A fuzzy-based routing protocol for cognitive radio networks

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Abstract: With the growing spectrum demand over the last decade, the use of cognitive radio networks (CRN) has provided a viable solution to spectrum scarcity problem. These networks basically employ two types of users: primary user (PU) and secondary user (SU). The PUs are allocated a license to use the spectrum at their will. On the other hand the SUs communicates via other SUs or through the licensed spectrum of PU nodes opportunistically. In such a scenario it is important that routing protocol that is deployed must take into consideration the stability of the route. Therefore, this paper proposes a novel fuzzy-based routing strategy with this objective in mind. Further, an attempt has been made to evaluate the performance of proposed routing strategy in realistic environment. The simulation results shows that the path selection utilising the fuzzy theory presents far better results when compared with shortest path routing protocol employing CR capabilities.

Keywords: fuzzy logic controller; cognitive radios; ad-hoc network; realistic environment; Dijkstra algorithm.


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1 Introduction

In the era of rapid growth in the wireless technologies there is huge requirement of spectrum. However, the spectrum is not freely available and its distribution is controlled by various government agencies. The supply of the spectrum is limited whereas the demand is huge and increasing exponentially. The demand is surpassing the supply of spectrum. Under such a scenario we must look for other alternatives. Cognitive radio network (CRN) (Liang et al., 2011; Kamruzzaman et al., 2011; Mitola and Maguire, 1999) could be a one such alternative to support the emerging wireless applications. CRN consists of two types of users i.e., primary user (PU) and secondary user (SU).

PUs are the ones using licensed band for communication purpose. On the other hand SUs are not allocated any spectrum, their communication relies on PUs i.e., the SU opportunistically utilise the spectrum when the PUs are ideal. Since the PU is the one entitled to use the band, SU must give up the communication as soon as PU needs it; hence the SU must be equipped with the capability to sense changes in the environment and must act accordingly. In such a scenario it is important for any routing strategy to take stability of the route into consideration since the transmission characteristics are not static. In order to select stable route it should consider many factors such as residual energy of the nodes, reliability of the paths, mobility of nodes etc.

Various routing strategies (Chen and Liao, 2012; Talay and Altilar, 2011; Datla et al., 2009; Zhu et al., 2008; Pefkianakis et al., 2008; Tang et al., 2012; El Masri, 2011; Sher and Afzal, 2012) for selecting the most suitable path from source to destination have been proposed that takes into account a single performance metric only. We are of the opinion that a strategy having optimal number of parameters as input will be the best for CRN. Therefore in this paper we present a routing scheme based on fuzzy logic controller (FLC) (El Masri, 2011) that takes into consideration various performance parameters to provide most stable path. The reason for using the fuzzy logic is its capability to combine various parameters easily.

In addition to the above work, the performance of the routing protocol using proposed scheme is also evaluated in the realistic environment. The realistic environment comprises of the obstacles (Jardosh et al., 2003; Meghnathan, 2009; Gupta et al., 2013, 2012) that hinders the nodes to come within each other’s transmission range. A significant change in the above mentioned parameters is witnessed when simulation region is added with the constraints i.e., the obstacles.

The rest of the paper is divided into following sections: Section 2 illustrates the literature survey and the problem identification. Section 3 illustrates the proposed routing scheme. Section 4 provides the setup parameters and flow chart of the simulation process. In addition, it provides the snapshot of the simulation region. Section 5, gives the simulation and results followed by conclusion and then references.
2 Literature survey and problem identification

Various routing schemes have been proposed by researchers dealing in CRNs. The effectiveness of the protocol depends on the number of parameters considered in the routing decision. The strategies for routing can be divided in two categories based on number of parameters used:

2.1 Strategies based on single performance metric

Kamruzzaman et al. (2011) proposed an energy efficient routing protocol, using the available licensed channels as the metric for path selection on time division basis. Although the utilisation of channels on time division basis significantly improves the channel utilisation, but his work did not focused on the efficiency of channel utilisation scheme he adopted, as the transition properties of available channel for routing decisions were not taken into account.

Pefkianakis et. al. (2008) proposed a protocol that considered the spectrum availability as the performance metric for path selection. This protocol too did not consider the residual energy of nodes. Besides this, the spectrum availability metric does not provide the complete description of channel transition characteristics.

Chen and Liao (2012) proposed a probability-based model for determination of optimal channels. Here the channel transition characteristics as performance metric was studied by each SU, the Path with minimum expected transition time is considered to be the optimal path. The inclusion of reliability and residual energy in the routing strategy can considerably impact performance analysis.

The above work concentrated on only single performance metric. In order to combine these metric few researchers used mechanisms as follows:

2.2.1 Strategy based on multiple performance metrics

Tang et al. (2012) proposed a protocol design for unicast routing in dynamic multi-hop CR networks. A set of CR nodes with geographical positions and temporarily available channels are considered. Based on these parameters, the parameter expected transmission time (ETX) is evaluated for each link. The path with maximum value of ETX was considered as the optimal one. The proposed methodology could be improved if the ETX evaluation considers the transition characteristics of the channel. Besides this, in determining the ETX value for each path, residual energy of nodes was not considered.

El Masri (2011) proposed a fuzzy-based routing protocol with channel transition rate and transmission power as stability metrics. He measured the path grades to signify the stability of all the paths. The proposed protocol too did not focused on the residual energy and reliability of all the possible paths. Design of FLCs changes significantly with inclusion of the above mentioned factors.

The numbers of parameters considered in the routing decision are accountable for the effectiveness of the protocol deployed in the CRN. One of the credible methods to combine the parameters in the design of routing strategy is the fuzzy logic theory. This paper is an effort to combine the necessary parameters required in the routing decision using the FLC in order to determine most suitable path. Beside this none of the work discussed so far made the performance evaluation in the realistic environment. The
analysis of the routing protocol in two different environments produces dissimilar results. The evaluation of the possible paths through fuzzy theory can yield far better analysis of the feasible paths, even if the information available is incomplete to a certain extent.

3 The proposal

3.1 The proposed routing scheme

Before discussing the proposal we would like to give an introduction to FLC that will help in better understanding of the proposal.

3.1.1 Fuzzy logic controller

Figure 1 shows the block diagram of FLC. The basic blocks of FLC have been explained as follows:

- **Fuzzification module**: This module converts each crisp input into a fuzzy set on the domain of the input variable. For this purpose different types of membership functions are used such as triangular, Gaussians, sigmoidal etc. The membership function used in our proposal is triangular.

- **Rule base**: This module contains rules of the form ‘IF-THEN’ where the ‘IF’ side of the rule is called antecedent and the ‘THEN’ side is called the consequent. On the basis of this rule base the inference engine works.

- **Inference engine**: An inference engine is a computer program that tries to derive the answer from rule base. The program used to calculate the result in inference engine is mamdani-type.

- **Defuzzification module**: This module converts a fuzzy set into crisp set. There are several methods available in literature for defuzzifications such as mean-of-maxima, centre of gravity (CoG), height method etc. In our proposed method we used CoG method for defuzzification.

Figure 1  Fuzzy logic controller
3.2 Protocol design through FLCs

A new fuzzy logic-based routing scheme is designed using FLC. Figure 2 shows the block diagram of proposed model. The new scheme is based upon five input parameters i.e., frequency of transition, on_period_deviation, off_period_deviation, residual energy and intermediate nodes. All these parameters are applied as an input to two FLCs i.e., FLC1 and FLC2. The output of two FLCs becomes the inputs of third FLC and gives a final output i.e., final stability. Based upon the values of these parameters, the FLC3 gives an optimum path to destination.

![Figure 2 FLC structure](image)

The design steps are as follows:

1. The first step is to determine the stability metric1 using FLC1 for each path on the basis of the available channels to the SU nodes in the CRN. FLC1 evaluates the stability of all the channels in terms of input parameters: frequency of transition, deviations in the ON Period and deviations in the OFF period and determine the finest channel on each SU among all the channels available. The stability metric1 for each path is the cumulative average of the outputs of the FLC1 installed at each node in the path.

2. The next step is to determine the stability metric2 using FLC2 for all the possible paths using residual energy of the nodes and intermediate number of nodes as an input.

3. The outputs of the above mentioned FLCs is now used to determine the final stability value of each path using FLC3. The path with highest stability factor is the optimal path.

The three FLC used in our proposal are described as under.

### 3.3 FLC1

The channel availability to SU nodes is on temporary basis. The output value of FLC1 describes the sporadic activity of the channels available or the stability metric 1. This factor describes how the channel availability changes over time. The stability of the
channel is measured in terms of the availability duration of the channel, the off time width between two available periods, the difference in the availability durations.

3.3.1 Inputs to FLC1

To calculate the stability metric 1 the FLC1 uses the following inputs as follows:

3.3.1.1 Frequency of transition

This parameter describes the transition rate of a channel between availability and unavailability. A channel with higher rate of transition switches rapidly (see Figure 3), certainly such channel will not offer a significant data rate. Although the overall duration available for communication may be approximately same but the transmission time of the data in two cases can vary significantly.

**Figure 3** (a) Low transition rate (b) High transition rate

3.3.1.2 Deviation in on period

This parameter corresponds to the differences in successive ON periods durations available to SU nodes for the communication.

Since the PU usage period may vary depending on the size of data transmission, consequently the ON period widths available to SU may vary. Figure 4 shows the ON period availability. A channel with transition characteristics as shown in Figure 4(a) is more suitable to use in comparison to a channel with characteristics as shown in Figure 4(b).

**Figure 4** (a) High deviation in on period (b) Low deviation in off period
3.3.1.3 Deviation in OFF period

This parameter corresponds to the difference in the OFF period durations unavailable to SU nodes. If the difference in the duration of unavailable periods is large, the distribution model of channel unavailability resembles closely with the time distribution model of the stable channel. Channel with characteristics as shown in Figure 5(a) is more suitable than the channel with characteristic as shown in Figure 5(b) from the stability point of view.

![Figure 5](a) High deviation in off period (b) Low deviation in off period

3.3.2 Fuzzification

The measurement devices in technical systems provide crisp measurements, i.e., values input to the FLC are in the form of crisp set. The fuzzification process transforms the crisp values into fuzzy sets by using the membership functions as follows.

![Figure 6](a) Membership function for frequency/number of transition in 360 msec (b) Membership function for on period deviation (c) Membership function for off period deviation

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*A fuzzy-based routing protocol for cognitive radio networks*
3.3.2.1 Membership function for FLC1 inputs

In order to determine the stability metric for the available channels, the above discussed parameters are combined using the FLC1. The three linguistic variables input to FLC1 are frequency of transition, deviation in the ON periods; Deviation in OFF periods and the output linguistic variable is termed as stability metric 1. Each of the linguistic variables is characterised by the membership functions as shown in the Figure 6. Membership function for all the three inputs are same, the crisp values are different for each of them. The linguistic variable for input are characterised by a term of three fuzzy sets, \( \{T(Input)\} = \{[Low, Medium, High]\} \).

3.3.3 Rule base for FLC1

IF-THEN rules or the fuzzy rule base to combine the input parameters is shown in Table 1. The frequency of transition greatly influences the stability 1 value as the channel transition characteristics are hugely impacted by the frequency of transition of the channel. An unstable channel switches rapidly between availability and unavailability. When the availability durations are quite large the channel is said to be stable, similarly when unavailable durations are small the channel is excellent to use. Initial rule base is built on the basis of the consideration of above mentioned factors. Finally, the necessary changes in the rule base are made through the repeated iterations performed in the simulator.

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A fuzzy-based routing protocol for cognitive radio networks

Table 1  Rule base for FLC1 (continued)

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3.3.4 Defuzzification

The output of FLC1 is the crisp value evaluated through the membership function as shown in the Figure 7. The method for determining the defuzzified value is CoG method as discussed below in equation (1):

\[
\text{Output}^{1\text{_sinlemode}} = \frac{m1*A1 + m2*A2}{A1 + A2}
\]

where \(m1, m2\) are membership values determined through the fuzzification process, the regions i.e., low, medium, high etc. are selected on the basis of rule base and \(A1, A2\) are the areas in the selected regions. The \(\text{Output}^{1\text{_sinlemode}}\) is the crisp value obtained by applying the centre of gravity method on the determined areas.

3.3.4.1 Membership function for FLC1 output

The output variable is defined as stability metric 1. The linguistic variable for output is characterised by a term of four fuzzy sets, \(\{\text{T(Output)}\} = \{\text{Very Low, Low, Medium, High}\}\), Figure 7. The output of FLC1 lies in the range 1 to 10.

Figure 7 Membership function for output of FLC1

![Membership function for output of FLC1](image)
3.4 FLC2

The purpose of FLC2 is to determine the reliability of all the possible paths. The input parameters considered to calculate the stability metric are residual energy and the intermediate number of nodes. These two parameters are accountable for the reliability of the paths and are described as below.

3.4.1 Inputs to FLC2

To calculate the stability metric the FLC2 uses the following inputs as follows.

3.4.1.1 Residual energy

Each node (SU) deployed in the network can act as a source/destination node or as a router. Each transmission proportionally decrements the available energy called the residual energy. The credibility of the transmission through a node will be influenced by the available energy (Gupta et al., 2011).

3.4.1.2 Intermediate nodes

This parameter describes the intermediate number of nodes involved in the path formed from the source to destination. This factor is directly accountable for the intactness of the path during the course of communication. A path from source to destination with a greater number of nodes is more likely to terminate before the complete data transmission in comparison to one with a lesser number of nodes.

3.4.2 Fuzzification

The process of fuzzification is applied on the crisp values of residual energy and intermediate nodes to determine the fuzzy sets using the membership function as shown in Figure 8.

**Figure 8** (a) Membership function for RE (b) Membership function for nodes

![Membership function for residual energy](a) ![Membership function for intermediate nodes](b)

3.4.2.1 Membership function for FLC2 inputs

Figure 8(a) describes the membership function of residual energy and intermediate nodes. The linguistic variable for residual energy is characterised by the fuzzy set $\{T(Input)\} =$
A fuzzy-based routing protocol for cognitive radio networks

{[Low, Medium, High]}. The residual energy allotted to all nodes prior to the beginning of iterations lies within the range 50–70%. Figure 8(a) describes the membership function of intermediate nodes. The linguistic variable for intermediate nodes is characterised by the fuzzy set \( \{ T(\text{Input}) \} = \{ \text{Very Low, Low, Medium, High} \} \).

Figure 9  Membership function for output

![Figure 9](image)

Figure 10  (a) Membership functions for stability factor 1 (b) Membership functions for stability factor 2

![Figure 10](image)

3.4.3 Rule base for FLC2

Table 2 describes the rule base of the FLC2. As discussed the input parameters are residual energy and number of intermediate nodes. It is advised that a path with lesser number of nodes is more reliable. The residual energy of all the nodes in the chosen path should be above a certain value even if the path has higher intermediate nodes in comparison to other feasible paths. Consequently a path with lesser intermediate nodes and energy values slightly above the threshold could be less suitable than a path with moderate residual energies and higher intermediate nodes. Such a consideration in the routing methodology could enhance the overall life time of the network. In order to select a suitable path, the study of intermediate nodes and residual energy is important, so through the possible combinations we get a reliable path. FLC2 is to determine the stability metric 2.
Table 2  Rule base for FLC2

<table>
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Table 3  Rule base

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3.4.4 Defuzzification

The output of the defuzzification block is the crisp value that corresponds to stability metric2. The crisp value is determined using the CoG method as discussed in section 3.3.4.
A fuzzy-based routing protocol for cognitive radio networks

3.4.4.1 Membership function for FLC2 output

The linguistic variable for output i.e., stability metric2 is characterised by the fuzzy set \( T(\text{Input}) = \{\text{Very Low}, \text{Low}, \text{Medium}, \text{High}\} \).

3.5 FLC3

The final stability factor which corresponds to the efficiency in the communication through each path is determined through the FLC3.

3.5.1 Inputs to FLC3

To calculate the final stability factor the FLC3 uses the following inputs as follows.

3.5.1.1 Stability metric1

Stability metric1 for each path is determined from individual stability metric values of the channels available to each SU. The metric1 for a path is derived from cumulative average of FLC1 outputs of individual nodes.

3.5.1.2 Stability metric2

Stability metric2 is calculated from FLC2 on the basis of the least energy among the residual energies of all the nodes and number of intermediate nodes in the considered paths. The final stability factor is determined through an optimal selection strategy employed between the two stability metrics.

3.5.2 Fuzzification

3.5.2.1 Membership function for FLC3 input

The linguistic variable for stability metric1 and 2 i.e., the input parameters for FLC3 are characterised by the fuzzy sets \( T(\text{Input}) = \{\text{Very Low}, \text{Low}, \text{Medium}, \text{High}\} \).

3.5.3 Rule base for FLC3

The rule base for FLC3 is initially constructed by the analysis and understanding of stability1 and stability2, finally the changes are made in the rule base through the repeated iterations.

3.5.4 Defuzzification

The final stability factor is obtained after the defuzzification process of FLC3, again the CoG method is used.

3.5.4.1 Membership function for FLC3 output

The linguistic variable for final output i.e., final stability factor (FSF) is characterised by the fuzzy set \( T(\text{Input}) = \{\text{Very Low}, \text{Low}, \text{Medium}, \text{High}\} \). The membership function used in FLC3 is shown in Figure 11.
4 Experimental setup

The proposed FLC-based routing strategy is implemented in MATLAB along with modified shortest path routing strategy employing CRN. The metrics that have been used to evaluate the performance of CRN in the idealistic and realistic scenarios are also discussed in this section.

4.1 Metrics used

- **Average packet delivery ratio (PDR)** – defined as the ratio of summation of PDR for each path to the total number of possible paths.
- **Hop count** – defined as the number of intermediate hops from source to the destination.
- **Probability of reach ability (PoR)** – defined as the ratio of total paths actually formed in the cognitive network to the total number of possible paths.
- **Throughput** – defined as the ratio of cumulative PDR for the network to the number of actual paths formed in the network during simulation.
- **Average delay** – defined as the difference in the transmission time when the data is transmitted through optimised path and when data is transmitted though the unoptimised or the shortest path to the total number of paths actually formed in the network.

4.2 Set up parameters

Various set up parameters needed in order to describe the simulation environment and simulation requirements have been shown in Table 4.

4.3 Simulation region

Figure 12 is the snapshot of the simulation region devoid of any obstacles. Nodes in red colour are PU nodes, and the nodes in the black colour are the SU nodes. The different colour line segments correspond to the possible paths between the source and destination. The yellow colour segments indicate that the particular SU node is in the vicinity of the PU node, whose frequency can be sensed by the SU node to use it opportunistically. The
feasible paths are those through which the destination is reachable but the actual feasible paths are the one in which all the nodes of the path are in the range of one or more PU node indicated by yellow line segments. These segments are responsible for the distinguishing between total feasible paths and the actual feasible paths between the source and destination.

**Table 4** Simulation setup parameters

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<tr>
<th>Setup parameter</th>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of simulation region</td>
<td>$2000 \times 2000$ sq units</td>
<td>PU nodes position</td>
<td>Fixed random</td>
</tr>
<tr>
<td>Number of SU nodes</td>
<td>Varied from 20 to 50, step size of 10</td>
<td>SU nodes position</td>
<td></td>
</tr>
<tr>
<td>Numbers of PU nodes</td>
<td>16</td>
<td>Routing algorithm</td>
<td>Optimal path determination</td>
</tr>
<tr>
<td>Transmission range</td>
<td>300 m</td>
<td>Packet transmission interval</td>
<td>0.9 sec</td>
</tr>
<tr>
<td>Mobility model</td>
<td>Random walk</td>
<td>Packet size</td>
<td>512 bytes</td>
</tr>
<tr>
<td>PU nodes mobility</td>
<td>NIL, PU nodes are fixed</td>
<td>Number of packet sent</td>
<td>130</td>
</tr>
<tr>
<td>Speed of SU nodes</td>
<td>15 m/s</td>
<td>Initial residual energy available at each SU</td>
<td>Between 50 to 70%</td>
</tr>
<tr>
<td>Number of obstacles in realistic case</td>
<td>4</td>
<td>Total time allotted for transmission of all packets</td>
<td>360 msec</td>
</tr>
<tr>
<td>Routing strategy number of FLCs used</td>
<td>FLC based 3</td>
<td>Type of the obstacles-shape of obstacle</td>
<td>Mountain type rectangle</td>
</tr>
</tbody>
</table>

In the realistic scenario four obstacles of rectangle shape are introduced as seen in Figure 13. The obstacles are mountain type i.e., the SU nodes cannot sense the frequency of the PU if an obstacle appears in the line of sight of the two users. Besides the packets are dropped if an obstacle appears in the line of sight joining two SU nodes during communication.
4.4 Algorithm

To evaluate the performance of the network in terms of performance metrics, the algorithm used is described as under.

Initially the 16 PU nodes are placed at fixed positions in the simulation region; each PU node is awarded four channels with different characteristics. The iterations are performed by increasing the concentration of SU nodes from 20 to 50 with step size of ten. Iteration with particular SU concentration tests efficiency of the paths for the entire source, destination pairs. Each time a path devoid of the obstacles is formed, value of count variable is incremented by 1. Value of PoR is calculated using the count variable. For the value of variable iter equal to 1 the optimal path is determined by running the functions \textit{stability\_metric1()}, \textit{stability\_metric2()}, \textit{optimal\_path()} in succession. Using FLC3 the optimal path is determined and data transmission is carried out through it using the optimal channels. The optimal channel on each node are determined using FLC1. Transmission time is calculated using function \textit{transit\_time1()}. The data transmission is accomplished by \textit{send\_data()}. For iter equal to 2, if optimal path is not the shortest path, check its efficiency using optimal frequencies else check the efficiency of the shortest path through randomly selected frequencies. Determine the transmission time using \textit{transit\_time2()}. Delay is the difference of the transmission time in iter 2 and iter 1. PDR is determined for each iter value. Ultimately the PDR values are determined for the entire network.
Algorithm 1: To calculate the performance metrics for CRN

Total SU Nodes $N = \text{variable}$;
Total PU Nodes $= 16$ (g)

count = Data_Packets = hop_count = 0;
for $i = g + 1$ to $N - 1$
for $j = i + 1$ to $N$
for iter = 1 to 2
  If (S-D path exists)
    Fsible_paths()
    Actual_fsible_paths()
    If Actual_fsible_paths() == Nil
      Continue
    Else
      Count++
    End
    If iter==1
      Stability_metric1()
      Stability_metric2()
    End
    Optimal_path()
    Cum_Data_Packets = Cum_Data_Packets + Send data() + Transmit_time1()

    Else
    Cum_Data_Packets 1 = Cum_Data_Packets 1 + Send data() + Transmit_time2()
  End
  Cum_hop_count 1 = Cum_hop_count 1 + Hop_count;
  Delay = Transmit_time 2 - Transmit_time 1;
End
End
Avg_PDR = 2 * Cum_Data_Packets / $N / (N-1)$;
Avg_PDR1 = 2 * Cum_Data_Packets 1 / $N / (N-1)$;
Avg_delay = Delay/count.
Throughput = Cum_Data_packets/count;
PoR = 2 * Count / $N / (N-1)$;
Hop Count = Cum_hop_count/count;
5 Results

5.1 Average PDR comparison

Figure 14 shows the impact on the value of average PDR with the increase in the SU concentration for the following cases:

1. path is optimised in idealistic environment
2. path is not optimised in idealistic environment
3. path is optimised in realistic environment
4. path is not optimised in realistic environment.

Inference

- It can be seen that PDR results for the network are better when the packets are routed through the optimised path in comparison to results when the packets are routed through an un-optimised path.
- PDR in the idealistic situation for any concentration of SU is higher in comparison to the realistic situation.
- As the number of SU nodes increases number of communication paths between the sources, destination pair increases. It ultimately leads to increase in PDR value.
- With the increase in concentration of the SU nodes the PDR increases as shown in the Figure 14 for both idealistic and realistic scenarios.
- A comparable value of PDR for unoptimised path is attained on the cost of larger transmission time of data through the un optimised or shortest path.

5.2 Probability of reach ability (PoR)

Figure 15 shows the impact in the value of PoR with the increase in the SU concentration when the simulation is done in the both idealistic and realistic environment. The following inference can be drawn from the results:
Inference

- Value of PoR increases with an increase in the SU concentration as the possibility of the path formation increases with increase in SU concentration.

- The PoR value for the idealistic scenario is always higher than the PoR value for realistic scenario. This is due to reason that, the obstacles present in the simulation region obstructs the node movement as well as prevents the SU nodes from sensing the status of the frequencies of the PU nodes.

5.3 Hop count comparison

Figure 16 shows the impact on the value of hop count with the increase in the SU concentration when the simulation is done in the idealistic and realistic environment. The following inference can be drawn from the results:

Figure 16 Hop count comparison (see online version for colours)
Inference

- With the increase in the SU concentration the paths with greater number of nodes are feasible both in the realistic and idealistic environments.
- The hop count value for the optimal path is greater than the hop count value for the shortest path (unoptimised).
- Hop count in realistic scenario for each SU concentration is comparatively lower than the hop count value in the idealistic scenario. As the presence of obstacles hinders the transmission between nodes lying on either side of obstacle, the paths with greater number of intermediate nodes are less likely to occur in comparison to the idealistic case.

5.4 Throughput comparison

Figure 17 shows the impact in the value of throughput with the increase in the SU concentration when the path is idealistic and realistic.

Figure 17  Throughput comparison (see online version for colours)

Inference

- The throughput value for optimal path (unoptimised) is higher than the throughput value for the shortest path both in the idealistic and realistic environment.
- Throughput value is maximum, when the SU concentration is 20, both in idealistic and realistic environment.
- With the increase in the SU concentration the throughput values decrease both in idealistic and realistic environments.
- Throughput value for each SU concentration is greater in the idealistic environment in comparison to the realistic environment.
- Decreasing nature of the throughput w.r.t increase in the SU concentration is due to the rise in the unsuccessful communications due to the drop in the residual energy.
5.5 Average delay comparison

Figure 18 shows the variation in the average delay i.e., the difference in the transmission times with respect to an increase in the SU concentration in the idealistic and realistic environments.

**Figure 18** Average delay comparison (see online version for colours)

**Inference**

- The average delay for the network increases with the increase in the SU nodes concentration.
- As paths with greater number of nodes are feasible with an increase in the SU concentration, consequently the difference in the two transmission times increases as the length of path increases.
- The impact on delay in realistic and idealistic is quite similar as transmission time is affected mainly by the selected channel characteristics and the path lengths.

6 Overall conclusions

In this paper an effort has been made to use FLC for providing a reliable path for communication purpose. The following inferences can be drawn:

- communication efficiency is enhanced by making fuzzy-based decision for path selection
- the simulation results show dissimilarities in results of proposed strategy while considering realistic and idealistic conditions
- the number of SU nodes considered in the simulation region directly influences the performance of the network, i.e., it directly affects the overall life time of the network
- more paths are feasible if the SU concentration is increased
• a significant value of PDR for each SU concentration in un-optimised transmission is attained on the cost of larger transmission time, in comparison to the lower transmission time required in the optimised path.

References


A fuzzy-based routing protocol for cognitive radio networks


Annexure

*Equations for fuzzification in FLC1*

For the purpose of fuzzification, the following equations that characterise the membership function are used in FLC1, here ‘FoT’ represents the crisp set of the corresponding input and ‘output value’ of the equation is the Fuzzy set for the input parameters.

<table>
<thead>
<tr>
<th>FLC1 input1: Frequency of transition (FoT)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1 if FoT ≤ 4.046</td>
</tr>
<tr>
<td></td>
<td>= 4.22 − 0.85*FoT if 4.06 ≤ FoT ≤ 5.22</td>
</tr>
<tr>
<td>Medium</td>
<td>0.45 FoT − 2.16 if 4.8 ≤ FoT ≤ 7</td>
</tr>
<tr>
<td></td>
<td>= 4.5 − 0.5*FoT if 7 ≤ FoT ≤ 9</td>
</tr>
<tr>
<td>High</td>
<td>0.66 FoT − 5.7 if 8.793 ≤ FoT ≤ 10.34</td>
</tr>
<tr>
<td></td>
<td>= 1 if 10.34 ≤ FoT ≤ 16.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FLC1 input2: On period deviation (On _ PD)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1 if 5.09 ≤ On _ PD ≤ 12.36</td>
</tr>
<tr>
<td></td>
<td>= 6.5 − 0.446*On _ PD if 12.36 ≤ On _ PD ≤ 14.6</td>
</tr>
<tr>
<td>Medium</td>
<td>0.130*On _ PD − 1.79 if 13.8 ≤ On _ PD ≤ 21.44</td>
</tr>
<tr>
<td></td>
<td>= 3.7 − 0.132*On _ PD if 21.44 ≤ On _ PD ≤ 29</td>
</tr>
<tr>
<td>High</td>
<td>0.49*On _ PD − 13.8 if 28.2 ≤ On _ PD ≤ 30.23</td>
</tr>
<tr>
<td></td>
<td>= 1 if 30.23 ≤ On _ PD ≤ 40.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FLC1 input3: Off period deviation (Off _ PD)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1 if 5.33 ≤ Off _ PD ≤ 12.92</td>
</tr>
<tr>
<td></td>
<td>= 4.7 − 0.288*Off _ PD if 12.92 ≤ Off _ PD ≤ 16.4</td>
</tr>
<tr>
<td>Medium</td>
<td>0.143*Off _ PD − 2.15 if 15.42 ≤ Off _ PD ≤ 22.4</td>
</tr>
<tr>
<td></td>
<td>= 4 − 0.147*Off _ PD if 22.4 ≤ Off _ PD ≤ 29.2</td>
</tr>
<tr>
<td>High</td>
<td>0.369*Off _ PD − 10.17 if 28.26 ≤ Off _ PD ≤ 30.97</td>
</tr>
<tr>
<td></td>
<td>= 1 if 30.97 ≤ Off _ PD ≤ 41.26</td>
</tr>
</tbody>
</table>

*Equations for defuzzification in FLC1*

For the purpose of defuzzification at FLC1, the following equations that characterise the membership function are used, the output variable for FLC2 is stability metric1 (SM1).
FLC1 output: Stability metric 1 (SM1)

Very low = 1 if 1.007 ≤ SM1 ≤ 2.197
= 4.2 – 1.5*SM1 if 2.197 ≤ SM1 ≤ 2.847
Low = 0.72*SM1 – 1.6 if 2.393 ≤ SM1 ≤ 3.75
= 3.7 – .74*SM1 if 3.75 ≤ SM1 ≤ 5.086
Medium = 0.71*SM1 – 3.3 if 4.753 ≤ SM1 ≤ 6.155
= 5.4 – 0.725*SM1 if 6.155 ≤ SM1 ≤ 7.534
High = 0.95*SM1 – 6.7 if 7.135 ≤ SM1 ≤ 8.185
= 1 if 8.185 ≤ SM1 ≤ 10

Equations for fuzzification in FLC2

For the purpose of fuzzification, the following equations that characterise the membership function are used:

FLC2 input1: Residual energy (RE)

Low = 1 if 1 ≤ RE ≤ 10.32
= 2.16 – 0.21*RE if 10.3 ≤ RE ≤ 14.91
Medium = 0.083*RE – 1.12 if 13.6 ≤ RE ≤ 25.09
= 3.5 – 0.1*RE if 25.09 ≤ RE ≤ 35.3
High = 0.19*RE – 6.16 if 32.46 ≤ RE ≤ 37.63
= 1 if 37.63 ≤ RE ≤ 70

FLC2 input2: Intermediate nodes (N)

Very low = 1.66*N – 1.56 if 0.9499 ≤ N ≤ 1.599
= 1 if 1.599 ≤ N ≤ 2.91
= 5.9 – 1.69N if 2.91 ≤ N ≤ 3.518
Low = 0.714*N – 2.49 if 3.372 ≤ N ≤ 4.707
= 3.96 – 0.6258N if 4.707 ≤ N ≤ 6.342
Medium = 0.76*N – 4.5 if 5.911 ≤ N ≤ 7.217
= 5.7 – 0.66*N if 7.217 ≤ N ≤ 8.756
High = 1.43*N – 12 if 8.434 ≤ N ≤ 9.129
= 1 if 9.129 ≤ N ≤ 12

Equations for defuzzification in FLC2

For the purpose of defuzzification, the following equations that characterise the membership function are used.
A fuzzy-based routing protocol for cognitive radio networks

FLC2 output2: Stability metric2(SM2)

Very low = 2.2 * SM2 – 2.1 if 0.986 ≤ SM2 ≤ 1.44
= 1 if 1.44 ≤ SM2 ≤ 2.607
= 4.16 – 1.6 * SM2 if 2.607 ≤ SM2 ≤ 3.23
Low = 0.67 * SM2 – 1.98 if 2.96 ≤ SM2 ≤ 4.44
= 4 – 0.69 * SM2 if 4.44 ≤ SM2 ≤ 5.87
Medium = 0.8 * SM2 – 4.39 if 5.49 ≤ SM2 ≤ 6.75
= 6.4 – 0.8 * SM2 if 6.75 ≤ SM2 ≤ 8.01
High = 1.7 * SM2 – 12.9 if 7.679 ≤ SM2 ≤ 8.25
= 1 if 8.25 ≤ SM2 ≤ 9.56

Equations for fuzzification in FLC3

For the purpose of fuzzification, the following equations that characterise the membership function are used.

FLC3 input1: Stability metric1(SM1)

Very low = 1.35 * SM1 – 0.27 if 0.205 ≤ SM1 ≤ 0.945
= 1 if 0.945 ≤ SM1 ≤ 2.345
= 5.92 – 2.1 * SM1 if 2.345 ≤ SM1 ≤ 2.82
Low = 0.21 * SM1 – 5.25 if 2.583 ≤ SM1 ≤ 3.04
= 1 if 3.04 ≤ SM1 ≤ 4.32
= 7.44 – 1.5 * SM1 if 4.32 ≤ SM1 ≤ 4.96
Medium = 2.4 * SM1 – 11.28 if 4.72 ≤ SM1 ≤ 5.13
= 1 if 5.13 ≤ SM1 ≤ 6.89
= 14.6 – 2 * SM1 if 6.89 ≤ SM1 ≤ 7.393
High = 2.4 * SM1 – 17.25 if 7.179 ≤ SM1 ≤ 7.584
= 1 if 7.584 ≤ SM1 ≤ 10

FLC3 input2: Stability metric2(SM2)

Very low = 2.6 * SM2 – 2.23 if 0.869 ≤ SM2 ≤ 1.25
= 1 if 1.25 ≤ SM2 ≤ 2.869
= 6.12 – 1.8 * SM2 if 2.869 ≤ SM2 ≤ 3.4
Low = 1.92 * SM2 – 5.56 if 2.9 ≤ SM2 ≤ 3.42
= 1 if 3.42 ≤ SM2 ≤ 4.94
= 11.07 – 2.04 * SM2 if 4.94 ≤ SM2 ≤ 5.43
Medium = 2.7 * SM2 – 14 if 5.19 ≤ SM2 ≤ 5.56
= 1 if 5.56 ≤ SM2 ≤ 7.37
= 11.08 – 1.5 * SM2 if 7.3 ≤ SM2 ≤ 7.964
High = 2.68 * SM2 – 20 if 7.521 ≤ SM2 ≤ 7.893
= 1 if 7.893 ≤ SM2 ≤ 10
Equations for defuzzification in FLC3

FLC3 output: Final stability factor (FSF)

Very low = 1.82 * FSV – 1.01 if 0.56 <= FSV < 1.107
= 1 if 1.107 <= FSV < 2.39
= 5.78 – 2 * FSV if 2.39 <= FSV < 2.89

Low = 2.43 * FSV – 6.43 if 2.65 <= FSV < 3.06
= 1 if 3.06 <= FSV < 5.036
= 10.96 – 1.98 * FSV if 5.036 <= FSV < 5.54

Medium = 1.8 * FSV – 9.48 if 5.27 <= FSV < 5.82
= 1 if 5.82 <= FSV < 7.131
= 12.69 – 1.64 * FSV if 7.131 <= FSV < 7.74

High = 1.98 * FSV – 15.2 if 7.46 <= FSV < 7.964
= 1 if 7.964 <= FSV < 10