

# Performance Modelling and Analysis of the Delay Aware Routing Metric in Cognitive Radio Ad Hoc Networks

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**Abstract** - Cognitive Radio Networks have been proposed to solve the problem of overcrowded unlicensed spectrum by using the cognitive ability built in software radios to utilise the underutilised licensed channel when the licensed users are not using it. Successful results from the research community have led to its application to wireless technologies like Ad Hoc networks due to their extensive advantages. Cognitive Radio Ad Hoc networks are a novel technology that will provide a solution to many communication challenges. This paper investigates the end-to-end performance modelling of a link using quality of service parameters; delay vs. link capacity while considering the factors of spectrum management and node mobility of two nodes in tandem representing a hop in Cognitive Radio Ad Hoc networks. We modelled spectrum management and node mobility using the pre-emptive resume priority M/G/1 queuing model and the gated node model respectively. We considered delay aware routing schemes; shortest queue and random probability routing and compared them with the analytical link-capacity for analysis. The study shows that already existing mathematical models can be used as close approximations to analyse the queuing models proposed for Cognitive Radio Ad Hoc Networks.

**Index Terms**—MANET, Cognitive, CRAHN, Routing.

## I. INTRODUCTION

Over the recent years, the significant advancements in technology have led to the overcrowding in the ISM band. Wireless applications like mesh networks, MANETs and WSN have had tremendous success due to their applicability in different areas. Due to the applicability and success of MANETs, vigorous research that has seen MANETs be able to support different platforms of wireless technology [10]. This growth has led to limited spectral resources for the wireless networks. This problem is being solved with the notion of dynamic spectrum access after a study showed that the utilization of the licensed spectrum was between 85% and 15% [7] unlike the overcrowded unlicensed spectrum.

Under the dynamic spectrum access system, unlicensed users (secondary users) are be allowed to opportunistically use the licensed spectrum without interfering with the licensed user (Primary users) activities which became possible with the advancement

of software defined radios (SDR) [13] and thus the development of cognitive radios (CR). These radios have the ability to reconfigure their physical layer which is defined by software to parameters as required by the spectral environment around the radio to define Cognitive Radio Networks. With this technology applied to ad hoc networks, Cognitive radio ad hoc networks (CRAHNs) are now a new emerging area of interest in the research community. With the defined characteristic of CR and MANETs, CRAHNs present new design challenges that affect the dynamic spectrum access techniques and the routing schemes developed to support CRAHNs. Dynamic Spectrum access has been extensively studied under CR networks. Different routing schemes for CRAHNs have been proposed based on different algorithms and QoS parameters [17,22,15,10]. Each QoS parameter introduces new challenges to the suggested routing schemes and routing protocols which enable high performance in networks based on the metrics considered when designing the algorithm.

We present this paper on Performance modeling and analysis of Delay Ware Routing metric in CRAHN, where existing mathematical models are used with a few approximations as building blocks for analysis of Cognitive Radio Ad Hoc Networks.

## II. BACKGROUND

*Cognitive Radio Ad Hoc Networks (CRAHN):*

CRAHNs can best be described by the two technologies that define the network;

*Mobile Ad-Hoc Networks (MANETs)*

Mobile Ad hoc Networks were introduced more than two decades ago to increase the efficiency and application of mobile wireless networks by adding the routing ability in mobile nodes. The wireless nodes can perform as routers therefore becoming self-organising in order to route packets from one node to another without need for a fixed structure [19] and since they are always moving randomly, their arbitrary connections produce very dynamic and unpredictable topologies. In these topologies, an end to end transmission can easily be completed by different routes which provide different power and quality of service. The route chosen should always meet the user requirements.

*Advantages of MANETS*

- There is a reduced cost required for their set up since they don't require infrastructure.
- They can be set up in any environment and situation without the worry of a Base station requirement.

- The network's mobility depends on the movement structure of the network nodes and their transmission ranges and is not geographically limited as is the case of fixed networks.

#### Limitations of MANETS

The challenges include but are not limited to [13,19];

- MANETS have unpredictable and dynamic.
- There is the constraint of nodal energy since the nodes are mobile devices which operate on battery.
- MANETS operate in the wireless network spectrum band (ISM) which is quite crowded and very limited.
- It also faces interference from domestic appliances like the microwave making the technology interference prone.
- The networks quite insecure due to their lack of centralised monitoring and the fact that the routing protocols operate on the principle of mutual trust.

The limitations of MANETS have been the focus of the research community because they define QOS constraints which must be optimised in order to have a high performance network [3].

#### MANET routing

MANET routing is charged with find and maintain optimum routes in the dynamic network topology and ensuring the best QOS level is maintained. [3]. Based on the limitations described above, the QOS level is defined by the constraints:

- Limited bandwidth
- Limited energy resources
- Lack of physical security

#### Cognitive Radio Networks (CRN)

A cognitive radio is a radio that changes its transmission parameters based on its experience with its operative environment [10].

#### Characteristics of CRNs

The cognitive radio network has the following characteristics [10,17,18,20,22,24];

- It is always aware of its spectral environment so that PU interference is avoided and the optimum route is used.
- It has the ability to reconfigure its physical layer independently to work in the variance spectrum bands as and when required based on its experience and the statistics collected.
- It is able to perform the cognitive cycle strategies efficiently.

#### Cognitive Cycle/ Spectrum Management

CR networks are assumed to function without any information from the primary network therefore all the network actions depend on the radio observations by the SUs [10]. The most crucial requirement in cognitive systems is spectrum management. The cognitive cycle first coined by Dr. Joseph Mitola III in 2002 [24] describes how the nodes intelligently adapt to the changes in the environment and have reliable transmission.

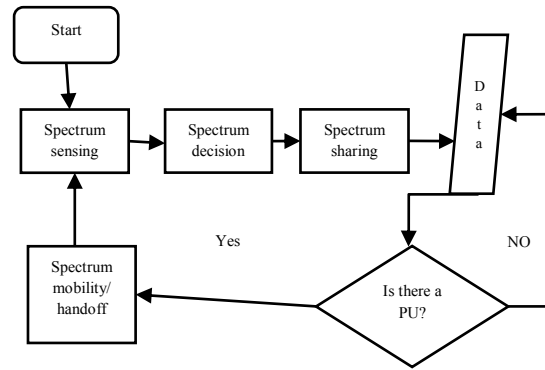


Fig 1. The Simplified Cognitive Cycle

The main principle is that the SU will keep sensing the environment radio parameters (Spectrum Sensing), choose the spectrum hole [1,10] and perform reconfiguration based on the detailed analysis of the measured parameters and cooperation from other users (Spectrum Sharing) [20,24]. The spectrum chosen (Spectrum Decision) should enable the setup of reliable communication routes (Spectrum Mobility/Handoff) which depends on the parameters that the SU observes from the radio environment and the signalling received from other users. The devices are programmed to switch to different Spectrum holes based on the calculated link parameters. Once the handoff is done, the node parameters might need to be reconfigured due to the difference in the band characteristics [11,12].

#### Cognitive Routing

Cognitive routing is the process of understanding the network's current conditions, planning, learning and acting on them in order to achieve network efficiency [18, 17]. The algorithms used in the cognitive routing protocols must be aware of the dynamic variable spectrum characteristics and be able to adapt their operation to them and also be able to choose and use the optimum route with the lowest interference in the discovered spectrum holes [16].

In [17], it is shown that there are 3 main challenges that need to be overcome in any routing protocol put forward for CR networks; 1) "Spectrum awareness", 2) "Set-up of quality routes in the dynamic variable environment" and 3) "Route maintenance/ reparation" These challenges are used to group the already suggested routing schemes detailed in [17]. The main interest of this work is the delay based and Link quality based routing schemes.

#### Delay Based Routing metric:

Delay on a route can be used to determine its connection quality and therefore can be used in building and maintaining efficient and fast multi hop routes. The different delay components in a CR node are further identified and defined in [17] as:

- The *Queueing Delay* defined by the throughput capacity of the node over the frequency band in use.
- The *Switching delay* defined by the time taken for a node to switch from one frequency to another band.
- The *Medium access Delay* based on the MAC access schemes defined in a frequency band.

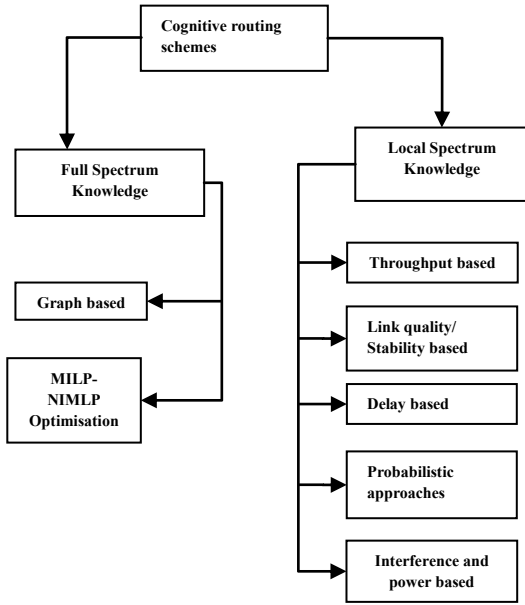


Fig 2. Classification of cognitive routing schemes [17]

#### Link Quality Based Routing Metric

CRN channel availability is affected by PU presence and the number of SUs contending for the band. This leads to the need to know the traffic on a spectrum band before a node can switch to that frequency and the factor that once a band is chosen, the usability of that band is time constrained. This is why in the QOS routing metric proposed in [22], the frequency bands are defined by:

$F_v = \{b_m, d_m, r_m\}$  where

$F_v$  is the frequency band,  $b_m$  is the bandwidth,  $r_m$  is the transmission range,  $d_m$  is the available time

These three variables are used to compute the link quality parameters.

### III. NETWORK DESIGN:

The proposed model to implement the routing in CRAHNs is designed based on the two concepts that form the technology and a hop design.

1. Spectrum management modeled by a two class priority queue with a single server.
2. Ad Hoc mobility which is modeled by the gated node
3. A Hop in the network is modeled using nodes in Tandem model.

#### Model Input Distributions:

The arrival process and inter service-time process is defined by the General Exponential distribution algorithm that can also be used to generate the exponential distribution.

The generalised exponential distribution [6] is an inter-event distribution that is defined by the cumulative probability function:

$$F(t) = 1 - a e^{-avt} \quad (1)$$

$$\text{Where } a = \frac{2}{(C^2+1)}, \quad (2)$$

$t$  is the random variable of inter-event distribution,  $\frac{1}{v}$  is the mean and  $C^2$  is the squared coefficient of variation (SCV). SCV is defined by

$$SCV = \frac{\text{Var}(t)}{E(t)^2} \quad (3)$$

The use of the GE distribution ensures least bias due to the distribution's two moments [24]. The method used to generate the input distribution is further described in [14].

#### Spectrum management Model:

CRN which defines Spectrum management in the routing scheme is designed by using the models proposed in [21] and [4]. The two schemes are compared for one with better performance parameters. Both the models have the server as the channel with two classes with primary users having a higher priority and secondary users having a low priority. The models have two main schemes [4];

- “Always Stay” Model where when the SU once pre-empted by the PU goes back to the queue to await service in the same channel.
- “Always Leave” model where when the SU leaves the channel and joins the queue of another channel once pre-empted by the PU.

In this study, only one model with the two options is adopted.

The “Always Stay” Model is evaluated with both the case of EOL and HOL resume service options. Modeling of the Cognitive node with spectrum handoff modeled as an M/M/1/ PRP- HOL system as proposed in [21, 4] with 2 classes where only one stream for each class is considered.

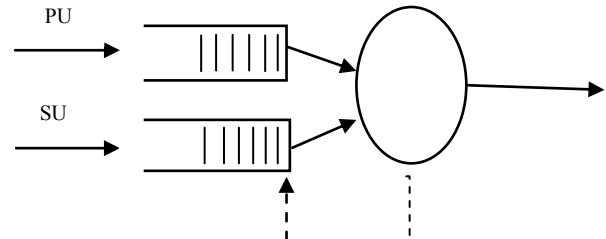


Fig 3. The M<sub>2</sub>/M<sub>2</sub>/1/ PRP- HOL Queue representing Spectrum handoff

In this model, when a PU is in service and a SU job arrives, the job continues to be serviced until it is finished. However, when a SU is in service and the PU job arrives, the SU is pre-empted out of the channel and directed to the Head of Line (HOL) with the time remaining for service save until the channel is empty then it can continue service. Modeling of the Cognitive node with spectrum handoff modeled as an M/M/1/ PRP- EOL system as proposed in [4] with 2 classes.

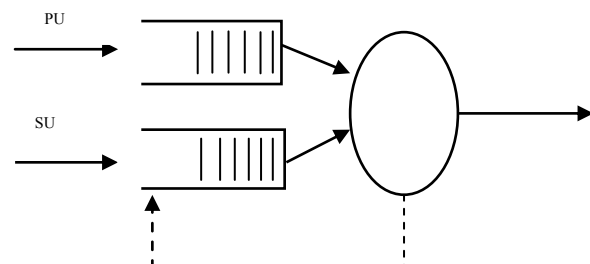


Fig 4. The M<sub>2</sub>/M<sub>2</sub>/1/ PRP- EOL Queue representing Spectrum handoff

In this model, when a PU is in service and a SU job arrives, the job continues to be serviced until it is finished. However, when a SU is in service and the PU job arrives, the SU is pre-empted out of the channel and directed to the End of Line (EOL) with the time remaining for service to wait for service after all the jobs ahead have finished service. Using the Maximum Entropy method adopted from [5], the 2 class Mean Queue length  $L_i$  of the network model can be closely approximated to:

$$L_i = \rho_i + \left[ \frac{\rho_i}{2(1-\gamma_i)} \right] (C_{ai}^2 - 1) + \gamma_i'(\alpha_i + \beta_i) \quad (4)$$

For HOL,  $i=1,2$  (The number of classes in the order of priority).

Where

$\rho_i$  is the server utilization of the class,

$C_{ai}^2$  is the square co-efficient of variation of the class input,

$C_{si}^2$  is the square co-efficient of variation of the class service.

$$\gamma_0 = 0,$$

$$\gamma_i = \sum_{k=1}^j \rho_k, \quad j=1 \text{ and } 2.$$

$$\gamma_i' = (2(1-\gamma_{i-1})(1-\gamma_i))^{-1}, \quad i=1, 2$$

$$\alpha_i = \rho_i^2 (C_{si}^2 + 1) + \sum_{j=1}^{i-1} \left[ \frac{\lambda_j}{\lambda_j} \rho_j^2 (C_{si}^2 + C_{ai}^2) \right]$$

for  $i=2$ .

$$\alpha_i = \rho_i^2 (C_{si}^2 + 1) \quad \text{for } i=1.$$

$$\beta_i = 0 \quad \text{for } i=2$$

$$\beta_i = \sum_{j=i+1}^2 \left[ \frac{\lambda_j}{\lambda_j} \rho_j^2 (C_{si}^2 + C_{ai}^2) \right], \quad \text{for } i=1.$$

Once the Mean Queue length is obtained, using Little's law, the Mean Queue Delay can be obtained from

$$W_i = L_i / \lambda_i \quad (5)$$

The equations above are used to approximate the theoretical Queue length to compare with the results obtained from the simulation.

#### Ad Hoc Mobility model

In order to model mobility in Ad hoc networks, the channel is represented as a gated node [9] with time variation of being ON when a required node is in range and OFF when the node is out of range. The node is first built as a class for validation. In this model, only one flow is considered and a FCFS method is considered in the evaluation.

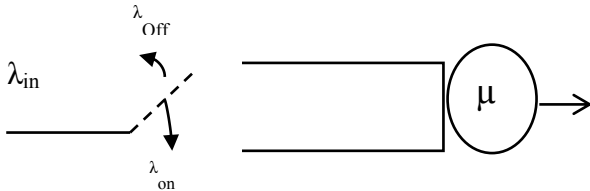


Fig 5. A gated Single server Queue

Using the model above, the queuing model M/M/1 is modelled by Poisson inter-arrival rate  $\lambda_{in}$  and inter-service time  $\mu$ . The gate is scheduled by the exponential ON and OFF period where the ON is scheduled by a rate  $\lambda_{ON}$  and variance  $V_{ON}$ , and the OFF is scheduled by rate  $\lambda_{OFF}$  and variance  $V_{OFF}$ .

The effective input at a node is then [9],

$$\lambda' = \frac{\lambda_{OFF}}{\lambda_{OFF} + \lambda_{ON}} * \lambda_{in} \quad (6)$$

if a queue model where the arrival and service process defined by the GE distribution is considered then the effective arrival SCV at a node is given by;

$$C'^2 = C^2 + \left\{ \left( \frac{\lambda_{ON} * (V_{ON} * \lambda^2_{ON} + V_{OFF} * \lambda^2_{OFF})}{(\lambda_{OFF} + \lambda_{ON})^2} \right) * \lambda_{in} \right\} \quad (7)$$

where  $C^2$  is the squared coefficient of variation of the channel.

The server utilisation of a node is defined by ;

$$\rho = \lambda' * \mu \quad (8)$$

The performance measures are defined as;

$$\text{Mean Queue Delay } W = \frac{1}{\mu(1-\rho)} \quad (9)$$

$$\text{Mean Queue Length } L = \frac{\lambda'}{\mu(1-\rho)} \quad (10)$$

The analytical formulae are programmed using java for the verification of the model built.

#### Relay Nodes Model

To understand the delay routing metric in the network, 3 nodes each modelled as M/M/1/ PRP- HOL are connected in tandem. The analysis of the performance is to get the end to end delay on 2 link connection for an SU packet while the channel utilisation is kept to maximum. Two simulations, one using Random routing and another modelled as the forward-to – the shortest queue model are compared.

Random Probability branching was chosen because all occurrences in a network can be described using a probability distribution and is thus easier to define while shortest queue method was chosen because it's a phenomenon that follows human behaviour and logic where a job will join a queue that has fewer jobs no matter the service rate of the server. The probability matrix is defined by 0.5 chance of the connection using either channel.

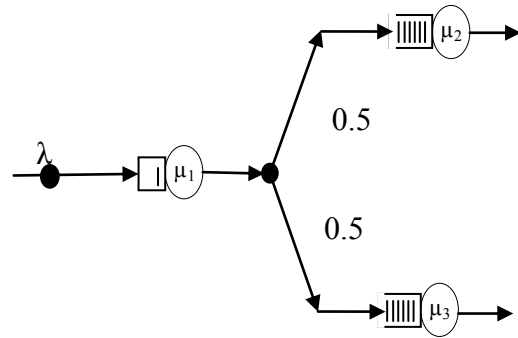


Fig 6. The OQNW of the Queues in Tandem using random routing

Using the Open Queuing NetWorks [2], the Network is split into three nodes and analysed differently to verify the performance of the network.

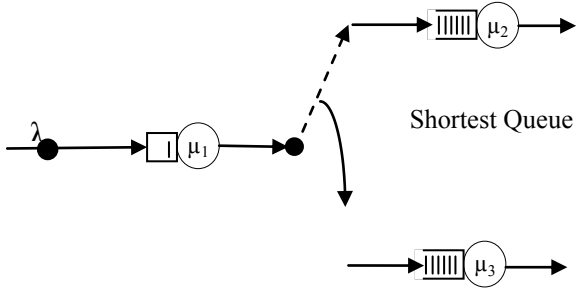


Fig 7. The OQNW using the shortest queue node access

#### CRAHN Queuing Model

In order to model the CRAHN network as a tandem, there are some assumptions made in this study:

- The SU can only access one channel that they share with the PU. The unlicensed channel is not considered.
- When the SU is pre-empted out of the channel, it waits HOL until the PU is finished. This might not be realistic but this assumption makes the model less complex.
- The model assumes there are no signalling packets in the network so the nodes act as relays in the network.
- The ME solution is used as an approximation to analyse each node, the gated node method is introduced for mobility and to make the model less complex.
- The channel utilisation is kept to the maximum value in order to support the assumption of gated nodes and HOL approximation in the queuing models.
- Both the SU and the PU are stationary.

Using the models already explained above, the model proposed is for analysing connection between two links that represent the end to end delay

#### IV. PERFORMANCE EVALUATION.

In this evaluation of the models used, the simulations are tested and validated by comparing their results against the results got from the mathematical analytical formulae as detailed in the sections above. The models are checked for adequacy in their approximations to the analytical results. In building the simulation, the program of choice was java using the NetBeans IDE 6.9.1 since the environment is available as an open source and has been the IDE of choice during the course study. Event driven simulation is used to build the models[14].

##### Spectrum Handoff Single Channel

The node was modelled using the  $GE_2/GE_2/1$  / PRP-HOL and  $GE_2/GE_2/1$  / PRP-EOL the queuing models. With the adoption of the “Always Stay” case, the two options were evaluated to ensure that the best case is chosen for the model to be built. The following parameters were used;

Table 1. Spectrum Handoff Simulation Model Input parameters

Service rate (GE - distribution) $\mu$	4
Arrival rate (GE - distribution) $\lambda_{su}$	[0.44, 4]
Arrival rate (GE - distribution) $\lambda_{pu}$	$\lambda_{su}-0.08$
$C_{ai}^2, C_{si}^2$	1

The arrival rates for the two classes were varied but each time equivalent till the maximum utilisation was achieved. The model was to have the input distribution behave with Poisson arrival and departure rates so the Square Coefficient Variation for both the arrival and service process were set to 1.

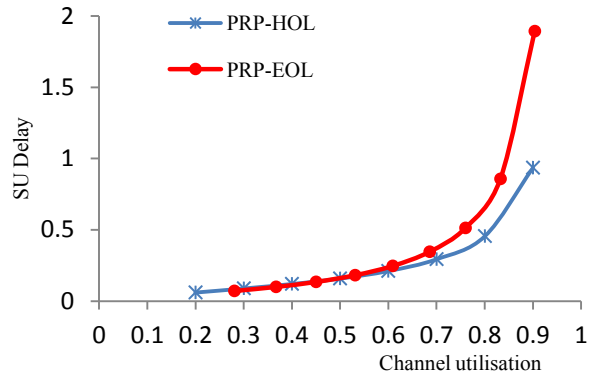


Fig 8. Comparing PRP HOL and PRP EOL

From the above results, it can be clearly observed that as long as the channel utilisation is  $\geq 0.6$ , the  $GE_2/GE_2/1$  / PRP-HOL model gives the better delay results. In this study, the main concern is the delay in the system so the HOL is picked for further analysis in the study. The utilisation of the channels is always kept to a minimum of 0.6 to ensure that the condition of better performance is achieved.

##### Test and Validation of the Model:

Table 2. Spectrum Handoff comparative Model Input parameters

Theoretical input	Service rate $\mu$	4
	Channel utilisation $\rho_{su}$	[0.00,0.11,0.16,0.21,0.26,0.31,0.36,0.41,0.46,0.0]
	Channel utilisation $\rho_{pu}$	[0.00,0.09,0.14,0.19,0.24,0.29,0.34,0.39,0.44,0.0]
	$C_{ai}^2, C_{si}^2$	1
Simulation input	Service rate $\mu$	4
	Arrival rate $\lambda_{su}$	[0.44, 4]
	Arrival rate $\lambda_{pu}$	$\lambda_{su}-0.08$
	$C_{ai}^2, C_{si}^2$	1

In order to test the model, the parameters in Table 2 were used in the theoretical programme using the maximum

entropy method [6,7] to test the simulation. These values were chosen because of the following mathematical analysis:

From the theoretical input:

$$\rho_{su} - \rho_{pu} = 0.02$$

therefore;  $\frac{\lambda_{su}}{\mu} - \frac{\lambda_{pu}}{\mu} = 0.02$  and since  $\mu = 4.0$

$$\lambda_{pu} = \lambda_{su} - 0.08.$$

The results show that as long as the utilisation of the channel is kept  $\geq 0.6$  and above, the Error Tolerance[6] value is  $< 0.1$  which means that the evaluation can be done using the ME solutions. The graph below shows the correlation of the simulated results and the theoretical values from the mathematical analysis

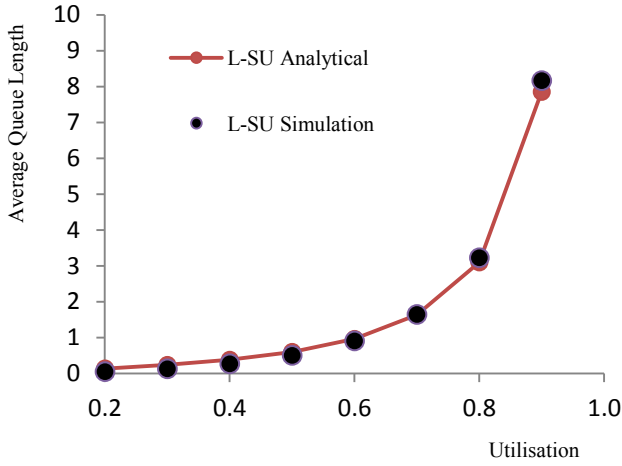


Fig 9. Comparing Simulation results and Analytical results

From the behavior of the graph, the ME method can be used as an approximation for the network since the simulation results exhibit a close relation with the theoretical values.

The channel's capability to have a new arrival from the SU is based on the node load which can be evaluated from the queue size of the SU class. If the node needs the activity of the PU on the channel, it can also be evaluated using the queue length of the PU class on the channel.

These two parameters are of great importance in evaluating the issue of spectrum management in CRN.

#### Mobility of an Ad Hoc node

The node was modelled using the gated node as previously detailed. The simulation was done using the GE/GE/1 model with the following inputs to simulate an M/M/1 model.

Table 3. The gated Node Model Simulation inputs

Service rate (GE - distribution) $\mu$	0.17
Arrival rate (GE - distribution) $\lambda_{in}$	[0.5, 4]
$C_{ai}^2, C_{si}^2$	1
Rate of the link going ON $\lambda_{ON}$	10/9
Rate of the link going OFF $\lambda_{OFF}$	25

#### Test and Validation of the Model

In order to validate that the model is good enough to be used in the simulation of further models, the results from

the simulation were compared against the theoretical results got from the mathematical analysis. The results were further plotted to observe the behaviour of the simulation against that of the analytical.

The graph shows that the simulation output values lie on the theoretical output curve. This shows that the simulation is an adequate model that can be further used for the simulation of the network.

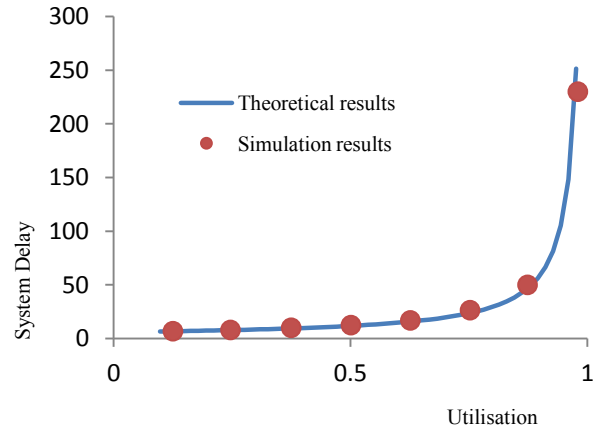


Fig 10. Comparing Simulation results and Analytical results

#### Node Relay Model

Using the network topologies described above, the simulations were written in java using the building block of the spectrum handoff priority class node. Two cases were considered; the random access with equal branch probabilities and the shortest queue access. The simulation and theoretical input parameters are as detailed below;

Table 4. The OQNW Model Simulation inputs

Service rate (GE - distribution) $\mu_1, \mu_2, \mu_3$	5.0, 2.5, 2.5
Arrival rate (GE - distribution) $\lambda_{cu} & \lambda_{pu}$	[1.5, 2.5]
$C_{ai}^2, C_{si}^2$	1
Number of nodes	3
Probability matrix	{0.0, 1.0, 0.0, 0.0}, {0.0, 0.0, 0.5, 0.5}
	{1.0, 0.0, 0.0, 0.0}, {1.0, 0.0, 0.0, 0.0}

In this simulation, the system was considered as a unit where the results obtained were the overall system utilisation, the average system delay for SU and the mean queue length for the SU.

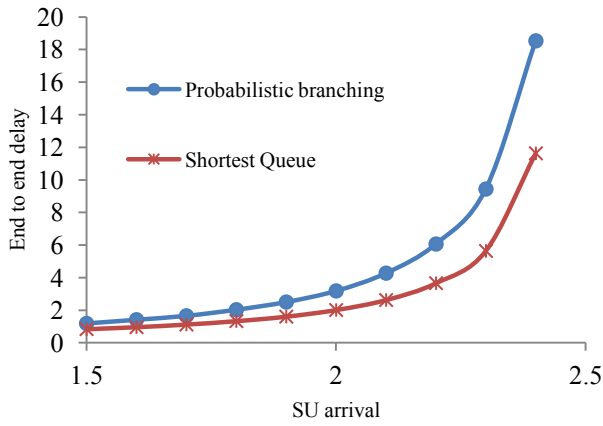


Fig 11. Comparing Probabilistic Branching results and Shortest Queue results.

*Comparative Performance Analysis of the delay-aware model vs. the Link quality aware analytical method.*

In this study, since the assumption is that the PUs and the SUs are stationary, the model was modified to have stationary streams of SU and PU users.

In parameters that were used to evaluate the models are as shown in the table below:

Table 5. Input parameters to compare the models

Parameter	Value
Service rate (GE - distribution)	5.0, 2.5, 2.5
$\mu_1, \mu_2, \mu_3$	
Arrival rate (GE - distribution)	2.6, 2.2
$\lambda_{cu}, \lambda_{pu}$	
$C_{ai}^2, C_{si}^2$	1
Number of nodes	3
Probability matrix	{0.0, 1.0, 0.0, 0.0}, {0.0, 0.0, 0.5, 0.5}
	{1.0, 0.0, 0.0, 0.0}, {1.0, 0.0, 0.0, 0.0}
Number of PU	100
Number of SU	[100- 250]

These parameters were used for all the simulations to ensure uniformity.

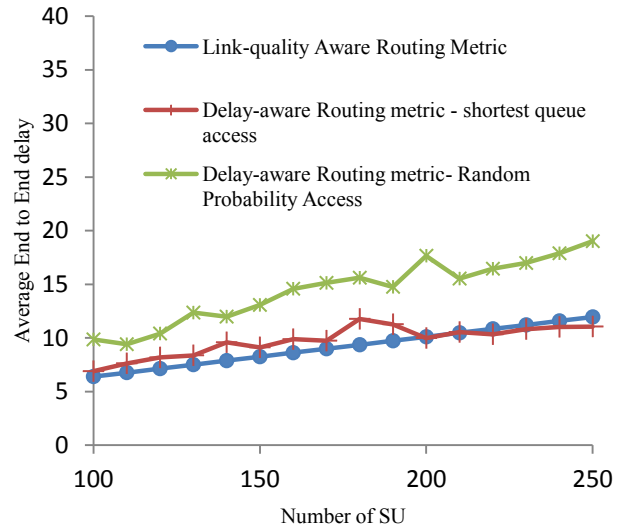


Fig 12. Comparing Probabilistic Branching, Shortest Queue and Link- quality aware routing metric

The graphs show that though both the proposed models following the same positive increase in the delay with increase in the number of SUs in the system, they also show a big deviation in the values of the actual end to end.

The random probability access gives the worst delay results in all the models both the proposed and the link quality aware routing metric.

Although the shortest Queue Access method starts with average delay values higher than those of the link quality aware metric, with increase in the SU after 200 SUs in the system, the delay starts reducing. This shows that delay as a routing metric is important for many SUs because the number of mobile nodes contending for the spectrum become many. The amount of load on the spectrum band heavily affects its effectiveness during transmission and therefore delay at such times is an important factor to consider.

## V. CONCLUSION

During this study, analysis network model for delay – aware routing metric for CRAHNS has been proposed and compared with an analytical Link capacity based method. From the simulations, it is noted that the model though not very good for small number of SUs in an area, works better for larger numbers than the QOS metric method. The work further shows that indeed, gated nodes can be used for mobility.

In the modelling of the Spectrum management, it is observed that the PRP-HOL method gives much better results than PRP-EOL and the model can be analysed using Maximum Entropy solution as long as the channel utilisation is kept above 0.6 thus an approximation that can be used with the existing mathematical model.

The models gives an average start to the queuing models for stationary CRAHNS though mobility can be included in the model using the gated node method. This method however would introduce new analytical challenges as there is need to introduce methods for priority class

queues with gated inputs for further development. For future work, more channels will be introduced in the model to include the unlicensed channels.

## REFERENCES

1. A.C. Talay and D.T. Altılar, "ROPCORN: Routing protocol for cognitive radio ad hoc networks," *Ultra Modern Telecommunications & Workshops, 2009. ICUMT '09. International Conference on*, pp.1-6, 12-14 Oct. 2009 doi: 10.1109/ICUMT.2009.5345349
2. A. O. Allen, (1990) *Probability, Statistics, and Queueing Theory: With Computer Science Applications* New York: Academic Press
3. A.M. Abbas and O. Kure "Quality of service in mobile ad hoc networks: A Survey." *International Journal of Ad Hoc and Ubiquitous Computing*, Vol 6, no 2, July 2010
4. C.-W. Wang and L.-C. Wang, "Modelling and analysis for Proactive- decision Spectrum handoff in Cognitive Radio Networks" IEEE (2009)
5. D. Kouvatsos and N. Tabet-Aouel, "A maximum Entropy Priority Approximation for a Stable G/G/1 Queue" *Acta Informatica* 27 247-286 (1989)
6. D.D. Kouvatsos, I. Awan and Y. Li, "Performance Modelling of a wireless 4G cell under a GPS scheme with Hand Off", IEEE 2005, pp 413-419.
7. F.C Commission, Spectrum policy task force. Technical report, November 2002.
8. G. M. A. Miskeen and D. D. Kouvatsos "On the simulation of GE- type Distribution" *Technical Tutorial – TT-06-2011*, June 2011.
9. H.Bhatia, R.B. Lenin, S. Srivastava and V. Sunitha, "Application of QNA to analyse the 'Queueing Network Mobility Model' of MANET". (2007)
10. I. f. Akyildiz, W.-Y. Lee, K. R. Chowdhury, "CRAHNS: Cognitive Radio ad hoc networks." *Ad Hoc Networks*, vol 7, no.5, pp 810-836, 2009
11. I.F. Akyildiz, W.-Y. Lee, M.C. Vuran, M. Shantidev, "A Survey on Spectrum Management in Cognitive Radio Networks," *IEEE Communication Magazine*, vol 50, pp. 40-48, April 2008.
12. I.F. Akyildiz, W.-Y. Lee, M.C. Vuran, M. Shantidev, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey", *Computer Networks Journal (Elsevier)* 50 (2006) 2127–2159.
13. K. Gorantala, "Routing Protocols in Mobile Ad-hoc Networks.", Master's Thesis in Computing Science, Umeå University, Department of Computing Science, Sweden, 2006.
14. L. Leemis, "Discrete Event Simulation – A first course" as access on <http://coins.csrlab.org/imamu/akoubaa/cs433/Textbooks/Discrete%20Event%20Simulation%20-%20A%20First%20Course%20-%20Leemis%20Park.pdf>, Dec 2004 [access on 12<sup>th</sup> November 2012]
15. L.Geng, Y.-C. Liang and F.Chin, "Network coding for wireless ad hoc cognitive radio networks," in *Proc. IEEE Personal Indoor Mobile Radio Commun. (PIRMC'07)*, Athens, Greece, Sep 2007, pp.570-573, Oct 2005
16. M. Abolhasan, T. Wysocki and E. Dutkiewicz, "A review of routing protocols for mobile ad hoc networks". *Ad hoc Networks*. Vol 2, Issue 1, pp 1-22, Jan 2004.
17. M. Cesana, F. Cuomo and E. Ekici, "Routing in cognitive radio networks: Challenges and Solutions". *Routing in Cognitive Radio Networks: Challenges and Solutions*, *Ad Hoc Netw.* (2010), doi:10.1016/j.adhoc.2010.06.009 as accessed on September 22<sup>nd</sup> 2012.
18. R.W.Thomas, D.H. friend, L.A. DaSilva and A.B.MacKenzie,"Cognitive Networks Adaptation and learning to Achieve End to End Performance Objectives," in *IEEE Commun. Mag.*, vol 44 Dec 2006 pp 51-57.
19. S.K.Gupta and R.K.Saket, "Performance Metric Comparison Of Aodv And Dsdv Routing Protocols In Manets Using Ns-2" *IJRRAS* 7(3), June 2011.
20. S. Lei; L. Lei; Z. Cheng, "A Novel Cluster-Based Architecture of Cognitive Wireless Ad-Hoc Networks," *Industrial Control and Electronics Engineering (ICICEE)*, 2012 *International Conference on*, vol., no., pp.1861-1865, 23-25 Aug. 2012.
21. S.M.B.Zahed, I.U.Awan and G.min, "Performance evaluation of Secondary Users in cognitive radio Networks" *Performance Engineering*, 27<sup>th</sup> UKPEW, pp 340-343, July 2011.
22. Y. Wen and W. Liao, "On QOS Routing in Wireless Ad-Hoc Cognitive Radio networks," *Vehicular Technology Conference (VTC 2010-Spring)*, 2010 *IEEE 71st*, pp.1-5, 16-19 May 2010 doi: 10.1109/VETECS.2010.5494068
23. Y.Liang, K. chen, G.Y.Li and P. Mahonen, "Cognitive Radio Networking and Communication: An Overview" *IEEE Transactions on Vehicular Technology*, vol 60, Issue no. 7, Sept 2011.
24. Y.-L. Chen and C. Chen, "Performance Analysis of NON-Preemptive HOL GE/G/1 Queue with two priority classes of SIP-T Signalling system in Carrier Grade Voip Network". *Journal of the Chinese Institute of Engineers*, Vol. 33, No. 2, pp 191-206 (2010)
25. Z.Zhang and X.Xie,"Intelligent Cognitive Radio: Research on Learning and Evaluation for CR based on neural network", *Information and Communications Technology, 2007. ICT 2007. ITI 5th International Conference*, pp.33-37, 16-18 Dec. 2007. doi: 10.1109/ITICT.2007.4475612.