Characterization of End-to-end Path Selection for Cognitive Radio Wireless Mesh Networks

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Abstract: The Cognitive Radio (CR) can delivers the environment to Secondary Users (SUs) of Wireless Mesh Network (WMN) to utilize unused spectrum of Primary Users (PUs) opportunistically. The CR can improve the spectrum usage of the WMN. However, this rises the some additional complexities for the SUs such as spectrum heterogeneity, unpredictable PU activity and interference constraints. In this paper an analytical model has been developed to analyse these complexities for each SU node and link characteristics for end-to-end optimal Path and channel assignment. Numerical results show that the analytical model is an effective tool to investigate the effects of the PU activities and channel heterogeneity on the network performance.
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1. Introduction

Wireless Mesh Networks (WMNs) are intended to be a leading technology that provides the ever-present connectivity to clients through homogeneous channels. A conventional WMN comprise mesh routers (MRs) and Mesh clients (MCs) (Akyildiz, Wang et al. 2005). The MRs could be connected to backbone network and provides services as gateway or serve to their MCs. MRs forward data traffic of other MRs to gateway multi-hop manner. There is strong motivation (Gupta and Kumar 2000), (Kyasanur and Vaidya 2005) to identify the spectrum which is unused by the primary network. The unused spectrum can be used to carry traffic of secondary mesh network. The secondary network is defined as a Cognitive Radio (CR) Network that intelligently aware of spectrum information and decide transmission parameters on environment conditions (Akyildiz, Lee et al. 2006). In CR-WMNs spectrum utilization is improved compare to the classical WMN. However, CR-WMNs introduce some additional complexities to resource allocation and unitization such as each node can access a set of available spectrum bands that may have different transmission ranges and different data rates, the channel bandwidths may vary because of spectrum heterogeneity. These constraints can have a significant effect on resource allocation, interference and utilization. To establish a link between two nodes; they must have some common subset of channels available to link onto to exit into the network.

To connect a pair of two nodes in CR-WMN it is necessary to select potential paths that possess the best channels with the best path. A traditional WMN is one in which the homogeneous channel selection algorithms are proposed by (Alicherry, Bhatia et al. 2005), (Kodialam and Nandagopal 2005), (Tang, Xue et al. 2005), that cannot be applicable in CR environment with the different types of heterogeneous channels with different transmission ranges. Both path selection and CA are very challenging problems in CR-WMN. Most of the current studies (Yong, Pongaliur et al. 2013), (Hincapie, Jian et al. 2008), (Kumar, Kumar et al. 2011), (Pefkianakis, Wong et al. 2008),(Mumey, Xia et al. 2010), (Mumey, Jian et al. 2012), (Ramamurthi, Reaz et al. 2011), (Nejatian, Syed-Yusof et al. 2013), (Nejatian, K. et al. 2012), (Almasaeid, Jawadwala et al. 2010), (Nejatian, Syed-Yusof et al. 2013) in this area propose that the heuristic algorithms cannot deliver any performance guarantees.

This work is different from previous works on path selection and channel assignment (Yulei, Geyong et al. 2012), (Tang, Misra et al. 2008; Chao-Fang, Wanjiun et al. 2011) that mainly dealt with the problem of scheduling and the channel assignment of links in order to maximize the throughput. In this paper the end-to-end analytical model is developed for the single node selection problem jointly with the problem of channel assignment in multi hop end-to-end path. This is a much harder problem due to constraints related to PU, other SUs, interference and node characteristics (Nejatian, Syed-Yusof et al. 2011; Nejatian, Syed-Yusof et al. 2013).

The analytical modeling approach is developed to estimate the effects of four key parameters of end-to-end paths which are PU activity, interference, channel heterogeneity and node characteristics. In the first phase, optimal node and channel selection for the best link establishment in a hop is addressed. The aim of this research is to develop an efficient analytical model approach which delivers the prime method of emerging wireless applications that has end-to-end paths with long term stability and low end-to-end delay.

In this paper, the parameters which affect the resource utilization in the network are explored. The model divided in two phases. The two phases are respectively named as: 1) *single hop node and channel assignment (SHNCA)* and 2) *End-to end path and channel assignment (EEPCA)*. The *SHNCA* select the best neighboring node among available options and for the channel of the link to be established for single hop based on node characteristics and channel availability. Characterization and modeling of each node in the network provides the best neighboring node selection. If the node satisfies certain criteria, which is defined in Section 4, then channel assignment modeling is introduced with a neighboring node. The *EEPCA* problem is NP-hard for any wireless network.

The rest of this paper is organized as follows. Related work is discussed in section 2. The network model and user activity is defined in section 3. Section 4 analyze the proposed analytical model. Then, the numerical results are shown in section 5. Finally, the paper is concluded in section 6.

2. Related Work

In the literature, Channel assignment (CA) and Routing Path Selection (RPS) are challenging issues facing CR-WMN networks. An algorithm is proposed by (Tang, Misra et al. 2008) for joint scheduling and spectrum allocation based on fair spectrum sharing. In (Alicherry, Bhatia et al. 2005) (Kodialam and Nandagopal 2005), the constant-bound approximation and fast primal-dual algorithm is proposed for the channel assignment, routing and scheduling.

An interference-aware channel assignment algorithm is proposed by (Tang, Xue et al. 2005) to ensure the guaranteed end-to-end bandwidth. In (Yeh 2007), the power control and congestion control method based distributed algorithms is proposed for joint spectrum allocation and routing path selection. In (Yi and Hou 2008), the joint scheduling and routing based distributed algorithm is proposed to maximize data rates for a set of communication sessions.

Joint spectrum allocation and routing algorithms is proposed by developing a layered graph model in (Chunsheng, Bo et al. 2005). In (Kumar, Kumar et al. 2011; Wajahat Maqbool 2013), the linear programming-based model and the link capacity based model are proposed to develop the link scheduling and channel assignment. A novel approach for link scheduling and channel assignment (CA) is proposed to improve the overall capacity and throughput (Kumar, Kumar et al. 2011).

An interference aware channel assignment (IACA) algorithm is proposed to reduces the end-to-end delay and packet delivery ratio (Maqbool, Yusof et al. 2013). In (Hou, Yi et al. 2007), the joint spectrum allocation and routing algorithm is proposed based on mixed-integer nonlinear programming. Spectrum-aware mesh routing (SAMER) and Spectrum aware routing (SPEAR) protocols are proposed to account for the routing of data traffic over paths by considering end-to-end optimization and link flexibility (A. Sampath 2008; Pefkianakis, Wong et al. 2008). In (Mumey, Xia et al. 2010), the constant factor approximation algorithm is proposed by using graph coloring method to solve the problem of CA together with the transmission scheduling of the path. The route discovery procedure for a distributed protocol based on dynamic source routing, rout selection, channel allocation and time slotting is proposed to meet end-to-end bandwidth requirements in (Hincapie, Jian et al. 2008).

A heuristic channel aware routing algorithm is proposed by (Mumey, Jian et al. 2012) to find the best routing path and channel assignment and maximize the end-to-end throughput. A heuristic methods and convex nonlinear optimization model are proposed to solve the joint problem of channel capacity assignment and flow assignment (Ramamurthi, Reaz et al. 2011). In (Yong, Pongaliur et al. 2013), the Adaptive Dynamic Channel Allocation (ADCA) and Interference and Congestion Aware Routing (ICAR) protocols are developed. In ADCA they consider the optimization method for both throughput and delay. In ICAR protocol the static and dynamic links are balanced for channel utilization in the network.

The probabilistic estimation is proposed to ensure channel availability for each node and performing routing management in the network (Nejatian, Syed-Yusof et al. 2013), (Nejatian, K. et al. 2012). In order to minimize end-to-end packet delay the optimal dynamic programming algorithm was proposed for CA and path selection without consideration of interference (Almasaeid, Jawadwala et al. 2010). The algorithms proposed for traditional WMNs with homogeneous channels cannot be applied in CR-WMN due to channel heterogeneity.

In this study, the objective is to develop an analytical model for End-to-end path. End-to-end path existence was obtained from probabilistic estimation in which the CA problem and the routing path were jointly considered. Interference, node and link characteristics are included that guarantees end-to-end delay minimization and throughput maximization, which has not been explored by the literature.

3. Network Model and User Activities

The CR-WMN comprise of Mesh Router (MR), Mesh Gateway (MG), and Mesh Clint (MC). The MCs, MRs and MGs have CR enabled features, and use common control channels (CCC) to communicate with each other. The total number of heterogeneous channels are *C+1* in the network, in which one of them is used as the CCC. According to channel heterogeneity, they are further defined under three terminologies which are the same as those mentioned in (Nejatian, Syed-Yusof et al. 2013) (Nejatian, Syed-Yusof et al. 2014), where *T* used as set of channels based on different transmission ranges, $T = \{T_1, \ldots, T_L\}$. The set of each type can be shown by T_l in which $l = \{1, 2, \ldots, L\}$, $|T_l| = C_l$, and $C = C_1 + \ldots + C_L$. Any SU can detect any of these *C* channels at any position in the network. The number of available channels of type T_l detected by an individual node is c_l. It means that the total number of available and detected channels at a node is $c = c_1 + c_2 + \ldots + c_L$. The transmission range of channels of type T_l is R_l.

Onward the word node is used for MC, MR and MG. The CRWMN is modeled as an unidirectional graph using graph theory $G = (V, E)$ where *V* is the vertices representing a set of nodes and *E* is the edges and represents a set of wireless links. Suppose $s_v = \{n_1 = S, n_2, \ldots, n_i, \ldots, n_n = D\}$ be the sequence of *n* vertices and $s_e = \{e_1, e_2, \ldots, e_i, \ldots, e_{n-1}\}$ the sequence of *n-1* edges composes path (*S*, *D*) (Fig.1).

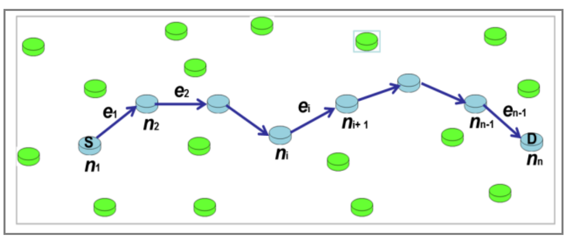

Figure 1. Representation of nodes and hops in graph theory

The fact that the graph is complete does not mean that all nodes are mutually within transmission range of each other. Links and nodes will be divided into two different categories. The two categories are defined as: State *A* (Active state) and State *D* (De-active). To be in an active state at least one channel is available at the node n_i and an de-active state means there is no channel available at the node n_i. Similarly, an edge in *E* is in the state *A* when its end point vertices are within transmission range of each other independently of the states in which they are; otherwise, the edge is said to be in state *D*. A path *(SD)* is defined as a sequence of *n-1* undirected links from a source node *S* to a destination node *D*. A path exists when all its links are in state *A*.

3.1. Node Characteristics

In this section, the node characteristics are explained. Consider an established route from the source node S to the destination node *D* (Figure 1). Using graph theory the probability p_n can be defined as:

$$p_n = P_A(n_i, t) \quad (1)$$

where P_A is the probability that node *i* (vertex) at a given instant is an active state, i.e. PU is not using the spectrum and it can be available to the SU. Consequently the probability p_{nn} of an immediate neighbouring node will be

$$p_{nn} = P_A(n_{i+1}, t) \quad (2)$$

3.2. Link Existence Characteristics

However the condition of link existence between two nodes cannot be achieved unless they have at least one common channel between them. With the condition that the common channel is within the transmission range of two nodes. Therefore, the probability that a common channel is available and in the transmission range consecutive nodes as:

$$p_e = P_A(e_i, t) \quad (3)$$

The link between two nodes will exist when the two nodes will be in an active state and have at least one channel common between them with the condition that the common channel is within the transmission range of these two nodes, therefore, the link existence probability is defined as follows:

$$P_E(e_i, t) = P_A(n_i, t).\ P_A(n_{i+1}, t).P_A(e_i, t) \quad (4)$$

where P_E is the probability that a link exists between two nodes on edge e, at a given time *t.*

4. Analytical Model

End-to-end delay and throughput is the key QoS metrics used to evaluate the overall performance of CR-WMNs. This study will investigate important performance metrics by modeling PU activity, channel heterogeneity and node characteristics in which the each node analyze the hop and end-to-end path in the network. The PU activity and node characteristic is computed for each node, each hop existence and for end-to-end path existence.

The probability of PU as P_{on} and in the interference boundary it can be assumed from the interference temperature model (ITM). To calculate PU in the interference boundary, the spatial distribution of mobile nodes as a Poisson variable with density λ (Ting-Chao and Li 1986). Thus,

P_r(There are k nodes in a region with disc area S) $= \frac{\lambda S^k \exp(-\lambda S)}{k!}, k = 0, 1, 2, 3, \ldots$ (5)

As defined in (Nejatian, K. et al. 2012), the single channel is unavailability at a SU node is depends on the activity of the PU. Many traffic models for the activity of the PU can be applied. Here, an alternating renewal two state birth-death process with a death rate α and birth rate β is considered to model the activity of the PU. The arrival time of each user is independent, so the transmission time of each user is considered as a Poisson arrival process. Therefore, the length of the off and on period has an exponential distribution with means of $\frac{1}{\alpha}$ and $\frac{1}{\beta}$, respectively. Consequently, the activity of the PU can be stated as follows:

$$P_{on} = \frac{\beta}{\alpha+\beta} \text{ and } P_{off} = \frac{\alpha}{\alpha+\beta}$$

The probability that PU is within the interference boundary within a disc S with one node in range can be obtained by dividing the interfering area by total disc area as:

$$\frac{\pi r_l^2 - \pi R_l^2}{\pi r_l^2}$$

$$P' = P(P_{on} \cap PU\ is\ in\ interference\ boundary\ IB) \quad (6)$$

Substituting the expression of above two,

$$P' = \frac{\beta}{\alpha+\beta} X \lambda \pi r_l^2 \exp(-\lambda r_l^2)\, X\, (\frac{\pi r_l^2 - \pi R_l^2}{\pi r_l^2}) \quad (7)$$

since PU is on this channel is not available to SU. The probability of a channel being available to a SU in a single node can be calculated as:

$$P_{CHA} = (1 - P') \quad (8)$$

4.1. Node Characteristics of CR-WMN

Another important parameter is defined as the mesh node characteristic in which the effects of node will be analysed. In a wireless mesh, three types of nodes communicate with each other which are as follows: Mesh Client, Mesh Router, and Mesh Gateway. Each type can be described with different characteristics and behavior, for example, sometimes they work as an intermediate node. The communication between a source node and a destination node is via intermediary nodes, and because of node characteristics degradation occurs. Consider three communicating nodes n_1, n_2, n_3. In this case because n_2 acts as intermediate node and has to send packets in both directions and if it is mesh router then the transmission buffer is shared by other SUs then n_2 has a relatively lower packet-transmission opportunity and that packet build up and transmission-buffer overflow can occur resulting in significantly degraded throughput characteristics and an increased delay time. This means that the node characteristics must be considered in CA and JPCA in order to achieve QoS.

When n_2 received packets at transmission rate (A_{tr}) from n_1 and sends packets to n_3 at transmission rate (S_{tr}), then following condition must be staisfiied:

$$A_{tr} \leq S_{tr}$$

Therefore each node in system must have a defined sending transmission rate S_{tr} as a node characteristic so that before making the CS and JPCA a higher weighting is given to the higher S_{tr} path.

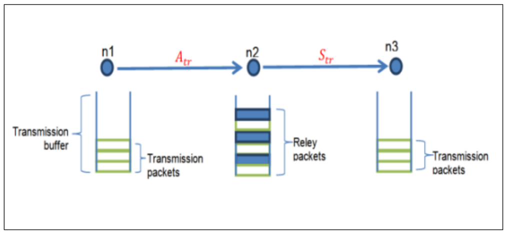

Figure 2. Packet arrivals at intermediate nodes

To model the number of packets arriving at each node as a M/M/1 queue (Zhang 2013). It is assumed that the node is in state *i* when any intermediate node, i.e any node between two hops. When a new packet is arriving at the node, the node changes from state *i* to *i+1*, or after a packet is sent from intermediate node, the node changes its state from *i* to *i-1*. The node is in an equilibrium state when it is in state *i* and the probability does not vary as time elapses in this state. Assume that P_i is the probability of a given state *i*, and A_{Ar} is the average arrival rate. The term A_{Ar}, P_i used to describe the number of changes per unit time during the time when system changes its state from i to *i+1* on average. The rate of change in the average from state *i* to state *i-1* is $\frac{P_i}{A_{st}}$, where A_{st} is the average service time for node in state *i*. In dynamic equilibrium, the average rate of packets arriving at the node in state *i* must be equal to the average rate of packets being transmitted from this node, thus by analogy, P_i can be obtained as:

$$P_i = P_0 \prod_{k=0}^{i-1} (A_{Ark})(A_{st(k+1)}) \ldots i = 1,2,\ldots \quad (9)$$

since total probability is equal to unity,

$$\sum_{i=0}^{\infty} P_i = 1$$

Using graph theory the probability p can be defined as:

$$p_n = P_A(n_i, t) = P_A((1 - P') \times P_i, t) \quad (10)$$

where P_A is the probability that node i (vertex) at a given instant it is an active state, i.e. PU is not using the spectrum and it can be available to the SU. Consequently the probability of an immediate neighboring node will be

$$p_{i+1} = P_A(n_{i+1}, t)$$

4.2. Link existence and Channel condition

The channel heterogeneity and mobility of the SU based on probability of channel availability must also be considered. In a heterogeneous network, each channel has different channel transmission ranges. When the SU nodes are assumed to be fixed and PU nodes are mobile, different channels will have different transmission ranges. A channel with a lower frequency range needs lower transmission power. Thus, in a heterogeneous network with different channel transmission ranges, the distance between the SUs will affect the probability of channel availability.

However, the condition of link existence between two nodes will not be achieved unless it is considered that two consecutive nodes have at least one common channel between them with the condition that the common channel transmission range must be higher than the hop length, if $d_{SU1,SU2}$ is the distance between two SU nodes. $R_{l,c1,SU1}$, $R_{l,c1,SU2}$ is the transmission range of channel type l and c is the common channel SU1 and SU2 respectfully, then the following condition must be satisfied:

$$R_{l,c1,SU1} > d_{SU1,SU2} \text{ and } d_{SU1,SU2} < R_{l,c1,SU2}$$

Suppose that r is the total number of routes, and n is the total number nodes in each of the routes, which means $n-1$ hops are in each of the routes. The probability of channel availability within two hops depends on the distance between the nodes, R_l defined as transmission range of channel type l. Assuming four types of channel of R_1, R_2, R_3, R_4.

$$R_1 < R_2 < R_3 < R_4$$

If the first hop distance is $d_{h_1} \leq R_1$, then the channel type is $c_1 \in R_1$ and if $R_1 < d_{h_1} < R_2$ then the channel type is $c_2 \in R_2$ available for selection. There are *N* hops in the route with distance d where $R_l - 1 < d < R_l$, such that hop = *h*, *(h=1, 2,3,..).*

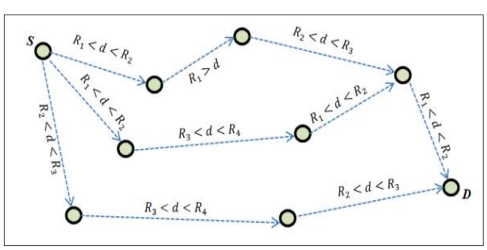

Figure 3. Channel heterogeneity based characteristics

If the first hop is using c_1 channels and the next hop last node is in interference of an intermediate node then second hop last node can't use the c_1 channel.

$$d_{n2,n3} < r_{ln2}$$

The R_l is defined as the channel transmission range without interference and r_l as the channel transmission range with interference. The r_{li} *and* r_{lj} represent the first hop two nodes *i* and *j*.

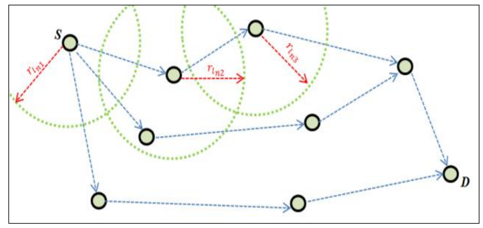

Figure 4. Two hops for the interference avoidance model

Distance $d_{ij} < r_{li}$ and $R_l > d_{ij}$. R_{li}^k is the transmission power range of node *i* on channel *c* such that $R_{li}^k \leq R_{lj}^{max}$ and $R_{li}^k \leq R_{li}^{max}$. R_{li}^{max} and R_{lj}^{max} are the maximum transmission power range of node *i* and an node *j* respectively.

$$\rho_{ij}^k R_{li}^{max} \geq th_r$$

th_r is the minimum power required for connectivity and ρ_{ij}^k is the channel power gain.

Therefore, the probability that a common channel is available and in the transmission range of consecutive nodes as $p_e = P_A(e_i, t)$.

Therefore,

$$p_e = p(t_r) \cap p(C_c) \quad (11)$$

Where $p(C_c)$ is the probability that a common channel is available and $p(t_r)$ is the probability that the transmission range of a common channel covers the distance between two consecutive nodes at a given instant, *t*. Thus,

$$p(t_r) = p(d_{n_i n_{i+1}} < t_r) \quad (12)$$

Considering disk area of each node transmission range, the area of intersection of two disks will be the area of interference. The common channels existence in this area as *CCE*. The total number of channels available as TCA. Thus the probability of having common channels ($p(C_c)$) can be calculated as follows:

$$p(C_c) = \frac{CCE}{TCA} \quad (13)$$

Computing $p_e = p(t_r) \cap p(C_c)$

$$p_e = p(t_r) \times p(C_c) = p(d_{n_i n_{i+1}} < t_r) \times \frac{CCE}{TCA} \quad (14)$$

The link between two nodes will exist when the two nodes are active and at least one channel is in common between them with the condition that the common channel is within the transmission range of these two nodes, therefore, The link existence probability as follows:

$$P_E(e_i, t) = P_A(n_i, t).\, P_A(n_{i+1}, t).\, P_A(e_i, t)$$

Substituting the probability of consecutive nodes and the respective edge, at a given time, *t* we obtain:

$$P_E(e_i, t) = \left[\left((1 - \left(\frac{\beta}{\alpha+\beta} \times \lambda\pi r_l^2 \exp(-\lambda r_l^2) \times \left(\frac{\pi r_l^2 - \pi R_l^2}{\pi r_l^2}\right)\right)) \times P_0 \prod_{k=0}^{i-1} (A_{Ark})(A_{st(k+1)})\right)^2 \times p(t_r/C_c) \times p(t_r)\right] \quad (15)$$

Where P_E is the probability that a link exists between two nodes on edge *e*, at a given time *t*. Equation 15 gives the analytical model for *OHNCA*.

4.3. End-to-end Path Existence

The probability of the existence of the path from a source node *S* to a destination node *D* at time t is the problem of *EECPS* as defined in the introduction section. The edge probability of source to destination includes all the edges in each link and all the links that exist in the path under consideration. Thus, the end to end path existence probability is obtained as:

$$P_E\big(path(SD)\big) = \prod_{n_i \in s_v} P_A(n_i, t) \prod_{e_i \in s_e} P_A(e_i, t) \quad (16)$$

To find the optimal path between the source and destination which is the one with the greatest probability of existence among all possible paths. Suppose that the $T_{(SD)}$ be the set of all possible paths from source node S to destination node *D*. The optimum path from source node *S* to destination node *D* with the greatest existence probability is then given by:

$$T_{opt(SD)} = Arg \max_{T \in T_{(SD)}} P_E(T) \quad (17)$$

and, consequently

$$T_{opt(SD)} = Arg \max_{T \in T_{(SD)}} ln P_E(T) \quad (18)$$

Incorporating Eq. (16) in Eq. (18):

$$T_{opt(SD)} = Arg \max_{T \in T_{(SD)}} \left(ln\left(\prod_{n_i \in T} P_A(n_i, t) \prod_{e_i \in T} P_A(e_i, t) \right) \right) \quad (19)$$

That leads to:

$$T_{opt(SD)} = Arg \min_{T \in T_{(SD)}} \left(\sum_{n_i \in T} -ln\, P_A(n_i, t) + \sum_{e_i \in T} -ln\, P_A(e_i, t) \right) \quad (20)$$

5. Simulation Results and discussion

In the first phase the effects of probability P_i is investigated considering P' as a constant. The P' values are simulated for three different end-to-end path probabilities. Two paths consist of eight nodes (as shown by red and blue lines) and one path consist of seven nodes (depicted by the green line on the graphs). Figure 5 expresses the effects of the probability of state *i* on the End-to-end path nodes in CR-WMN. Meanwhile, Figure 6 shows the effects of P' with other parameters being constant. Based on these figures, The P' and P_i probabilities are investigated throughout the paths using graph theory. In the second phase, the effects each node characteristics has on end-to-end path in Figure 7 using the computational results of equation 8.

Figure 8 shows the end-to-end path existence probability that is computed through numerical results for each available path in the network. The results show that the most optimum path is observed to be path 1, shown by the red line because the end to end path existence probability is higher when compared to other two paths. In this case, two of the considered paths consist of seven edges (as shown by red and blue lines) and one path consists of six edges (depicted by the green line on the graphs).

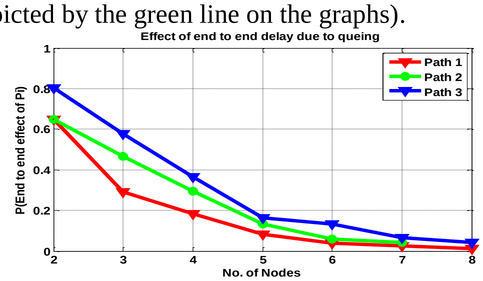

Figure 5. The effects of P_i on the End-to-end nodes

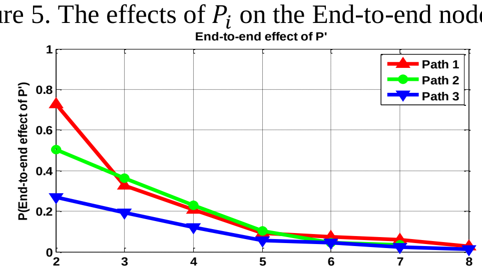

Figure 6. The effects of P' on the End-to-end nodes

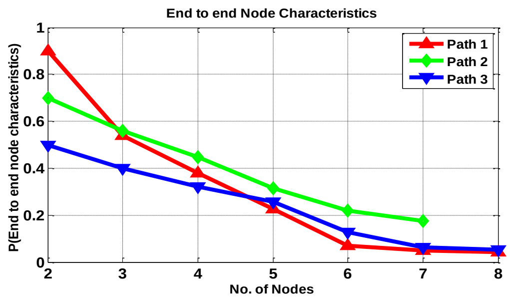

Figure 7. The effects node characteristic

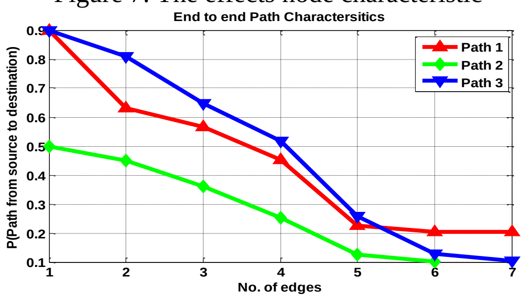

Figure 8. The End-to-end routing path

The results show that the analytical model derived in this paper in equation 16 provides best end to end path selection criteria.

6. Conclusion

CR-WMNs provide an effective way to allow secondary users to use the unutilized spectrum. In CR-WMNs, the problem is how the availability of vacant channel can be effectively utilized. In this paper, the analytical model is developed for node selection, end-to-end channels and path assignment. The problem is resolved in two steps. first solve the problem of *Single hop node and channel assignment (SHNCA)* and then address the problem of *end-to end path and channel assignment (EECPA).* The numerical analysis of the analytical model is provided at the end, which shows that the most suitable end to end path and channel may be selected using the proposed end to end path and channel existence probability model.

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