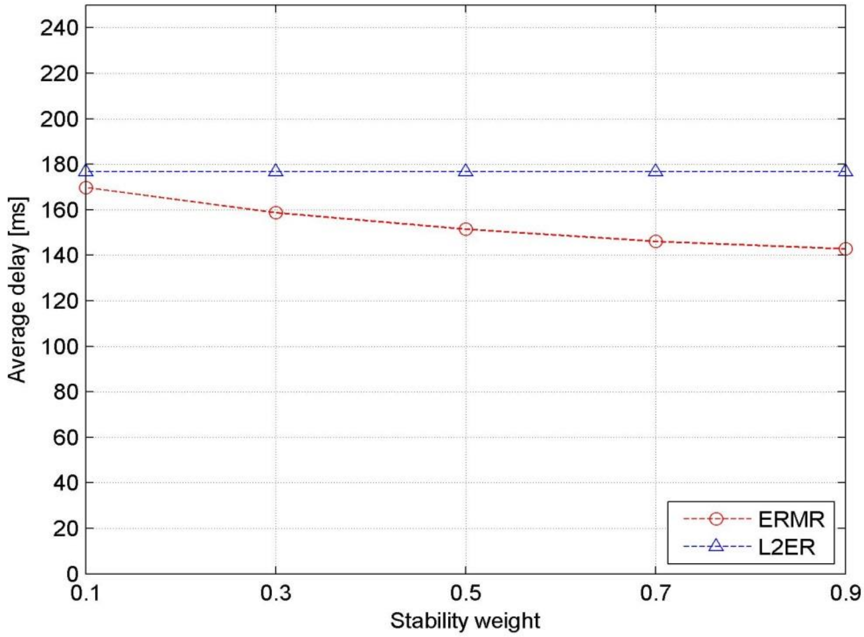

Figure 23. Average end-to-end delay vs. stability weight.

VI. CONCLUSION AND FUTURE WORKS

Cognitive radio ad hoc networks have huge possibility to alleviate under-utilization of licensed spectrum bands and bring uniformity in spectrum usage. But, unfortunately, in the flip side these networks suffer from their inherent features including dynamic topology, spectrum heterogeneity, primay user activity and limited energy to mention. In order to leverage the capabilities of such networks to the fullest, it is important that some energy preserving methods are coupled with algorithms to add robustness to the entire network.With this viewpoint, the routing protocol tends to lower the improvident energy consumption, confers robustness to the dynamic network environment and guarantees the longest existenece of the formed routes by virtue of channels associated. It discovers multiple energy efficient paths between the soure and destination in a single go, stores them such that the alternate path can be used if the first path fails. The route formation is integrated with the spectrum allocation so that the diversity can be exploited to the maximum. Channel selection is accomplished on the basis of the longest available time to make the routes more durable and network a gritty one. Simulation results reflect that the proposed protocol performs exceedingly well and outperforms state-of-art alogorithm. At the same time, the impact of weight factors on the network performance deserves a mentioning. It is clearly observed that the increase in stability weight during route selection procedures contributes to improvement in network performance with some increase in energy consumption which is fair enough.

As a possible future work, the impact of mobile primary users can be taken into account as it make the cognitive environment more challenging. Aslo, the presence of adversery or malicious nodes can easily disrupt the route formation and/or spectrum allocation procedure, a mechanism to preserve the privacy of secondary users and security of the communication procedure can be thought of.

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