

Adaptive Modular Fuzzy-based Handover Decision System for Heterogeneous Wireless Networks

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Abstract Future generation wireless networks will demand more intelligent and adaptive handover decision mechanisms to fulfil users' expectations in terms of seamless mobility over extensive area, minimum price, high data rate, adequate QoS provision and so on. For such a demanding networking environment the handover decision system (HDS) need to be highly intelligent. Fuzzy logic appears to be one of the methods that can be employed to enhance HDS intelligence. However, most existing fuzzy-based HDS designs proposed in the literature are monolithic, i.e. based on a single fuzzy engine. In view of the growing demand for real-time applications, it is becoming necessary to include a relatively large number of decision parameters (especially QoS-related) in the handover decision process. However, an increasing number of decision parameters give rise to generating a very large number of fuzzy rules. This in turn increases computational complexity and requires significantly long algorithm execution time, which may not be acceptable for real-time applications. Furthermore, if the same fuzzy membership functions (FMFs) and fuzzy rules are used for all traffic types (e.g. VoIP, video streaming etc), the HDS may not give the overall best decision results, as each traffic type has a different set of QoS requirements. In order to address the above issues, we are proposing a modular design concept to deal with the algorithm execution time and an adaptive mechanism to select FMFs and fuzzy rules which are best suited to the incoming traffic. The results show that the modular design significantly reduces the algorithm execution time while an adaptive mechanism improves the network selection performance considerably.

Keywords Fuzzy Logic, Monolithic, Modular Design, Adaptive, Handover Decision, Heterogeneous Wireless Networks

1. Introduction

Future wireless mobile network architectures are envisaged to comprise of an integration of multiple wireless technologies such as WLAN, WiMAX, 2G/3G Cellular wireless network and Long Term Evolution (LTE). They will allow mobile users to have universal and seamless mobility supporting various types of traffic (e.g. voice over IP, video streaming, web browsing, file transfers and so on), and at the same time offer the ability to transfer connection to a different wireless technology that may offer higher data rate, better QoS or lower price for a given application.

Figure 1 illustrates architecture for an integrated wireless mobile network. When a mobile node moves across different service areas, handovers become necessary in order to maintain connectivity. A mobile node may perform a horizontal handover (switching to a new network within a homogeneous wireless environment) or a vertical handover

(switching to a network of different wireless technology - heterogeneous wireless environment).

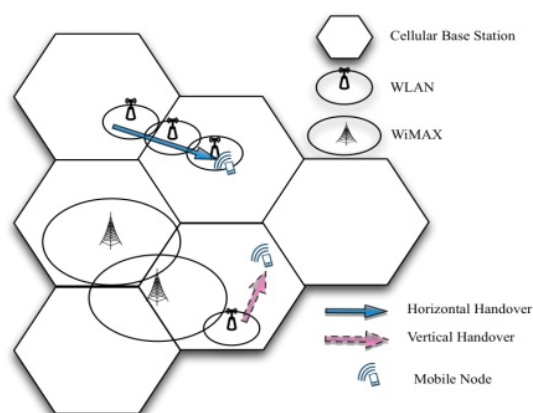


Figure 1. Handovers in Heterogeneous Wireless Networks

Clearly, a sufficiently intelligent handover decision system (HDS) is needed to perform these functions optimally. Fuzzy logic and related techniques (e.g. ANFIS) have been extensively employed to enhance HDS intelligence. Several fuzzy-based algorithms have been proposed in the literature[1] –[4]. Some of these algorithms

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consider rather a limited number of decision parameters, and in some cases none of the QoS-related parameters are taken into consideration. In view of the growing trends in real-time services over wireless networks such as, VoIP, video streaming and video conferencing, it is necessary that the QoS-related parameters are included in network performance evaluations.

Although fuzzy-based approaches have shown to have improved HDS intelligence, these approaches become inefficient in terms of execution time, due to computational complexity of the decision algorithm, as the number of decision parameters increases. In time-sensitive applications, minimization of the execution time (τ) is an essential requirement. Most fuzzy-based handover decision algorithms proposed in the literature are monolithic (contain one fuzzy engine) with no scope for minimization of τ .

In addition, most existing fuzzy-based handover decision algorithms, to our knowledge, use either fixed fuzzy membership functions (FMFs) or decision rules regardless of the incoming traffic type. This situation may not give the best results as each traffic type has different QoS requirements[5]. Clearly, it would be advantageous to consider adaptive FMFs and fuzzy rules for each individual traffic type.

In this paper, we consider all the above issues of concern. A new approach based on a modular (containing multiple fuzzy engines) HDS design is presented and it is shown that in this formulation the number of fuzzy rules is significantly reduced compared with a typical monolithic design for the same number of input decision parameters. As a result, the computational complexity is reduced, leading to a lower value of τ . Our results show an average reduction of approximately 90% in the value of τ compared with a monolithic fuzzy-based HDS.

The modular approach is then extended to incorporate an adaptive mechanism. In this formulation, the decision engines select tailored FMFs and rules that are most suited to the incoming traffic type. The results show that adaptive mechanism gives a relative improvement of 90.4%, 88.6% and 25.9% when compared with SAW, the monolithic fuzzy-based HDS and AHP, in the case of VoIP traffic. For video streaming traffic, a relative improvement of 29.83, 23.66% and 8.88% is achieved by the adaptive mechanism when compared with SAW, the monolithic fuzzy-based HDS and AHP.

The paper is organized as follows. The related work is presented in section 2. Section 3 gives an overview of the new approach for handover decision and explains the development of monolithic and modular fuzzy-based handover decision system. Adaptive modular design and enhancement of HDS is given in section 4. Section 5 gives conclusions and future work.

2. Related Vertical Handover Decision Algorithms

Fuzzy-based algorithms have been widely used for

dealing with decision making processes in many different areas, e.g. sensor networks[6], stock trading[7],[8], health care[9], business forecasting[10], and power management [11]. In more recent years, fuzzy-based and related algorithms (e.g. ANFIS) have been the focus of study for the design of intelligent HDSs by many researches.

More specific to handover in wireless networks, these techniques have been employed in a handover triggering algorithm[12]; pre-processing of imprecise input data for Analytical Hierarchy Process (AHP)[13],[14] and Simple Additive Weighting (SAW) algorithms[15]; decision algorithms that consider received signal strength (RSS) and velocity of mobile devices[16],[17]. However, the use of fuzzy logic in all the above applications has been only to assist handover decision engines.

Growing demand for real-time applications in recent years has created a new area of application for fuzzy-based algorithms. Guaranteed QoS (defined by commonly used standards) is one of the principal requirements for real-time applications, such as VoIP or video streaming. This means that the handover decision algorithms must be capable of dealing with the QoS issues. Fuzzy logic appears to have the potential to be used as an effective tool in this regard. As a result, a great deal of effort has been directed towards QoS-aware handover decision algorithms, which are based on fuzzy logic[18]–[21] and ANFIS[22],[23] techniques.

However, only a limited number of decision parameters (e.g. data rate and/or bit error rate (BER)) have been considered in the above works. In[24], jitter and latency have been included in the handover decision model. This work considers three wireless technologies (UMTS, GPRS and WLAN), each with different bandwidth and network delay, but jitter and BER (correlation between BER and packet loss has been explained in a separate study[25]), values are assumed to be identical for all the three networks.

A comparison between fuzzy-based and ANFIS-based algorithms has been carried out in[26]. This work considers three decision parameters (RSS, data rate and usage price), whilst the decision criterion is the number of handovers and execution time. A similar comparison is presented in[27]. In this work RSS and BER are considered as the decision parameters, whilst the decision criterion is the number of handovers.

Clearly, there is a need to extend the above work to include the full range of QoS-related parameters (jitter, latency, packet loss), ideally defined as network dependent variables. The decision process also needs to include other parameters (e.g. usage price of each wireless technology and battery life).

It has been shown that further improvements in fuzzy-based decision algorithms are possible by incorporating adaptive mechanisms within the decision process. In[28], different sets of FMFs are used for received signal strength (RSS) and data rate. Similarly, the adaptive mechanism is implemented by assigning dedicated FMFs to different applications[29]. The results show a reduction in the number of handovers as a result of the adaptive

mechanisms. In an alternative approach, the adaptive mechanism is realized by assigning different (and dedicated) set of decision rules to different types of traffic[24]. In this work, a lower end-to-end delay and higher average bandwidth has been achieved.

The above approaches consider either adaptive FMFs or adaptive decision rules to test the performance of their adaptive mechanisms. Furthermore, a limited number of QoS-related parameters are included in the above studies. An interesting extension of the above adaptive mechanisms would be to consider a combination of adaptive FMFs and decision rules in an integrated decision engine.

3. HDS Design Concept

In this section we are addressing two issues of concern, which were identified in the literature review presented in section 2. The first issue relates to the need for including the full range of QoS-related decision parameters in handover decision algorithms. The second relates to the computational complexity and an unacceptably large execution time as a result of increasing the number of decision parameters. The execution time appears to be a serious limitation of monolithic fuzzy-based decision engines. To deal with the above two issues, we had proposed the modular HDS approach[30]. Here, we present two HDS designs (a typical monolithic and the proposed modular) with much greater detail and compare the results in terms of their wireless network selection ability and the corresponding execution time. Our simulation model in this paper is extended to include random selection of decision parameters in order to achieve a realistic representation of the real-life scenarios.

3.1. Fuzzy System

3.1.1. General Architecture of Fuzzy System

The general architecture of a fuzzy system is shown in figure 2. It comprises five components. Fuzzifier converts crisp inputs into fuzzified data. Rule base contains if-then rules, which are required by the Fuzzy Inference System (FIS). Database defines membership functions of the fuzzy sets. FIS generates aggregated fuzzified data, based on fuzzy inference methods. Defuzzifier converts the aggregated fuzzified data into a scalar value (score). The score is then used to make the final decision.

3.1.2. Mathematical model of a Fuzzy System

Fuzzy rules comprise all possible relationships between decision parameters in IF-THEN rule-based form. The total number of possible rules, T_r , is obtained as follows:

Each input fuzzy variable (a decision parameter) is represented by an input fuzzy set and each set is comprised of a number of memberships, i.e.

$\tilde{A} = \{A_1, A_2, A_3, \dots, A_n\}$ represents a fuzzy set A

$\tilde{B} = \{B_1, B_2, B_3, \dots, B_n\}$ represents a fuzzy set B

:

$\tilde{M} = \{M_1, M_2, M_3, \dots, M_n\}$ represents a fuzzy set M

where n is a number of memberships in the input fuzzy sets, and may or may not have the same numerical value in each fuzzy set.

Assuming the same n for all fuzzy sets, thus the total number of rules, T_r , is given by:

$$T_r = n^M \quad (1)$$

Fuzzy rules are represented in IF-THEN form as follows.

IF A_p and B_p and ... and M_p THEN Z_q

where $p = 1, 2, \dots, n$ and $q = 1, 2, \dots, i$. Z_q is a membership of the output fuzzy set Z , which is given by:

$$\tilde{Z} = \{Z_1, Z_2, Z_3, \dots, Z_i\}$$

where i is the a number of memberships in the output fuzzy set.

Database (in figure 2) defines a mathematical function which embodies the mathematical representation of memberships in a fuzzy set. A number of mathematical functions are available e.g., Triangular, Trapezoidal, Gaussian, etc.

In fuzzification process, if crisp inputs x_1, x_2, \dots, x_m are memberships of fuzzy set $\tilde{A}, \tilde{B}, \dots, \tilde{M}$, respectively, then the degree of membership of x_1, x_2, \dots, x_m in fuzzy set $\tilde{A}, \tilde{B}, \dots, \tilde{M}$ (fuzzified data) is given by:

$$\mu_{\tilde{A}}(x_1) \in [0, 1]$$

$$\mu_{\tilde{B}}(x_2) \in [0, 1]$$

:

$$\mu_{\tilde{M}}(x_m) \in [0, 1] \quad (2)$$

There are two commonly used fuzzy inference methods, namely, Sugeno[31] and Mamdani[32]. Sugeno works well with linear techniques (e.g., PID control) and Mamdani is considered a good choice for its ability to capture expert knowledge in IF-THEN form[33]. In our application, Mamdani is more appropriate FIS.

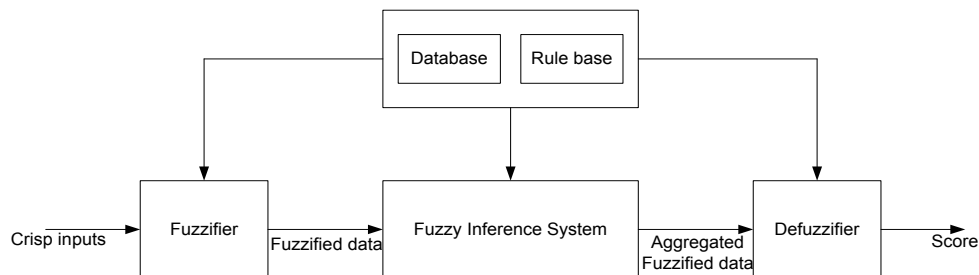


Figure 2. Architecture of a Fuzzy System

Assume Mamdani is applied in our application, a fuzzy system with M inputs (x_1, x_2, \dots, x_m) and a single output (y) is described by a collection of IF-THEN rules in the Mamdani form.

IF x_1 is A_p^k and x_2 is $B_p^k \dots$ and x_m is M_p^k THEN y is Z_q^k , for k^{th} rule, where $k = 1, 2, \dots, T_r$.

This IF-THEN form can be expressed by means of membership function.

$$\mu_{\tilde{Z}^k}(y) = \min[\mu_{\tilde{A}^k}(x_1), \mu_{\tilde{B}^k}(x_2), \dots, \mu_{\tilde{M}^k}(x_m)] \quad (3)$$

where $\mu_{\tilde{Z}^k}(y)$ is a degree of membership of y in output fuzzy set \tilde{Z} of k^{th} rule.

The next stage of the process is the aggregation of the fuzzified data. An aggregated fuzzified data, $\mu_{\tilde{Z}}(y)$, for the total number of T_r rules is given by:

$$\mu_{\tilde{Z}}(y) = \max_k [\min[\mu_{\tilde{A}^k}(x_1), \mu_{\tilde{B}^k}(x_2), \dots, \mu_{\tilde{M}^k}(x_m)]] \quad (4)$$

The aggregated fuzzified data is converted into the final score, y^* , using centroid method, and is given by:

$$y^* = \frac{\int \mu_{\tilde{Z}}(y) \cdot y \, dy}{\int \mu_{\tilde{Z}}(y) \, dy} \quad (5)$$

3.1.3. Monolithic Fuzzy-based HDS

The general principle of a conventional monolithic fuzzy-based HDS[3, 12] is shown in figure 3. In our study, six decision parameters: data rate (DR), latency (LA), jitter (JI), packet loss (PL), usage price (PR) and battery life (BA) are considered. The corresponding input fuzzy sets are denoted by \tilde{DR} , \tilde{LA} , \tilde{JI} , \tilde{PL} , \tilde{PR} , and \tilde{BA} , each with a specific number of fuzzy memberships.

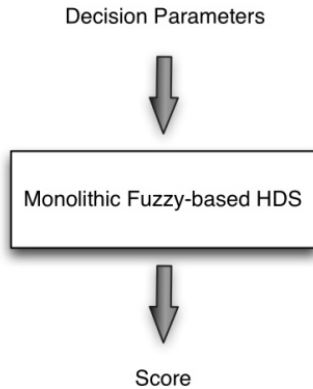


Figure 3. Monolithic Fuzzy-based HDS

The output score of each candidate wireless network is determined and the one which has the highest score is selected for handover.

3.1.4. Modular Fuzzy-based HDS

Our modular fuzzy-based HDS[30] consists of three fuzzy engines, namely Network QoS (NQ), Efficiency (Eff) and Degree of Satisfaction (DS) as shown in figure 4.

The decision parameters are categorized into groups, and each group is dealt with by a different fuzzy engine. The three fuzzy engines jointly determine the final score for each candidate wireless network. The wireless network with the highest final score is selected for handover.

NQ determines the QoS provided by each candidate

wireless network. Data rate (DR), latency (LA), jitter (JI) and packet loss (PL) are obtained from each of the candidate wireless networks. These parameters are used as inputs to NQ in order to formulate the corresponding four fuzzy sets. NQ determines the output score for each wireless network, following the same procedure as that employed by a monolithic engine, and the best score, Q_{best} , is fed to the next fuzzy engine, DS, as shown in figure 4.

Eff determines the efficiency of candidate wireless networks in terms of price (PR) and battery life (BA). The battery life is collected from the wireless node itself, while price is obtained from the candidate wireless networks. Following the same procedure as above, the best score, E_{best} , is fed to the next fuzzy engine, DS (figure 4).

Q_{best} and E_{best} are the two inputs to DS, which are used to formulate the corresponding two fuzzy sets denoted by \tilde{DQ} and \tilde{DE} . DS generates the final score, which is based on the values of Q_{best} and E_{best} . The wireless network with the highest final score is then selected for handover.

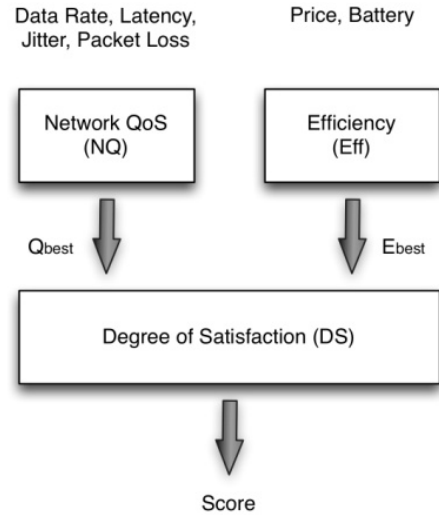


Figure 4. Modular Fuzzy-based HDS

3.2. Development of the Two HDS Designs

This section gives the developmental details for monolithic fuzzy-based and modular fuzzy-based HDS designs, and explains as to how a modular design concept helps to reduce the total number of fuzzy rules.

3.2.1. Monolithic Fuzzy-based HDS Design

With reference to section 3.1.3, six decision parameters ($M = 6$), each with three ($n = 3$) fuzzy memberships (low, medium and high) are used. Using equation 1, the total number of fuzzy rules = $n^M = 3^6 = 729$. Each rule is then assigned a decision output based on expert knowledge. This process formulates an output fuzzy set, \tilde{F}_{mono} , which contains seven memberships-Very Low, Low, Medium-Low, Medium, Medium-High, High and Very High. Our investigation revealed that when dealing with a large number of fuzzy rules, a minimum of seven memberships were required for good resolution of the outputs. A small portion of the fuzzy rules is shown in table 1, as an example.

In this HDS design, each membership of input and output fuzzy sets is represented by triangular function, $f(x)$, of the form:

$$f(x) = \begin{cases} 0, & x \leq a \\ \frac{(x-a)}{(b-a)}, & a \leq x \leq b \\ \frac{(c-x)}{(c-b)}, & b \leq x \leq c \\ 0, & x \geq c \end{cases}$$

where the parameters a , b and c (with $a < b < c$) determine the coordinates of the three corners of the underlying triangular function.

The corresponding FMFs are shown in figure 5. Then, using equation 2, the fuzzified data for the of parameter data rate (as an example) is

$$\mu \tilde{DR}^k(\text{data rate}) \in [0,1]$$

Using equation 4, the aggregated fuzzified data of monolithic fuzzy-based HDS, $\mu \tilde{F}_{mono}$, is given by:

$$\mu \tilde{F}_{mono} = \max_k [\min[\mu \tilde{DR}^k(\text{data rate}), \mu \tilde{LA}^k(\text{latency})],$$

$$\mu \tilde{J}^k(\text{jitter}), \mu \tilde{PL}^k(\text{packet loss}), \\ \mu \tilde{PR}^k(\text{price}), \mu \tilde{BA}^k(\text{battery})]] \\ \text{for } k = 1, 2, \dots, 729$$

where k is the total number of rules.

The final score of wireless network, $Fuzzy_{mono}$, is calculated using equation 5 and is given by:

$$Fuzzy_{mono} = \frac{\int \mu \tilde{F}_{mono}(y) dy}{\int \mu \tilde{F}_{mono}(y) dy}$$

3.2.2. Modular Fuzzy-based HDS Design

With reference to section 3.1.4, the same six decision parameters are categorized into groups of four and two, and used as inputs to NQ and Eff respectively.

Using equation 1, the total number of rules required for NQ and Eff are 81, 9 respectively. In addition, DS has two input requiring a further 9 fuzzy rules. Thus the total number of fuzzy rules becomes 99. The associated FMFs for NQ and Eff are the same as shown in figure 5. The FMFs associated with DS are shown in figure 6.

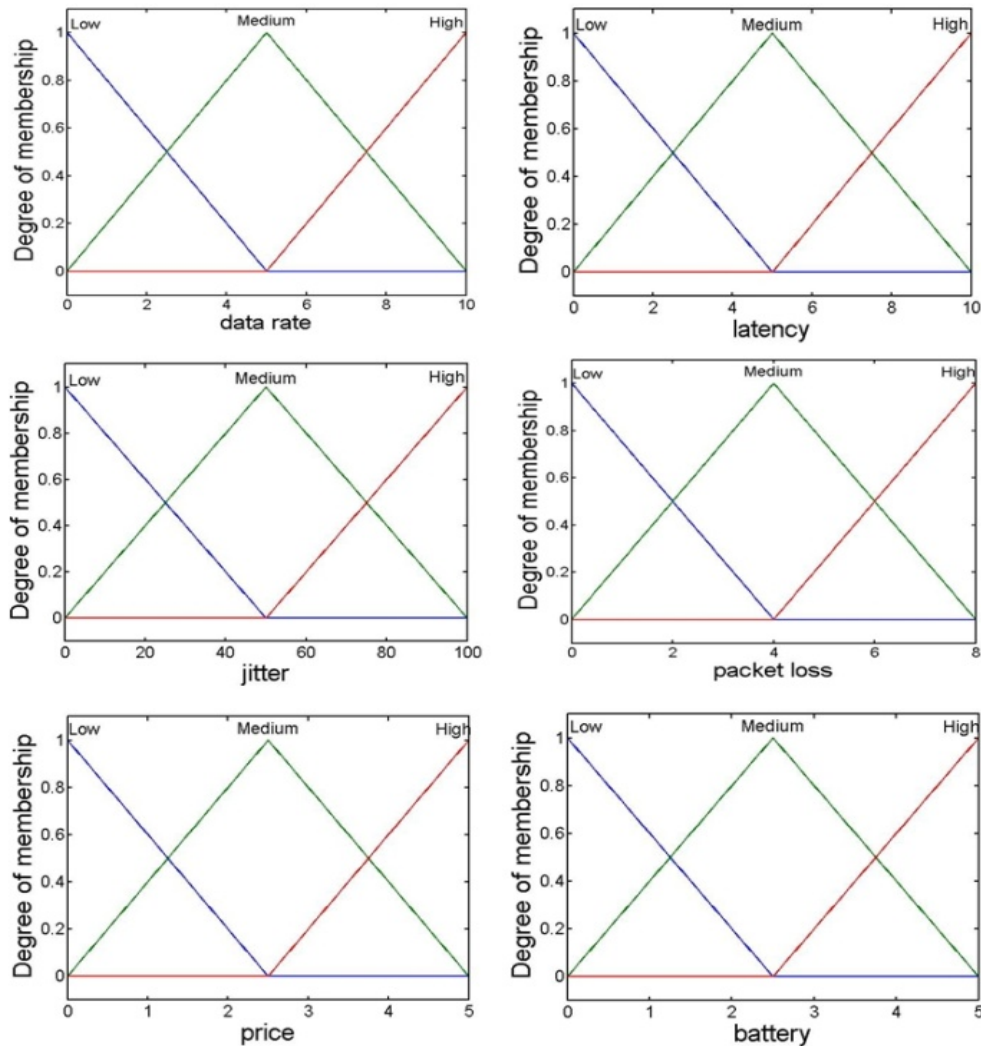


Figure 5. FMFs for Monolithic HDS Design

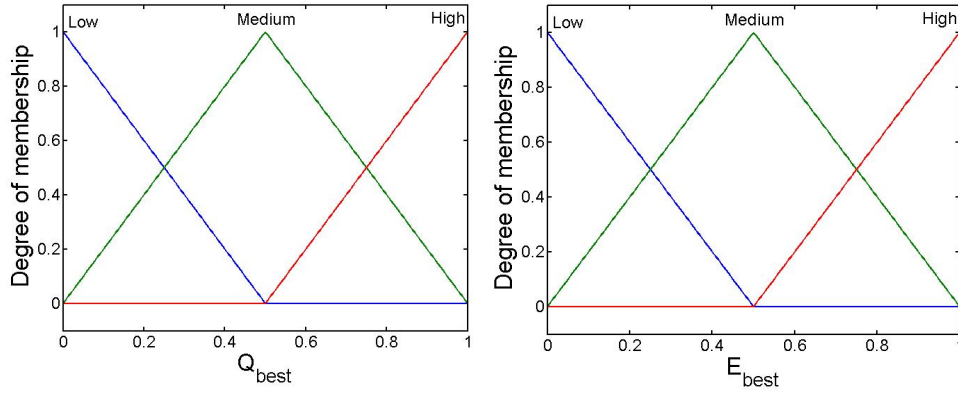


Figure 6. FMFs for DS Engine

Table 1. Fuzzy Rules for Monolithic Fuzzy-based HDS

Rule No.	DR	LA	JI	PL	PR	BA	Output
1	Low	Low	Low	Low	Low	Low	Medium
2	Low	Low	Low	Low	Low	Medium	Medium-High
3	Low	Low	Low	Low	Low	High	High
4	Low	Low	Low	Low	Medium	Low	Medium-Low
5	Low	Low	Low	Low	Medium	Medium	Medium
6	Low	Low	Low	Low	Medium	High	Medium-High
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
729	High	High	High	High	High	High	Very Low

Table 2. Fuzzy rules for NQ, Eff, DS engines

Fuzzy Rules for NQ Engine							
Rule No.	DR	LA	JI	PL			Output
1	Low	Low	Low	Low			Medium
2	Low	Low	Low	Medium			Low
⋮	⋮	⋮	⋮	⋮			⋮
81	High	High	High	High			Low
Fuzzy Rules for Eff Engine							
Rule No.					PR	BA	Output
1					Low	Low	Medium
2					Low	Medium	Medium-High
⋮					⋮	⋮	⋮
9					High	High	Medium
Fuzzy Rules for DS Engine							
Rule No.					Qbest	Ebest	Output
1					Low	Low	Low
2					Low	Medium	Medium-Low
⋮					⋮	⋮	⋮
9					High	High	High

Due to the grouping of the decision parameters, the number of fuzzy rules required for each decision engine is significantly reduced. As a result, only five fuzzy memberships (Low, Medium-Low, Medium, Medium-High, and High) are deemed to be sufficient in order to achieve satisfactory resolution of the outputs.

A small portion of the fuzzy rules for NQ, Eff and DS is shown in table 2.

The fuzzified data for each decision parameter is given by equation 2. The aggregated fuzzified data, $\mu N\tilde{Q}(y)$ and Eff, $\mu E\tilde{F}(y)$, associated with NQ and Eff are given by equation 4:

$$\begin{aligned}\mu N\tilde{Q}(y) &= \max_k [\min[\mu \tilde{D}\tilde{R}^k(\text{datarate}), \mu \tilde{L}\tilde{A}^k(\text{latency}), \\ &\quad \mu \tilde{J}\tilde{I}^k(\text{jitter}), \mu \tilde{P}\tilde{L}^k(\text{packetloss})]], \\ &\quad \text{for } k = 1, 2, \dots, 81 \\ \mu E\tilde{F}(y) &= \max_k [\min[\mu \tilde{P}\tilde{R}^k(\text{price}), \mu \tilde{B}\tilde{A}^k(\text{battery})]], \\ &\quad \text{for } k = 1, 2, \dots, 9\end{aligned}$$

The output scores, Q_{best} and E_{best} , generated by NQ and Eff engines respectively are given by equation 5:

$$\begin{aligned}Q_{best} &= \frac{\int \mu N\tilde{Q}(y).ydy}{\int \mu N\tilde{Q}(y).dy} \\ E_{best} &= \frac{\int \mu E\tilde{F}(y).ydy}{\int \mu E\tilde{F}(y).dy}\end{aligned}$$

Similarly, the aggregated fuzzified data, $\mu\tilde{DS}(y)$, associated with DS, is given by:

$$\mu\tilde{DS}(y) = \max_k [\min[\mu\tilde{DQ}^k(Q_{best}), \mu\tilde{DE}^k(E_{best})]],$$

for $k=1, 2, \dots, 9$

The final score of wireless network, DS, is given by:

$$DS = \frac{\int \mu\tilde{DS}(y).y dy}{\int \mu\tilde{DS}(y) dy}$$

3.3. Simulations and Results

To evaluate the performance of each design, three wireless network technologies, namely: WLAN, WiMAX and Cellular (supporting High Speed Packet Access (HSPA), which supports data rate up to 7.2 Mbps) and two traffic types (VoIP and video streaming) were included in the simulation model. VoIP CODEC (G.711) with a data rate of 64 kbps was assumed for voice traffic. For video streaming, H.264 coding format with a bit rate of 0.8 – 1 Mbps, and audio encoding (AAC) with audio bit rate of 96 kbps were assumed.

The actual values for the decision parameters were randomly selected from the range given in table 3 for VoIP and table 4 for video streaming traffic (a random selection for the decision parameters values gives a more realistic representation of the real-life scenarios). The usage price for individual technologies was set at a fixed value and assumed to be incremental (i.e. WLAN to be least expensive and Cellular to be most expensive[34]).

The range of values for decision parameters in tables 3 and 4 were taken either from real-life tests or commonly used standards, e.g. data rates were taken from the real-life speed tests given in [35],[36] and [37] for WLAN, WiMAX and Cellular network, respectively. The battery life values were obtained from the battery life analysis given in [38]. A suitable range of values was specified for each of the QoS parameters (latency, jitter and packet loss). Commonly used QoS standards for VoIP and video streaming are also given in table 3 and 4 respectively [5].

The two HDS designs given in section 3.2.1 and 3.2.2 were developed using MATLAB Fuzzy Logic Toolbox and simulated on MATLAB platform.

As the output score generated by the algorithms is based on a random process (the input parameter values are randomly selected), it is necessary to carry out a suitable number of simulation runs and then to take the average value of several rounds. Thus, the performance of the HDS designs was evaluated using the following procedure.

For each of the two traffic types 10 rounds, each round containing 200 runs of simulations, were carried out. The performance criterion chosen was the percentage success (PS), defined as the number of times (expressed as a percentage) the HDS selected the wireless network that had the highest score among the three wireless networks and fully satisfied the QoS requirements. Each round of 200 runs generated a value for PS. Finally, the average of the 10 rounds was taken as a trial (T). To observe the stability of T, the above process was repeated 10 times to obtain results for 10 trials.

The performance of the two HDS designs, in terms of network selection, is compared in figures 7 and 8 for VoIP and video streaming, respectively. The results, in figures 7, show that the performance of the modular fuzzy-based HDS is marginally better than the monolithic fuzzy-based HDS. In case of video streaming, figure 8, the performance is almost identical. The results in figure 7 and 8 also demonstrate stability of T as the fluctuations in the results are insignificant.

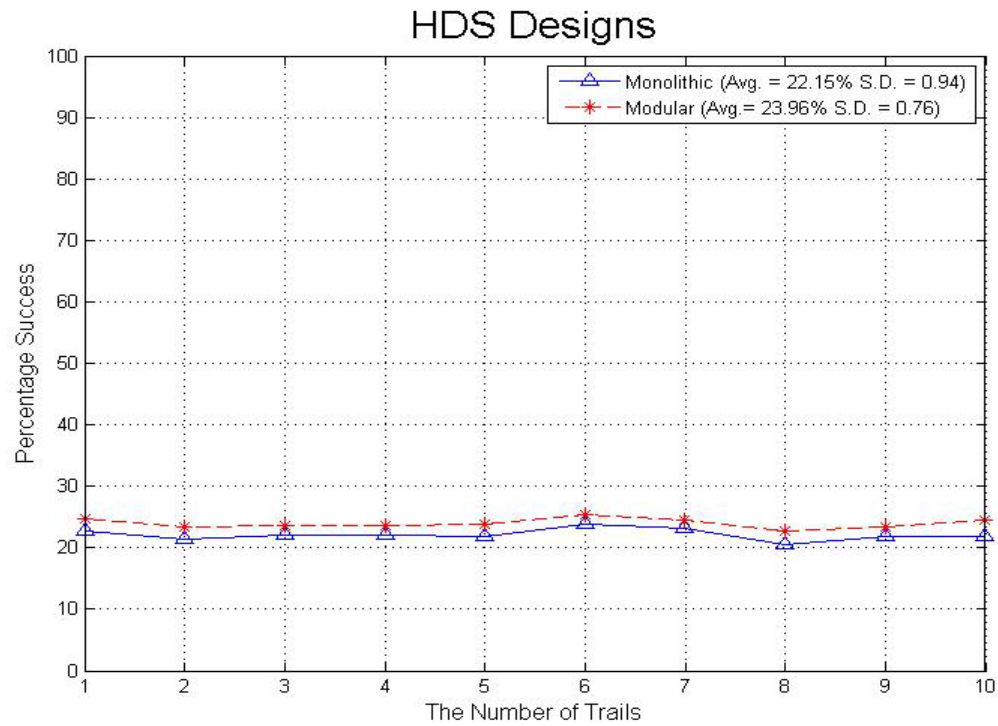
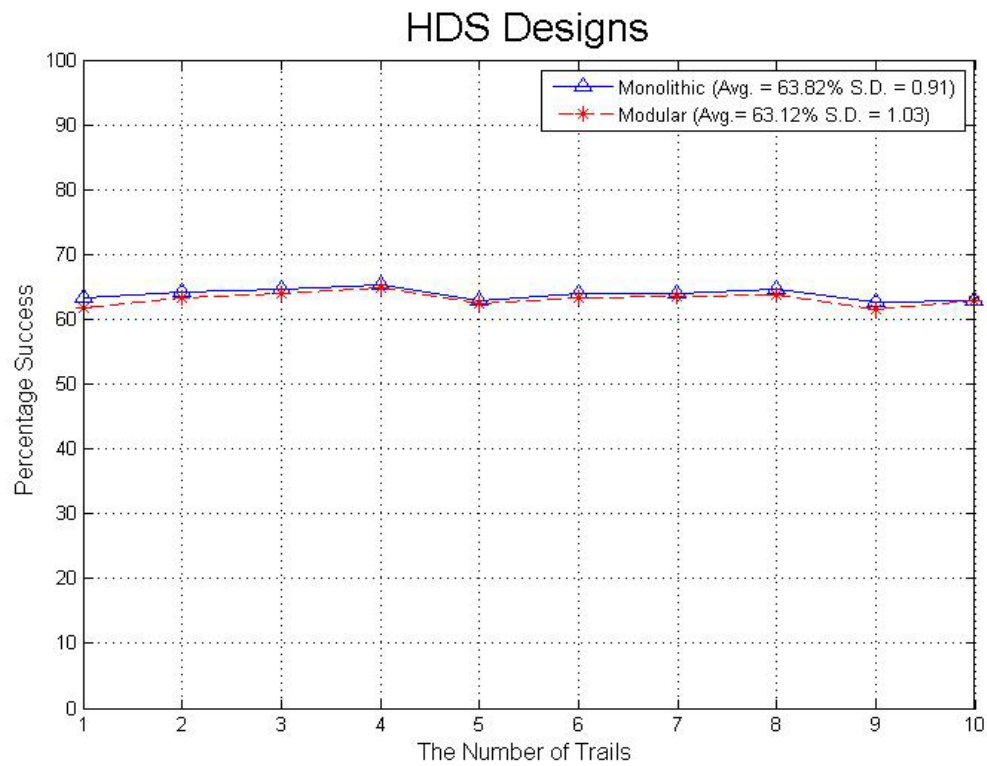
The second issue of concern was the unacceptably large execution time (τ) due to increasing number of decision parameters. This evaluation was carried out on a 1.86GHz Intel Core 2 Duo with 2GB memory. The performance of the two HDS designs, in term of τ , is compared in figure 9. The results show a reduction of 89.37% in the value of τ , which suggests that a significant improvement can be achieved by the modular design.

Table 3. Decision Parameters for VoIP traffic

Network	Data Rate (Mbps)	Latency (ms)	Jitter (ms)	Packet Loss (%)	Price (unit/min)	Battery (hours)
WLAN	1 - 8	0 – 300 (Rec.<150)	0 – 50 (Rec.<30)	0.01 – 2 Rec: <1%	1	2.5 - 5
WiMAX	3 - 6				2	0.55x[2.5– 5]
Cellular	1 - 5				3	0.74x[2.5– 5]

Table 4. Decision Parameters for Video Streaming Traffic

Network	Data Rate (Mbps)	Latency (s)	Jitter (ms)	Packet Loss (%)	Price (unit/min)	Battery (hours)
WLAN	1 - 8	0 – 7 (Rec. <4-5)	0 – 50 None	0.01 – 7 (Rec.<5%)	1	2.5 - 5
WiMAX	3 - 6				2	0.55x[2.5– 5]
Cellular	1 - 5				3	0.74x[2.5– 5]


Figure 7. Network Selection Performance – VoIP

Figure 8. Network Selection Performance – Video Streaming

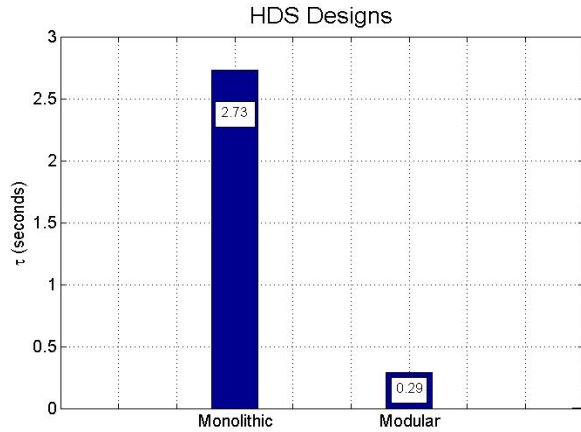


Figure 9. Algorithm Execution Time

4. Adaptive Modular Fuzzy-based HDS Design

It is a common knowledge that different traffic types have different QoS requirements. It therefore makes good sense to employ dedicated and tailored FMFs and fuzzy rules for different traffic types. In order to achieve this objective, we have incorporated an adaptive mechanism within the modular fuzzy-based HDS design.

4.1. Architecture of Adaptive Modular Fuzzy-based HDS

The general architecture of adaptive modular fuzzy-based HDS (AMHDS) is shown in figure 10. It has two dedicated NQ engines, namely, NQ-CBR and NQ-VBR and they are concerned with the QoS requirements of CBR and VBR traffics, respectively. Each engine contains a tailored set of FMFs and dedicated fuzzy rules to match the corresponding traffic. An additional module (NQ selector) is required to identify the incoming traffic type and select the appropriate NQ engine.

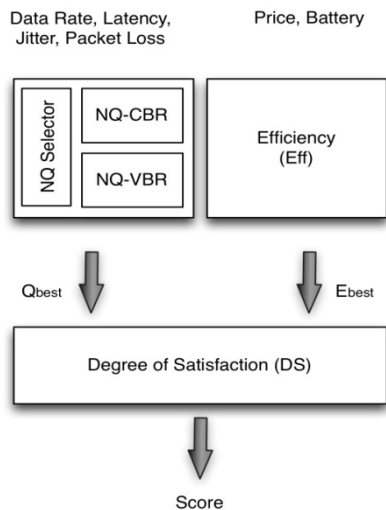


Figure 10. Adaptive Modular Fuzzy-based HDS

The NQ selector periodically sniffs incoming packets with sufficient frequency to detect traffic activity. The traffic type

is identified by receiving a flag from the application layer. This can be obtained from the commonly used session initiation protocol (SIP), which runs at the application layer. SIP has the ability to differentiate between CBR and VBR traffics. Thus, the NQ selector selects one of the two engines using the following logic (shown figure 11):

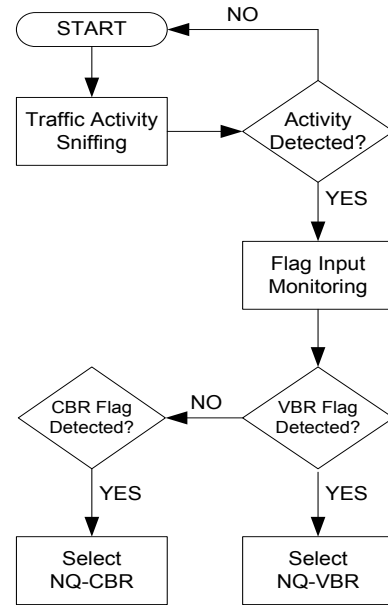


Figure 11. NQ Selection Logic

- Traffic activity is present and CBR flag is received - select NQ-CBR engine.
- Traffic activity is present and VBR flag is received - select NQ-VBR engine.

Figure 12 and 13 give tailored FMFs for NQ-CBR and NQ-VBR engines, respectively. Figure 14 gives FMFs for Eff and DS engines. Tables 5 and 6 give a small portion of fuzzy rules for NQ-CBR and NQ-VBR engines, respectively. The fuzzy rules for Eff and DS engines are given in table 2 (in section 3.2.2).

4.2. Simulation and Results

Based on the simulation procedures given in section 3.3, the performance of AMHDS design was evaluated. The results are compared with SAW[39], AHP[40] and the monolithic fuzzy-based HDS design in figures 15 and 16 for VoIP and video streaming, respectively.

Equal weighting is used for all decision parameters in the case of SAW. For AHP, the preference values for generating a pair-wise comparison matrix (for DR, LA, JI, LO, PR and BA) is 7, 9, 9, 9, 5 and 3. Hence the weighting values for AHP algorithm are 0.0772, 0.2901, 0.2901, 0.2901, 0.0336 and 0.0190.

It is convenient for comparison to take the average value of 10 trials for each of the two designs. The network selection performance of AMHDS is significantly better than others. AMHDS gives a relative improvement of 90.4%, 88.6% and 25.9% when compared with SAW, the monolithic design and AHP, in the case of VoIP traffic (figure 15).

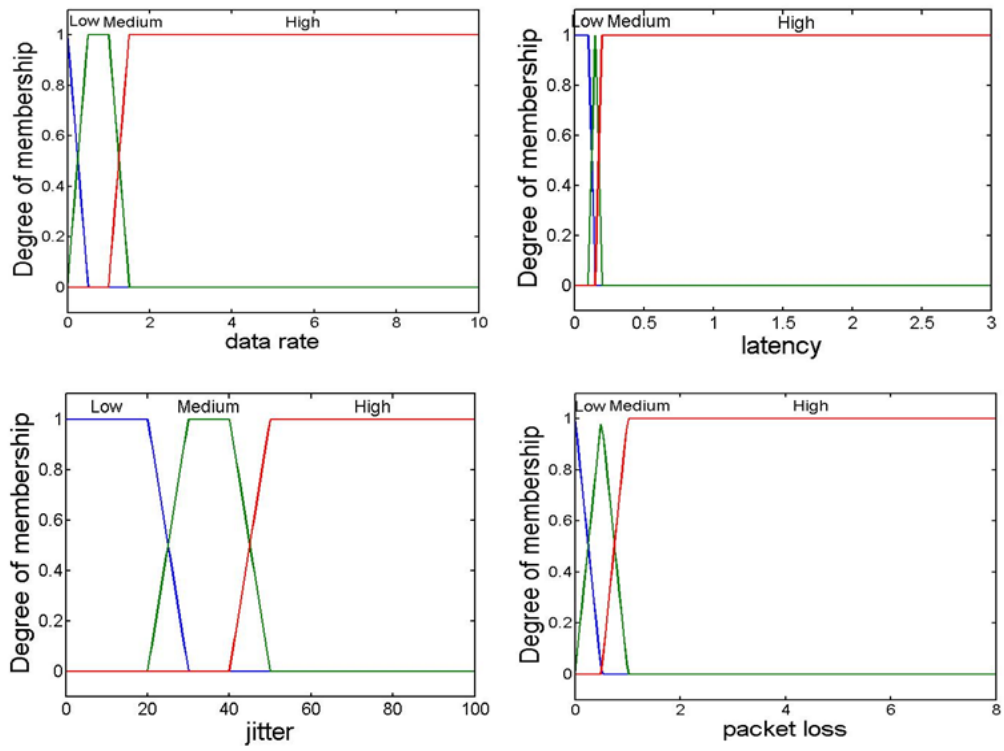


Figure 12. FMFs for NQ-CBR Engine

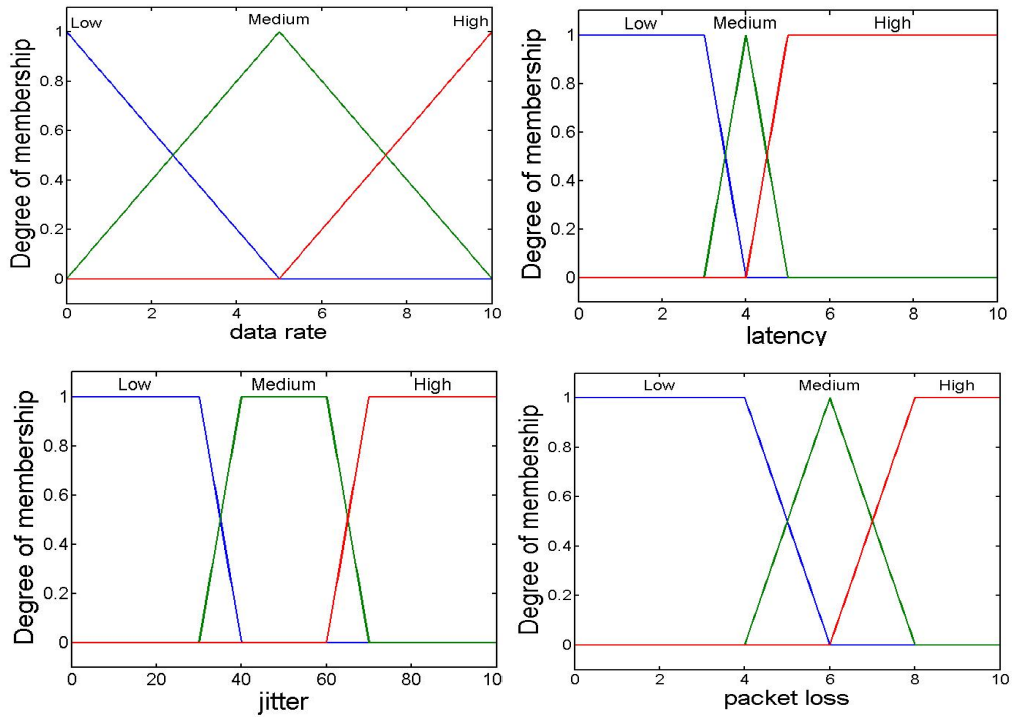
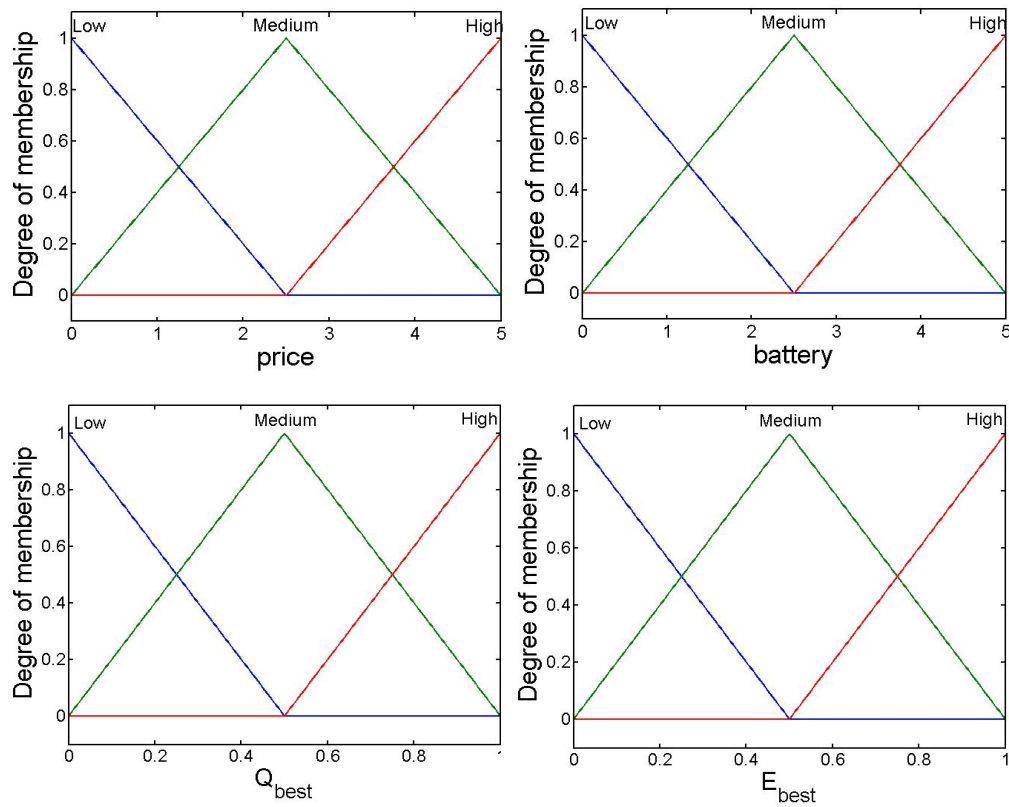


Figure 13. FMFs for NQ-VBR Engine

**Figure 14.** FMFs for Eff and DS Engines**Table 5.** Fuzzy Rules for NQ-CBR Engine

Fuzzy Rules for NQ-CBR Engine							
Rule No.	DR	LA	JI	PL			Output
1	Low	Low	Low	Low			Medium
:	:	:	:	:			:
4	Low	Low	Medium	Low			Medium-Low
5	Low	Low	Medium	Medium			Low
6	Low	Low	Medium	High			Low
:	:	:	:	:			:
81	High	High	High	High			Low

Table 6. Fuzzy Rules for NQ-VBR Engine

Fuzzy Rules for NQ-VBR Engine							
Rule No.	DR	LA	JI	PL			Output
1	Low	Low	Low	Low			Medium
:	:	:	:	:			:
4	Low	Low	Medium	Low			Medium
5	Low	Low	Medium	Medium			Medium-Low
6	Low	Low	Medium	High			Low
:	:	:	:	:			:
81	High	High	High	High			Low

In the case of video streaming traffic, a relative improvement of 29.83, 23.66% and 8.88% is achieved by AMHDS (figure 16) when compared with SAW, the monolithic design and AHP. The results in figures 15 and 16 clearly demonstrate that an adaptive mechanism that employs tailored FMFs and fuzzy rules, which are carefully matched to the incoming traffic, has the potential to give significant improvements.

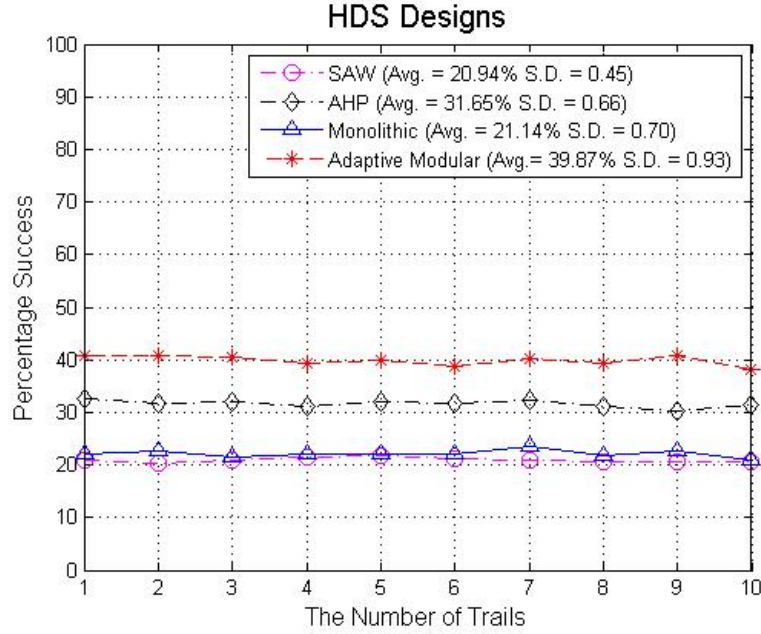


Figure 15. Network Selection Performance – VoIP

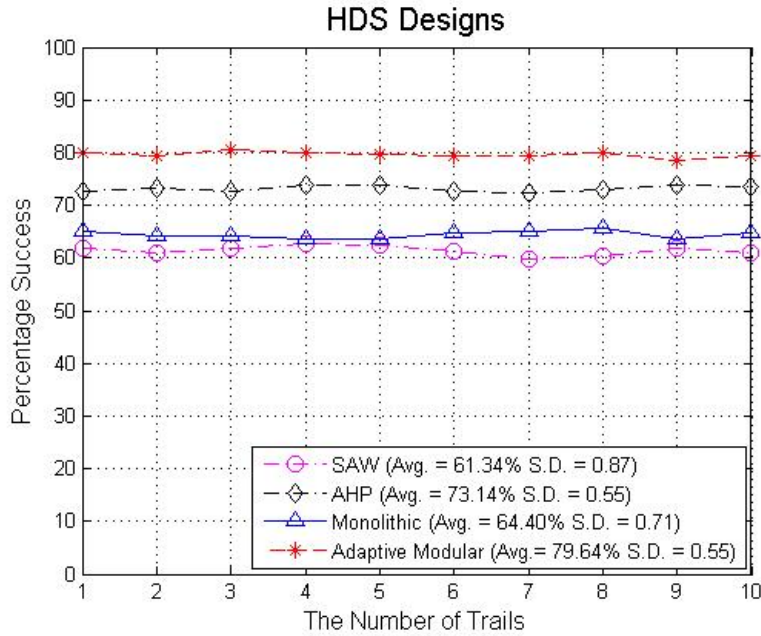


Figure 16. Network Selection Performance – Video Streaming

5. Conclusions

In view of the growing trends in real-time services over wireless networks, it is necessary to include the full range of QoS-related parameters in HDS performance evaluations. A fuzzy-based approach has the potential to improve HDS intelligence but often becomes inefficient in terms of execution time, due to computational complexity of the decision algorithms, as the number of decision parameters increases.

We have proposed a modular fuzzy-based HDS design to deal with the above problem. We have presented two HDS designs, namely, a typical monolithic fuzzy-based HDS and

the proposed modular fuzzy-based HDS and evaluated their performance in terms of network selection and the execution time. The results show that the performance of the two HDS designs is comparable for network selection but the proposed modular fuzzy-based HDS design gives a significant improvement in terms of algorithm execution time. The algorithm execution time has been reduced by almost 90%.

Recognizing the fact that different traffic types have different QoS requirements, we have incorporated an adaptive mechanism within the modular fuzzy-based HDS design, which employs dedicated and tailored FMFs and fuzzy rules for different traffic types. As the FMFs and the corresponding fuzzy rules are matched to the incoming

traffic, the performance, in terms of network selection, has been enhanced significantly. The results show that AMHDS gives a relative improvement of 90.4%, 88.6% and 25.9% when compared with SAW, the monolithic design and AHP, in the case of VoIP traffic. For video streaming traffic, a similar picture emerges when comparing AMHDS with SAW, the monolithic design and AHP.

The future direction of our research is to facilitate self-tuning of the FMFs in real-time, enabling the HDS to respond to changes in user preferences.

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