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RESEARCH ARTICLE - ELECTRICAL ENGINEERING

A Quality-Aware Fuzzy-Logic-Based Vertical Handover Decision Algorithm for Device-to-Device Communication

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Abstract

Device-to-device (D2D) communication is expected to play a significant role in the fifth-generation (5G) networks. To support seamless mobility and service continuity, the device(s) undergoing D2D communication should be handed over to the best access network among all the available wireless access networks. A seamless vertical handover (VHO) across the heterogeneous wireless networks is the key enabling solution for achieving the seamless service continuity and mobility. The VHO algorithm should be intelligent, and the decisions should also consider the quality requirements other than the conventional received signal strength (RSS). In this work, a two-stage fuzzy-logic-based VHO decision algorithm is developed to select suitable access network based on the quality-of-service requirements. The quality parameters like data rate and latency are given as the fuzzy inputs along with RSS. The resource availability check is also carried out for the target network, which makes the decision more intelligent. The simulation results show that the proposed scheme offers better performance than the traditional multi-attribute decision-making schemes.

Keywords Access network selection · Device-to-device (D2D) communication · Fuzzy logic · Quality of service (QoS) · Seamless mobility · Vertical handover (VHO)

1 Introduction

In order to support the exponentially growing traffic demands of the subscribers and to support various applications, fourth-generation (4G) standards will be soon replaced by 5G [1]. D2D is being considered as an important component for 5G networks. It is expected to increase the spectral efficiency, system capacity and throughput. Simultaneously, it is expected to reduce the power consumption and latency [2]. The various possible applications of D2D communication are elaborated in Fig. 1.

This technology allows two devices to communicate without the help of evolved node B (eNB). Due to direct links and smaller distances, it can support network power saving. It also effectively offloads the traffic from the core network. Due to the mobility, the device(s) undergoing D2D communication may move into the adjacent network. Because of this, link from the current network or the other device may break down. This may cause severe degradation in QoS. The devices may move across different wireless networks and wireless technologies. If the wireless technology used in the current network and target network is the same, then the horizontal handover is preferred, otherwise VHO is preferred [3].

When one of the D2D devices move away from the other device, the direct link between the devices may break down. To support seamless service, one of the devices is handed over to the best possible access network. Now, these two devices are not in D2D communication; instead, they may communicate each other with cellular links. This type of handover in D2D is called as half handover. At some point, there are chances that both the devices may move away from the current network. Due to this, the link quality from the current network may become poor. To support seamless services, both the devices are jointly handed over to the best possible network. This type of handover in D2D is called as joint handover. The half and joint handovers in D2D communication are explained in Figs. 2, 3 and 4. In Fig. 2, two devices D1 and D2 are in D2D connection. When one of the devices D2

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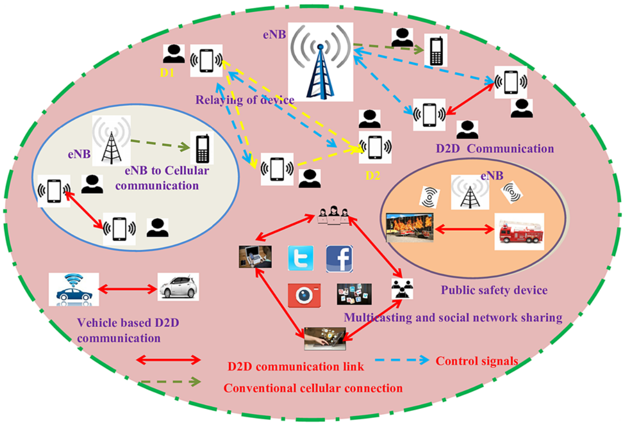


Fig. 1 D2D communication and its applications

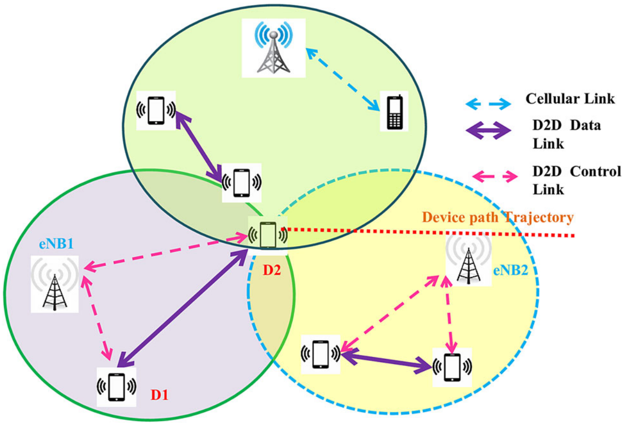


Fig. 2 Before handover

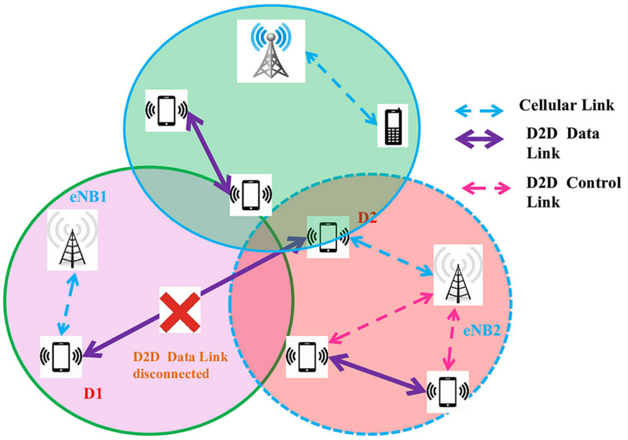


Fig. 3 After half handover

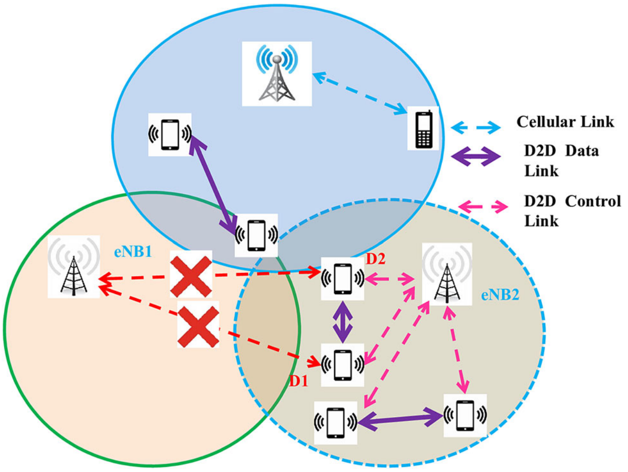


Fig. 4 After joint handover

move towards eNB2, the D2D link between D1 and D2 are disconnected. The device D2 is handed over to eNB2. Now the devices D1 and D2 will communicate through cellular links as displayed in Fig. 3. When both the devices in D2D communication move towards eNB2, the links from eNB1 are disconnected. Both the devices are jointly handed over to eNB2 as displayed in Fig. 4.

Most of the traditional approaches use RSS to make handover decisions. These approaches compare RSS of the current network with the RSS of the other available networks to make handover decisions. These approaches yield severe ping-pong effect when the device moves around the overlay region of various heterogeneous networks [4,5]. This ping-pong effect leads to unessential handover and brings low throughput, high handover delay and high dropping rate. In VHO, many network parameters have an effect on deciding the handover. These include security, cost, QoS performance (throughput, data rate, delay, jitter, latency, etc.), power consumption and available bandwidth [5]. The QoS criteria of various wireless technologies, which can be considered for handover, are listed in Table 1.

A cost function-based VHO algorithm is proposed in [6]. The cost function considers different parameters such as cost, power consumption and available bandwidth. A vertical handover decision function (VHDF) is proposed in [7]. This function is evaluated for all the available networks. The network with highest VHDF is selected as the most desirable network for handover. In order to obtain the highest possible QoS, the network with maximum available bandwidth is chosen as the target network.

Many of the VHO algorithms use rank to select the best network among different available networks. These algorithms depend on various QoS parameters as well as different criteria like terminal capabilities, user profile and network state. MADM algorithms are very popular to solve these types of problems [8]. The very popular MADM algorithms in the literature are simple additive weighting (SAW) [9], technique for order preference by similarity to ideal solution (TOPSIS) [10], VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [11]. Due to their decision accuracy and lower computational complexity, MADM methods are

Table 1 Various QoS criteria [5]

Radio Access Technology (RAT)	RSS (dBm)	DR (Mb/s)	LA (ms)
Long Term Evolution-Advanced (LTE-A)	− 115/− 50	30.4–80	40–80
Worldwide Interoperability for Microwave Access (WiMAX)	− 105/− 50	2–50	60–120
Wireless Fidelity (Wi-Fi)	− 100/− 50	1–13.5	100–150
High Speed Packet Access (HSPA)	− 100/− 50	0.2–6	30–100

widely preferred for VHO decisions. But these methods will not be the best choice when the number of QoS parameters is increased. The increase in the QoS parameters increases the computational complexity and decision delays.

In general, the artificial intelligence-based algorithms are expected to provide more accurate decisions. Because of the intelligent decisions, fuzzy systems can be effectively used in computer-based decision-making process. A fuzzy set theory represents ambiguous data in an innate form. It can be used to model complex systems fairly and without bias, which is not possible for analytic hierarchy process (AHP)-based algorithms [12]. The fuzzy rules are developed based on the human knowledge, which models the system output. Hence, the researchers started using it for various problems associated with wireless communication. Fuzzy systems can simultaneously process a large number of parameters and make a soft decision. A fuzzy system is composed of four components like fuzzifier, fuzzy inference engine (FIE), fuzzy rules and defuzzifier [13]. The crisp inputs are converted into fuzzified data with the help of fuzzifier. The fuzzy rules are used by FIE. Based on the membership functions and rules, FIE generates aggregated fuzzified data, which is changed to a crisp output using defuzzifier.

The input parameters used for VHO decision-making are not precise or numbered. Most of the VHO decision-making depends on RSS, which fluctuates based on the velocity, distance, shadowing factor, etc. This makes the handover decision unreliable. The imprecise input parameters may cause inaccurate VHO decision, which may cause under- or over-utilization of network resources. Fuzzy logic can effectively handle imprecise data related to radio, QoS parameters and user preferences [5].

Fuzzy logic can also be used in VHO decisions. Fuzzy-based algorithms are intelligent, fast and reliable, which always keeps decision delay lower even when the number of RATs and input parameters are increased. This minimizes unessential handovers and decision delays and maximizes the percentage of user satisfaction. Fuzzy-logic-based algorithms are highly accurate and offer higher network efficiency, but they are also highly complex [14–17]. The increase in the number of input parameters and the membership functions increases the complexity. Hence, to address the trade-off between reliability and complexity, the fuzzy input parameters, rules and the number of fuzzy controllers should be appropriately chosen as per the objectives.

In recent years, various fuzzy-logic-based handover decision algorithms are proposed. A fuzzy logic in conjunction with one of the MADM called TOPSIS is proposed in [18] to minimize the handover latency, blocking probability and unessential handovers between WiMAX and 4G standards. The proposed approach uses four fuzzy controllers like RSS, QoS, velocity and battery life to make decisions. The output from each fuzzy controller is fed into TOPSIS to determine the most appropriate target network for handover. To reduce handover latency and unessential handovers in LTE network, a fuzzy-logic-based handover triggering approach is proposed in [19], which triggers handover in a timely manner. A QoS-aware fuzzy-logic-based network selection scheme is proposed in [20] to guarantee the network QoS. This scheme suffers from unacceptable execution time, which actually increases with the number of decision parameters. The increased execution time increases the handover latency.

In [21], the trade-off between complexity and consistency in target network selection is addressed with the help of fuzzy logic. Here, the authors discuss three different approaches such as fuzzy-only approach, fuzzy integrated with AHP and principal component analysis (PCA) and fuzzy integrated with fuzzy analytic hierarchy process (FAHP) and PCA. Based on the parameters such as velocity, network traffic load and cost, fuzzy logic controllers estimate the user satisfaction degree (USD) and necessity of handover. As per the traffic, FAHP is used to determine the weights of the attributes. Fuzzy logic effectively handles the uncertainty and vagueness associated in mapping the customer preference to the priority scales. This improves the consistency level in target network selection. PCA is used to process the weighted decision matrix, and QoS factor of each network is calculated. Through simulation results, it has been shown that FAHP-PCA scheme offers better performance in reducing the number of handovers than fuzzy-only and AHP-PCA scheme. Fuzzy logic improves the consistency level of network selection by reducing the number of handovers 5, 7 and 10 times compared to fuzzy-only, TOPSIS and SAW-based schemes. FAHP-PCA also reduces the number of operations in network selection process. In [5], fuzzy MADM algorithms like Fuzzy-SAW, Fuzzy-TOPSIS and Fuzzy-VIKOR are proposed. Fuzzy logic is used in intelligent decision-making and MADM handles the issues associated with the increased number of inputs. Here, four different fuzzy logic controllers like RSS, QoS (data rate and delay), mobile velocity and battery level are used. FIE uses a total of 31 fuzzy rules. The fuzzy logic combined with classical MADM methods reduces the decision time, handover delays and complexity compared with classical MADM schemes.

The proposed scheme should select the target network very fast so that there may not be any service interruption. The quick handover mechanism should minimize the handover failures. The handover failure causes the packet loss, which degrades the system quality. The proposed scheme should also utilize the network resources efficiently. The handover process should be reliable so that after the handover, the QoS like data rate, latency, jitter and throughput must be satisfactory. The proposed scheme should also minimize unnecessary handovers. The unnecessary handover causes under-utilization of network resources.

The rest of the paper is organized in the following order: The fuzzy system used for VHO decision-making is elaborated in Sect. 2. A two-stage target network selection algorithm based on the fuzzy logic is briefed in Sect. 3. The complexity analysis is carried out in Sect. 4. The performance of the proposed scheme is validated through simulation results in Sect. 5. Section 6 concludes the paper by highlighting the scope for future work.

2 Fuzzy System for Handover Decision-Making

The efficient selection of appropriate inputs, membership functions and rules make fuzzy logic a suitable candidate for target network selection. In this work, RSS, data rate (DR) and latency (LA) are given as the input for FIE. Mamdani-based fuzzy system is used in this work [22]. Because of simple formulas and lower computational complexity, both trapezoidal and triangular membership functions are widely used in real-time applications. The subjective degree of convenience to achieve fuzzy linguistic scale coverage is more for trapezoidal than for triangular membership functions. Fuzzy input range is divided equally (approximately 30%) for three linguistic variables, and the membership functions are developed accordingly. Depending on this, 27 rules are developed. If we use five linguistic variables for every input, there will be 125 fuzzy rules, which will increase the overall computational complexity. The defuzzifier works based on centre-of-gravity method [23]. The crisp output from the defuzzifier is handoff factor (HF), which is used to rank the networks during the target network selection stage. Five membership functions for HF are framed. The three-input fuzzy system used for VHO decision-making is illustrated in Fig. 5.

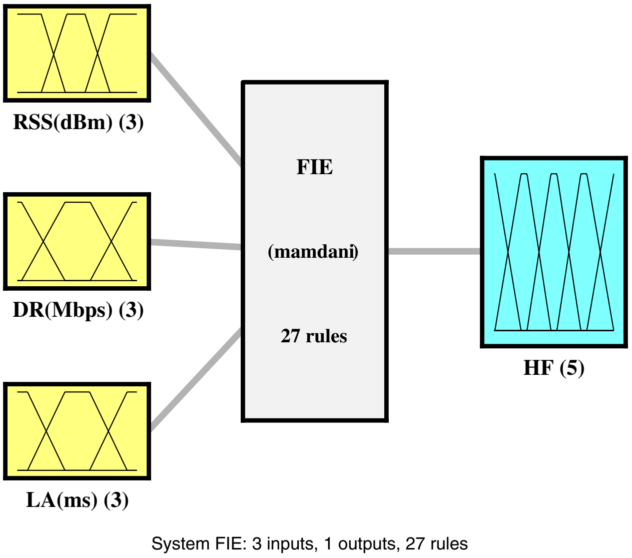


Fig. 5 FIE with three inputs

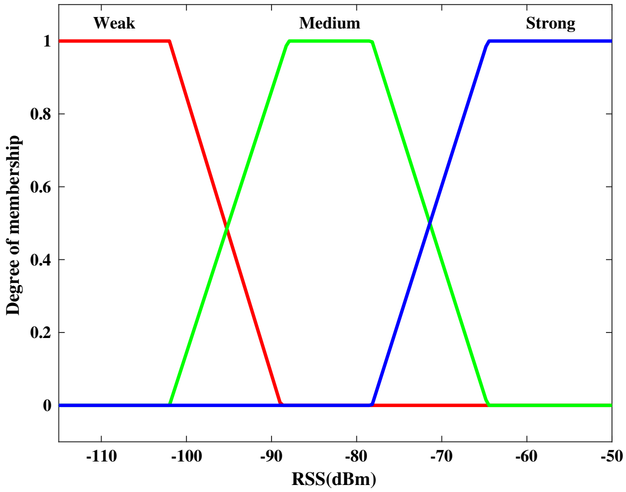


Fig. 6 Membership diagram for RSS

After the handover, the service received from the target network should have good quality. The RSS from the target network influences signal-to-noise ratio (SNR), signal-to-interference plus noise ratio (SINR), bit error rate (BER) and capacity [24]. The reduction in signal strength from a serving network leads to service interruption and service drop. Thus, RSS is an important metric in considering the target network for handover. The fuzzy sets for RSS of ith network are represented by the linguistic variables *weak*, *medium* and *strong*. These are described by the membership functions $R_1{}^i(\alpha)$, $R_2{}^i(\alpha)$ and $R_3{}^i(\alpha)$, respectively. The range for RSS is considered to be − 115 to − 50 dBm as shown in Table 1. The related degree of membership plot is displayed in Fig. 6.

$$R_1{}^{i}(\alpha) = \begin{cases} 1, & \text{if } -115 \le \alpha \le -102 \\ \frac{-88.9-\alpha}{13.1}, & \text{if } -102 \le \alpha \le -88.9 \\ 0, & \text{if } \alpha \ge -88.9 \end{cases} \tag{1}$$

$$R_2{}^{i}(\alpha) = \begin{cases} 0, & \text{if } \alpha < -102 \\ \frac{\alpha+102}{13.1}, & \text{if } -102 \le \alpha \le -88.9 \\ 1, & \text{if } -88.9 \le \alpha \le -78.2 \\ \frac{-64.6-\alpha}{13.6}, & \text{if } -78.2 \le \alpha \le -64.6 \\ 0, & \text{if } \alpha \ge -64.6 \end{cases} \tag{2}$$

$$R_3{}^{i}(\alpha) = \begin{cases} 0, & \text{if } \alpha \le -78.2 \\ \frac{\alpha+78.2}{13.6}, & \text{if } -78.2 \le \alpha \le -64.6 \\ 1, & \text{if } -64.6 \le \alpha \le -50 \end{cases} \tag{3}$$

As per International Mobile Telecommunication standard (IMT)-Advanced requirements, the peak data rate from a target network is expected to be 1 Gbps and user-experiencing data rate is expected to be 10 Mbps. As per IMT-2020 requirements, the peak data rate is expected to be 20 Gbps and user-experiencing data rate from a target network is expected to be in the range of 100–1000 Mbps. The data rate demand from a target network varies based on the service. The data rate demand for web services is less than 500 Kbps, and for video and streaming services, the demand can reach up to 10 Mbps. Maintaining a satisfactory user-experiencing data rate is a major challenging task during a handover process. Thus, data rate offered by a target network is also given as one of the inputs for FIE. The fuzzy sets for data rate of ith network are represented by the linguistic variables *low*, *medium* and *high*. These are described by the membership functions $D_1{}^{i}(\beta)$, $D_2{}^{i}(\beta)$ and $D_3{}^{i}(\beta)$, respectively. The range for data rate is considered to be 1–80 Mbps as shown in Table 1. The related degree of membership plot is displayed in Fig. 7.

$$D_1{}^{i}(\beta) = \begin{cases} 1, & \text{if } \beta \le 3.821 \\ \frac{32.5-\beta}{28.6}, & \text{if } 3.821 \le \beta \le 32.5 \\ 0, & \text{if } \beta \ge 32.5 \end{cases} \tag{4}$$

$$D_2{}^{i}(\beta) = \begin{cases} 0, & \text{if } \beta < 3.821 \\ \frac{\beta-3.821}{28.6}, & \text{if } 3.821 \le \beta \le 32.5 \\ 1, & \text{if } 32.5 \le \beta \le 49.2 \\ \frac{77-\beta}{27.8}, & \text{if } 49.2 \le \beta \le 77 \\ 0, & \text{if } \beta \ge 77 \end{cases} \tag{5}$$

$$D_3{}^{i}(\beta) = \begin{cases} 0, & \text{if } \beta \le 49.2 \\ \frac{\beta-49.2}{27.8}, & \text{if } 49.2 \le \beta \le 77 \\ 1, & \text{if } 77 \le \beta \le 80 \end{cases} \tag{6}$$

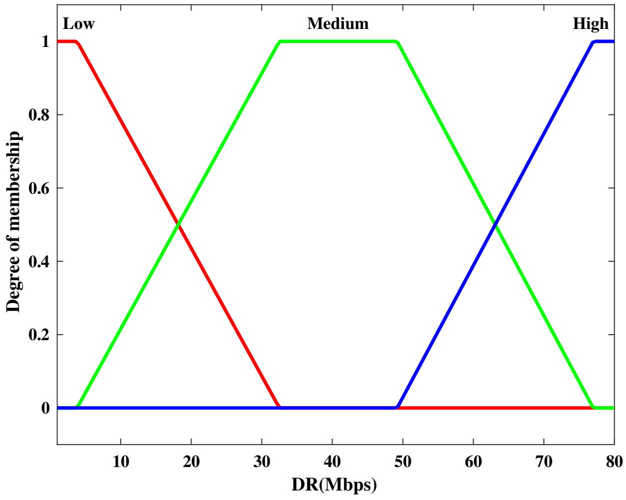


Fig. 7 Membership diagram for data rate

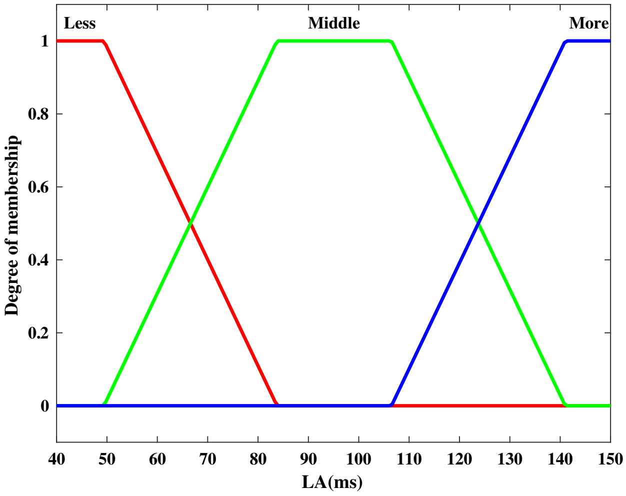


Fig. 8 Membership diagram for latency

As per IMT-Advanced, the latency is expected to be less than 10 ms and in IMT-2020, the latency is expected to be less than 1 ms. Latency increases the packet queuing delay, which is undesired for many real-time data services. Thus, latency is considered as one of the inputs for FIE. The fuzzy sets for latency of ith network are represented by the linguistic variables *less*, *middle* and *more*. These are described by the membership functions $L_1{}^{i}(\gamma)$, $L_2{}^{i}(\gamma)$ and $L_3{}^{i}(\gamma)$, respectively. The range for latency is considered to be 40–150 ms as shown in Table 1. The related degree of membership plot is displayed in Fig. 8.

$$L_1{}^{i}(\gamma) = \begin{cases} 1, & \text{if } \gamma \le 49.41 \\ \frac{83.76-\gamma}{34.35}, & \text{if } 49.41 \le \gamma \le 83.76 \\ 0, & \text{if } \gamma \ge 83.76 \end{cases} \tag{7}$$

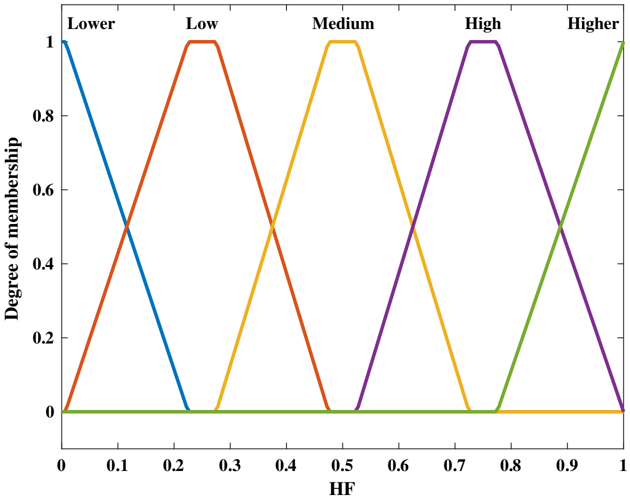


Fig. 9 Membership diagram for HF

$$L_2{}^i(\gamma)=\begin{cases}0, & \text{if } \gamma\le 49.41\\ \frac{\gamma-49.41}{34.35}, & \text{if } 49.41\le\gamma\le 83.76\\ 1, & \text{if } 83.76\le\gamma\le 106.5\\ \frac{141-\gamma}{34.5}, & \text{if } 106.5\le\gamma\le 141\\ 0, & \text{if } \gamma\ge 141\end{cases}\tag{8}$$

$$L_3{}^i(\gamma)=\begin{cases}0, & \text{if } \gamma\le 106.5\\ \frac{\gamma-106.5}{34.5}, & \text{if } 106.5\le\gamma\le 141\\ 1, & \text{if } 141\le\gamma\le 150\end{cases}\tag{9}$$

A fuzzy set called HF is used to decide the target network. The fuzzy sets for HF of ith network are represented by the linguistic variables *lower*, *low*, *medium*, *high* and *higher*. These are described by the membership functions $\text{HF}_1{}^i(\eta)$, $\text{HF}_2{}^i(\eta)$, $\text{HF}_3{}^i(\eta)$, $\text{HF}_4{}^i(\eta)$ and $\text{HF}_5{}^i(\eta)$, respectively. The related degree of membership plot is displayed in Fig. 9.

$$\text{HF}_1{}^i(\eta)=\begin{cases}1, & \text{if } \eta\le 0\\ \frac{0.225-\eta}{0.225}, & \text{if } 0\le\eta\le 0.225\\ 0, & \text{if } \eta\ge 0.225\end{cases}\tag{10}$$

$$\text{HF}_2{}^i(\eta)=\begin{cases}0, & \text{if } \eta\le 0\\ \frac{\eta}{0.225}, & if\ \ 0\le\eta\le 0.225\\ 1, & \text{if } 0.225\le\eta\le 0.275\\ \frac{0.475-\eta}{0.2}, & \text{if } 0.275\le\eta\le 0.475\\ 0, & \text{if } \eta\ge 0.475\end{cases}\tag{11}$$

$$\text{HF}_3{}^i(\eta)=\begin{cases}0, & \text{if } \eta\le 0.275\\ \frac{\eta-0.275}{0.2}, & \text{if } 0.275\le\eta\le 0.475\\ 1, & \text{if } 0.475\le\eta\le 0.525\\ \frac{0.725-\eta}{0.2}, & \text{if } 0.525\le\eta\le 0.725\\ 0, & \text{if } \eta\ge 0.725\end{cases}\tag{12}$$

$$\text{HF}_4{}^i(\eta)=\begin{cases}0, & \text{if } \eta\le 0.525\\ \frac{\eta-0.525}{0.2}, & \text{if } 0.525\le\eta\le 0.725\\ 1, & \text{if } 0.725\le\eta\le 0.775\\ \frac{1-\eta}{0.225}, & \text{if } 0.775\le\eta\le 1\\ 0, & \text{if } \eta\ge 1\end{cases}\tag{13}$$

$$\text{HF}_5{}^i(\eta)=\begin{cases}0, & \text{if } \eta\le 0.775\\ \frac{\eta-0.775}{0.225}, & \text{if } 0.775\le\eta\le 1\\ 1, & \text{if } \eta\ge 1\end{cases}\tag{14}$$

where HF ∈ [0,1]. In the fuzzy logic, linguistic variables are used to map the input sets to the output sets. The rules for the FIE are developed based on the input and output fuzzy sets. The fuzzy rules used by the FIE are listed in Table 2.

RSS is the fundamental parameter in VHO decision. In general, RSS-based algorithms are low complex and least accurate. The fluctuations in RSS will also cause inaccurate decisions [25–27]. In order to achieve higher data rate and lower latency, data rate and latency are also considered as the input parameters in VHO decision-making process. The conventional approaches do not consider the complexities arising when dealing with the uncertainties and sudden input variations. Because of its strength in adapting as per the randomly changing inputs and dealing with uncertainties, fuzzy logic is used in the proposed VHO decision-making process. RSS, DR and LA of every available network are given as the input for FIE. Based on the developed fuzzy rules, the FIE output HF of every network is identified. The network with maximum HF is the most preferable network for handover so that the handed over device may get highest data rate with lowest latency. Figure 10 explains the process of HF calculation, which is used in stage 1 of the algorithm. For a sample simulation scenario, RSS, DR and LA take values of − 55.9, 44.3 and 53.9, respectively. The degree of membership of RSS for the linguistic variables like *weak*, *medium* and *strong* are 0, 0 and 1, respectively. The degree of membership of DR for the linguistic variables like *low*, *medium* and *high* are 0, 1 and 0, respectively. Similarly, the degree of membership of LA for the linguistic variables like *less*, *middle* and *more* are

Table 2 Fuzzy rules for VHO decision-making

Rule	RSS	DR	LA	HF
1	*Strong*	*High*	*Less*	*Higher*
2	*Strong*	*High*	*Middle*	*Higher*
3	*Strong*	*High*	*More*	*High*
4	*Strong*	*Medium*	*Less*	*Higher*
5	*Strong*	*Medium*	*Middle*	*High*
6	*Strong*	*Medium*	*More*	*High*
7	*Strong*	*Low*	*Less*	*Low*
8	*Strong*	*Low*	*Middle*	*High*
9	*Strong*	*Low*	*More*	*Medium*
10	*Medium*	*High*	*Less*	*High*
11	*Medium*	*High*	*Middle*	*Medium*
12	*Medium*	*High*	*More*	*Medium*
13	*Medium*	*Medium*	*Less*	*Medium*
14	*Medium*	*Medium*	*Middle*	*Medium*
15	*Medium*	*Medium*	*More*	*Medium*
16	*Medium*	*Low*	*Less*	*Low*
17	*Medium*	*Low*	*Middle*	*Low*
18	*Medium*	*Low*	*More*	*Low*
19	*Weak*	*High*	*Less*	*Low*
20	*Weak*	*High*	*Middle*	*Low*
21	*Weak*	*High*	*More*	*Low*
22	*Weak*	*Medium*	*Less*	*Lower*
23	*Weak*	*Medium*	*Middle*	*Low*
24	*Weak*	*Medium*	*More*	*Lower*
25	*Weak*	*Low*	*Less*	*Lower*
26	*Weak*	*Low*	*Middle*	*Lower*
27	*Weak*	*Low*	*More*	*Lower*

0.86, 0.13 and 0, respectively. These values fall under rules 4 and 5. HF is calculated with the help of centre-of-gravity method [28] using

$$\mathrm{HF} = \frac{\sum_{i=1}^{T} \mathrm{HF}\,(\eta_i)\,\eta_i}{\sum_{i=1}^{T} \mathrm{HF}\,(\eta_i)} \tag{15}$$

where T is the number of samples required to calculate HF. For the considered sample scenario, HF obtained is 0.786.

The variations of HF value with respect to any two of the three inputs are shown in Figs. 11, 12 and 13. In Fig. 11, HF versus DR-RSS combination is plotted. It is clear that the increase in DR and RSS increases the HF. In Fig. 12, HF versus LA-RSS combination is plotted. From the surface plot, it is understood that for the higher RSS and lower LA, the HF is higher. In Fig. 13, HF versus LA-DR combination is plotted. It is observed that for higher DR and lower LA, the HF is higher.

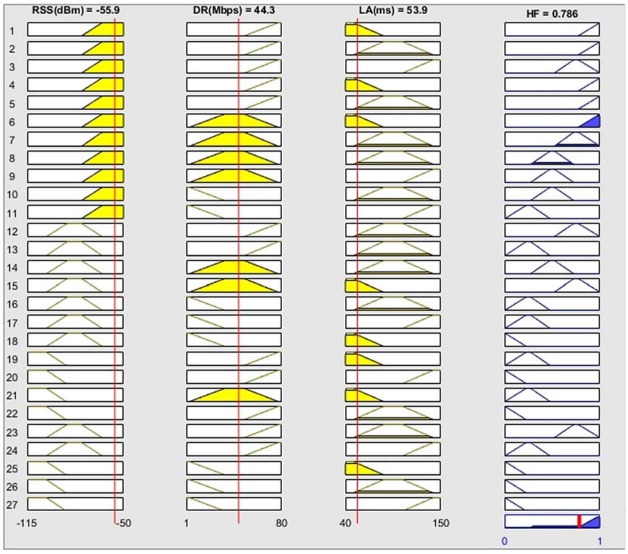


Fig. 10 Rule viewer plot for HF calculation

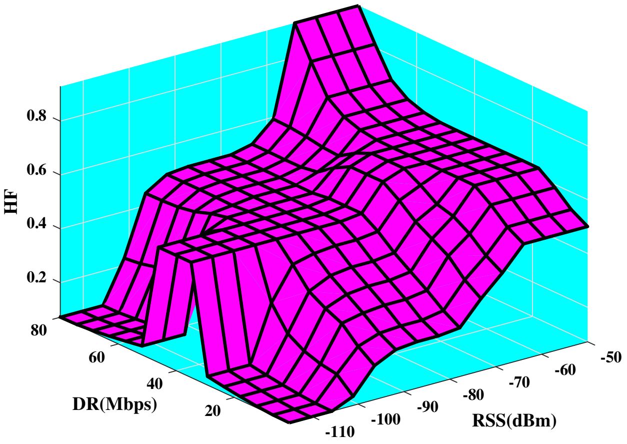


Fig. 11 Surface plot HF versus DR-RSS combinations

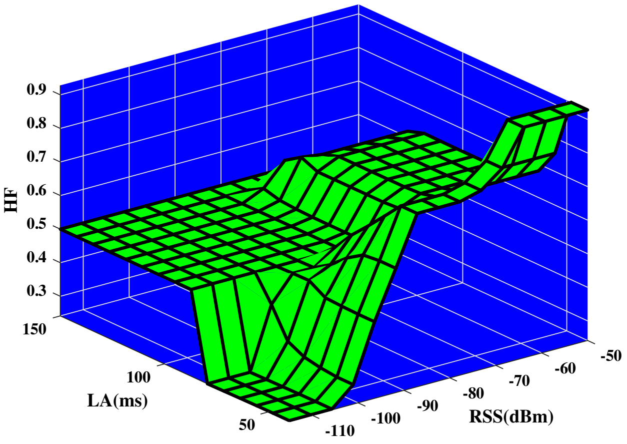


Fig. 12 Surface plot HF versus LA-RSS combinations

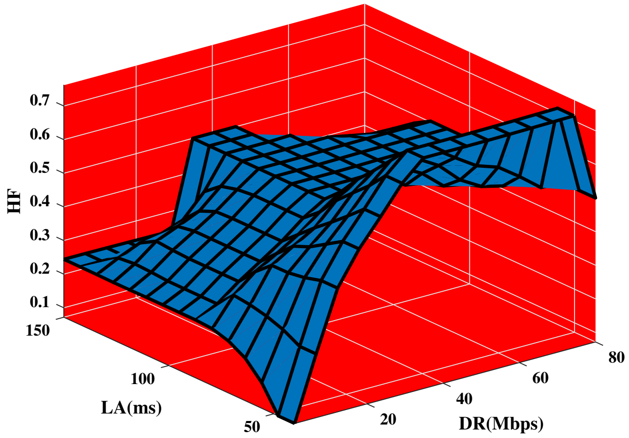
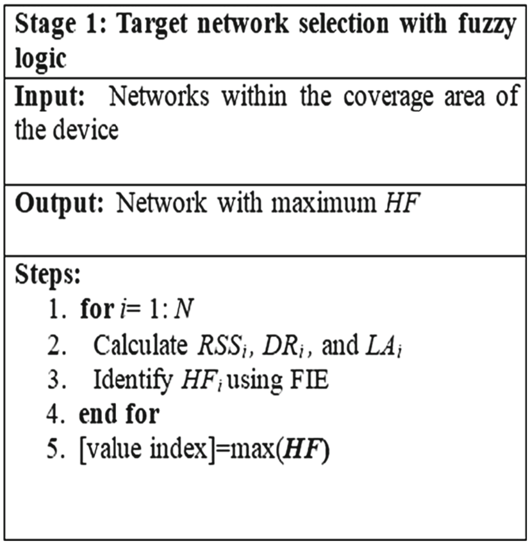


Fig. 13 Surface plot HF versus LA-DR combinations



```
Stage 1: Target network selection with fuzzy logic
Input: Networks within the coverage area of the device
Output: Network with maximum HF
Steps:
  1. for i= 1: N
  2.     Calculate $RSS_i$, $DR_i$, and $LA_i$
  3.     Identify $HF_i$ using FIE
  4. end for
  5. [value index]=max(HF)
```

Fig. 14 Algorithm for stage 1: network with maximum HF selection

3 Two-Stage Target Network Selection Algorithm

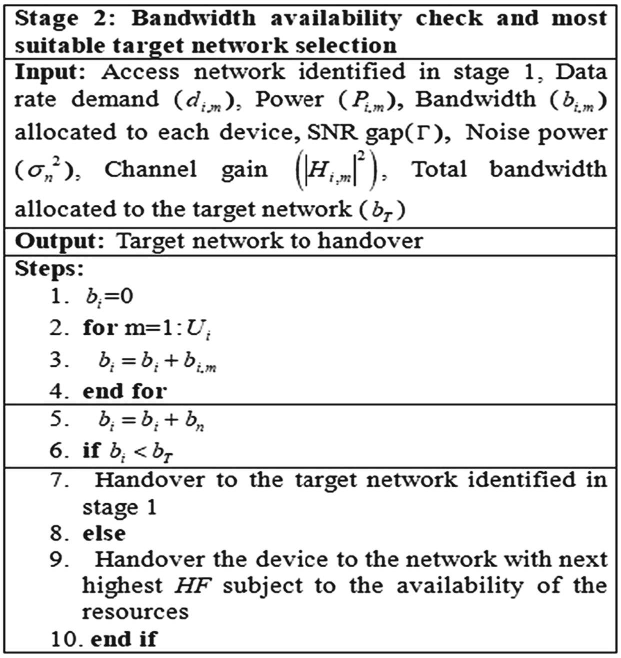
The objectives of the proposed scheme are summarized as

$$\mathrm{DR} \geq \overline{\mathrm{DR}} \tag{16}$$

$$\mathrm{LA} \geq \overline{\mathrm{LA}} \tag{17}$$

where $\overline{\mathrm{DR}}$ and $\overline{\mathrm{LA}}$ are target data rate and latency. The experienced data rate and latency should satisfy the conditions in (16) and (17). The proposed network selection scheme is executed in two stages. In the first stage, the network with highest HF is selected and in the second stage, bandwidth availability of the identified network is measured.

The steps involved in stage 1 of the proposed algorithm are displayed in Fig. 14. The networks within the coverage range of the device are given as the input for this stage. In step 2, RSS, DR and LA of each available network are given as the input for FIE. The corresponding HF is measured in step 3. Steps 2 and 3 are repeated for all available networks. The network with highest HF is recognized in step 5. N used in step 1 represents the number of available networks within the coverage area of the device. If the HF is maximum for the current network, no handover is required.



```
Stage 2: Bandwidth availability check and most suitable target network selection
Input: Access network identified in stage 1, Data rate demand ($d_{i,m}$), Power ($P_{i,m}$), Bandwidth ($b_{i,m}$) allocated to each device, SNR gap($\Gamma$), Noise power ($\sigma_n^2$), Channel gain ($|H_{i,m}|^2$), Total bandwidth allocated to the target network ($b_T$)
Output: Target network to handover
Steps:
  1. $b_i$=0
  2. for m=1:$U_i$
  3.     $b_i = b_i + b_{i,m}$
  4. end for
  5. $b_i = b_i + b_n$
  6. if $b_i < b_T$
  7.     Handover to the target network identified in stage 1
  8. else
  9.     Handover the device to the network with next highest HF subject to the availability of the resources
  10. end if
```

Fig. 15 Algorithm for stage 2: bandwidth availability check and most suitable target network selection

Many of the conventional algorithms do not consider the resource (bandwidth and power) availability of the target network. Insufficient resources significantly affect the QoS of the system. It may also lead to connection breakdown. This issue is taken care by the stage 2 of the proposed algorithm. The resource availability check for the network identified in stage 1 is carried out in stage 2. The data rate achieved from the ith network by mth device is given by [29]

$$d_{i,m} = b_{i,m} \log_2 \left(1 + \frac{P_{i,m} \left| H_{i,m} \right|^2}{\Gamma {\sigma_n}^2} \right) \tag{18}$$

where $b_{i,m}$ and $P_{i,m}$ are the bandwidth and power allocated to mth device by ith network, Γ is the SNR gap, ${\sigma_n}^2$ is noise power and $\left| H_{i,m} \right|^2$ is the channel gain between ith network and mth device. The minimum bandwidth required to maintain the expected data rate is given by [29]

$$b_{i,m} = \frac{d_{i,m}}{\log_2 \left(1 + \frac{P_{i,m} \left| H_{i,m} \right|^2}{\Gamma {\sigma_n}^2} \right)} \tag{19}$$

Table 3 Stage-wise complexity analysis of the proposed scheme

Stage	Number of additions	Number of multiplications	Number of comparisons	Number of LUT access
1	$2N(T-1)$	$N(T+1)$	$N(N\log N)$	–
2	$3U_i+1$	$5U_i+1$	1	U_i
Total	$2N(T-1)+(3U_i+1)$	$N(T+1)+(5U_i+1)$	$N(N\log N)+1$	U_i

Table 4 Complexity comparison of various fuzzy-based schemes

Factors	Fuzzy-only approach [31]	Fuzzy integrated with AHP-PCA [21]	Fuzzy integrated with FAHP-PCA [21]	Fuzzy MADM [5]	Proposed
Number of fuzzy logic controllers	4	3	3	4	1
Number of fuzzy rules	84	57	57	31	27

Stage 2 of the proposed algorithm is illustrated in Fig. 15. The access network identified in stage 1, data rate demand ($d_{i,m}$), power ($P_{i,m}$) and bandwidth ($b_{i,m}$) allocated to each device, SNR gap (Γ), noise power (${\sigma_n}^2$), channel gain ($\left|H_{i,m}\right|^2$) and total bandwidth allocated to the target network (b_{T}) are given as the input for stage 2. The best target network for handover is identified from stage 2. Total bandwidth utilized by the network is initialized to zero in step 1. Based on the data rate requirement, the required bandwidth to be allocated for mth device is calculated using (19). This is repeated for all devices under ith network. At the end of step 4, total bandwidth utilized by the network can be obtained. U_i in step 2 represents the total number of devices already connected to the target network. The bandwidth required for the new device to attain the target data rate is identified using (19). This bandwidth is added to the utilized bandwidth in step 5, which gives the total bandwidth required by the network to support the devices including the new device. b_n mentioned in step 5 is the bandwidth required by the new device. If this value is less than the total bandwidth allocated to the target network (b_{T}), the device is handed over to the target network identified in stage 1. This is carried out in steps 6 and 7. Otherwise, the device is handed over to the network with next highest HF subject to the availability of the resources. Step 9 is executed based on load- aware spectral-efficient routing (LASER) scheme [30].

4 Complexity Analysis

The computational complexity of the proposed fuzzy-logic-based two-stage network selection algorithm is explained in this section. In step 2 of stage 1, RSS, DR and LA of each network within the coverage area of the device are given as the input and the corresponding FIE output HF is calculated in step 3. HF is calculated using centre-of-gravity method [28]. Each HF calculation requires $2(T-1)$ additions and $(T+1)$ multiplications. Steps 2 and 3 are repeated for N times. In step 5, the network with maximum HF is recognized. This requires $N(N\log N)$ comparisons. Thus, stage 1 requires $2N(T-1)$ additions, $N(T+1)$ multiplications and $N(N\log N)$ comparisons.

The computational complexity of stage 2 is explained here. The channel gain $\left(\left|H_{i,m}\right|^2\right)$ computation requires 2 multiplications and 1 addition. Each of the operations $P_{i,m}\left|H_{i,m}\right|^2$ and $\Gamma{\sigma_n}^2$ requires 1 multiplication. $\frac{P_{i,m}\left|H_{i,m}\right|^2}{\Gamma{\sigma_n}^2}$ operation requires 1 multiplication. $\left(1+\frac{P_{i,m}\left|H_{i,m}\right|^2}{\Gamma{\sigma_n}^2}\right)$ requires 1 addition. $\log_2\left(1+\frac{P_{i,m}\left|H_{i,m}\right|^2}{\Gamma{\sigma_n}^2}\right)$ needs 1 lookup table (LUT) access. $\frac{d_{i,m}}{\log_2\left(1+\frac{P_{i,m}\left|H_{i,m}\right|^2}{\Gamma{\sigma_n}^2}\right)}$ requires 1 multiplication. Thus, in order to calculate bandwidth required for a device to meet the expected data rate require 6 multiplications, 2 additions and 1 LUT access. The b_i update in step 3 requires 1 addition. Step 3 is repeated for U_i number of times. Hence, steps 2 to 4 require $5U_i+1$ multiplications, $3U_i$ additions and U_i LUT access. The b_i update in step 5 requires 1 addition and step 6 requires 1 comparison. Thus, stage 2 requires $5U_i+1$ multiplications, $3U_i+1$ additions, 1 comparison and U_i times LUT access. The stage-wise computational complexity of the proposed scheme is summarized in Table 3.

The order of time complexity $(O(n))$ for Mamdani is $O\left(N_{\mathrm{rule}}\times N_{\mathrm{dim}}\right)$, where N_{rule} represents the number of fuzzy rules and N_{dim} represents the number of fuzzy inputs. It is clear that time complexity is directly related to the number of fuzzy rules framed for fuzzification and defuzzification process. The time complexity of various fuzzy-based VHO algorithms is tabulated in Table 4.

Table 5 Parameters considered for simulation

RAT	Transmit power (dBm)	Cell radius (km)	Bandwidth (b_T) (MHz)
LTE-A	46	3	100
WiMAX	47	10	40
Wi-Fi	13	0.25	20
HSPA	43	1	40
GSM	31	5	0.2

5 Simulation Results and Discussion

The VHO algorithms are simulated for various RATs like LTE-A, WiMAX (IEEE 802.16m), Wi-Fi (IEEE 802.11n), HSPA and Global System for Mobile Communication (GSM). The performance of the proposed scheme is compared with the traditional MADM approaches like SAW [9], TOPSIS [10], VIKOR [11] and fuzzy-based approaches like FAHP-PCA [21], Fuzzy-SAW [5] in terms of QoS indicators like decision delay, data rate and the probability of handover failure. We have used MATLAB 2017a tool to create the simulation scenarios and fuzzy toolbox to build the FIE. The parameters considered for simulation study are listed in Table 5. The noise variance and SNR gap are assumed to be −174 dBm/Hz and 7.63, respectively. For simplicity, we assume fixed power allocation to each service-requesting device. Based on the data rate demand, bandwidth allocated to each device is alone varied. The power allocated to each device is assumed to be 0.01 mW.

The path loss models considered for LTE-A [32], WiMAX (IEEE 802.16m) [33], Wi-Fi (IEEE 802.11n) [34], HSPA [35,36] and GSM [37] are listed below

$$\mathrm{PL(dB)}^{\mathrm{LTE-A}} = 103.8 + 20.9 \log_{10} \mathrm{d(km)} \tag{20}$$

$$\mathrm{PL(dB)}^{\mathrm{WiMAX}} = 130.62 + 37.6 \log_{10} \mathrm{d(km)} \tag{21}$$

$$\mathrm{PL(dB)}^{\mathrm{Wi-Fi}} = 34.48 + 32.79 \log_{10} \mathrm{d(m)} \tag{22}$$

$$\mathrm{PL(dB)}^{\mathrm{HSPA}} = 128.1 + 37.6 \log_{10} \mathrm{d(km)} \tag{23}$$

$$\mathrm{PL(dB)}^{\mathrm{GSM}} = 40 \log_{10} \mathrm{d(km)} + 30 \log_{10} \mathrm{(fc)} + 49 \tag{24}$$

Based on the transmit power and path loss, the RSS value can be measured. The RSS, bandwidth and noise power are used to measure the achievable data rate from a target network. The propagation delay influences the latency. As discussed in Sect. 3, RSS, data rate and latency of each of the above network are given as the input for FIE. The corresponding fuzzy output HF of each network for the considered sample scenario is displayed in Fig. 16. The HF of Wi-Fi network is higher than the other four networks, so the device chooses Wi-Fi as the target network subject to the availability of bandwidth.

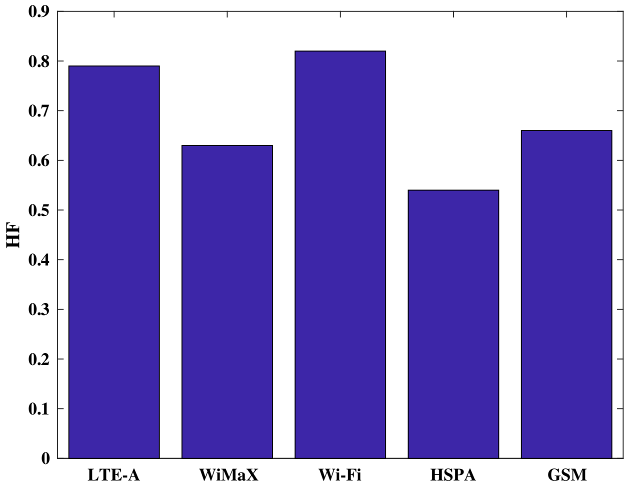


Fig. 16 HF output for each available networks

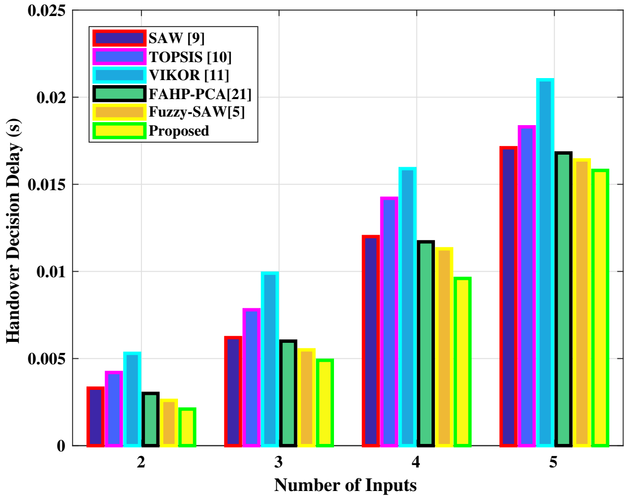


Fig. 17 Handover decision delay versus number of inputs

Since fast and reliable VHO is one of the objectives of this work, handover decision delay is considered as one of the performance metrics. The handover decision delay may cause severe QoS degradation. As discussed in [5], two different scenarios are considered. In the first scenario, the available target networks are fixed to be 3 (LTE-A, WiMAX and Wi-Fi). The decision delay is plotted for a various number of inputs in Fig. 17. The different inputs for VHO decision-making can be RSS, data rate, latency, jitter and throughput. It is noted that the increase in the number of inputs increases the decision delay irrespective of the VHO schemes. The traditional MADM methods need to compute a new AHP matrix [9] for every input. It also requires additional calculations to compute a ranking score for every network. This increases the decision delay. FAHP-PCA [21] and Fuzzy-SAW [5] schemes reduce the number of handovers and the number of operations in target network selection process.

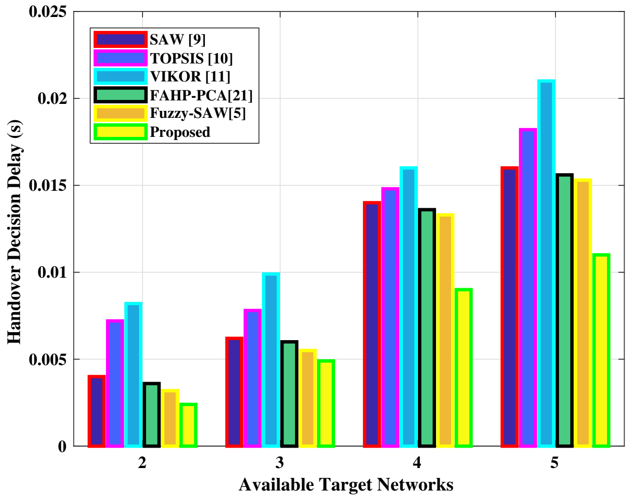


Fig. 18 Handover decision delay versus available target networks

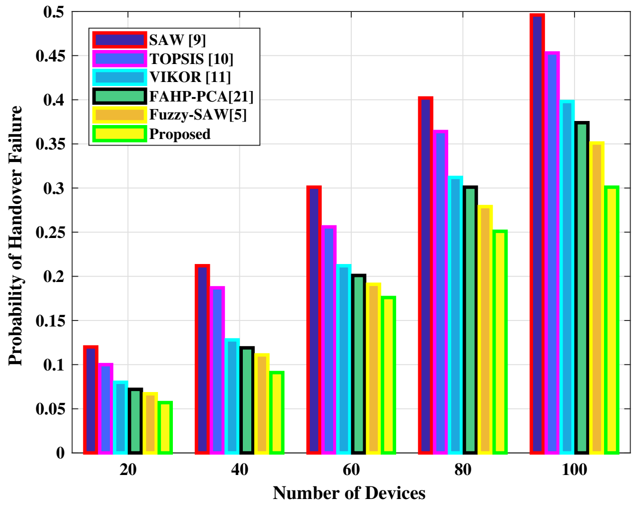


Fig. 19 Probability of handover failure versus number of devices

This fundamentally reduces the handover decision delay. In the proposed two-stage fuzzy- based decision scheme, all the inputs are grouped and given to one controller. Due to this, the decision time is greatly reduced. It is clear that the proposed scheme offers lower delay than the other schemes for all cases of inputs. For three inputs (RSS, data rate and latency), the proposed scheme offers 20.96%, 37.18% and 50.5%, 18.33% and 10.9% percentage reductions in decision delay over SAW [9], TOPSIS [10], VIKOR [11], FAHP-PCA [21] and Fuzzy-SAW [5] schemes.

Figure 18 describes the second scenario, where the number of inputs is fixed to be 3 (RSS, data rate, latency). The handover decision delay is plotted for a various number of available target networks. The available target networks are LTE-A, WiMAX, Wi-Fi, HSPA and GSM. The increase in the number of available networks increases the decision delay irrespective of the VHO schemes. The traditional MADM schemes need to compute a new AHP matrix for every new network, which obviously increases the decision delay. Fuzzy combined with AHP overcomes the vagueness and uncertainties in the basic AHP. Hence, the handover decision delay performance of FAHP-PCA [21] and Fuzzy-SAW [5] is superior to classical MADM schemes [9–11] and inferior to the proposed scheme. For three inputs (RSS, data rate and latency) and three available target networks (LTE-A, WiMAX and Wi-Fi), the percentage reduction in decision delay is similar to the results observed in Fig. 17.

To balance the network traffic load, the algorithm should distribute the network resources to mobile devices fairly. The bandwidth requirement depends on the traffic demand. The target network should have sufficient bandwidth to accommodate the handed over devices without compromising the QoS. The shortage of resources may cause decreased data rate and increased delay. It may also increase the handover failures. In the traditional MADM approaches, the concept of resource availability check in the target networks is not considered. The inclusion of resource availability check may slightly increase the decision time of the proposed scheme. But the inclusion of stage 2, i.e. bandwidth availability check, will have a great impact on the probability of handover failures and achievable data rate. The proposed scheme selects the target network with high HF and sufficient bandwidth. This feature will increase the achievable data rate of the proposed scheme after handover over the other traditional MADM and fuzzy-based schemes.

In Fig. 19, the probability of handover failure versus number of devices is plotted for various VHO schemes. The number of handovers increases with the number of devices. Since the decision delay is larger for the traditional MADM approaches, the probability of handover failure is larger for them. The increase in the decision delay may cause the connection breakdown and handover failures. The other reason for handover failure is the shortage of radio resources in the current and the target networks. Due to the unavailability of the radio resources, new call or handover call may not be established leading to handover failures. In the proposed scheme, bandwidth availability check is included in the handover decision-making process. The decision delay is also less for the proposed scheme than the handover latency. These features make the proposed scheme to offer the better probability of handover failure performance over the other traditional MADM schemes even with the increased number of devices. For 60 devices, the proposed schemes offer 41.52%, 31.25%, 16.98%, 12.43% and 7.85% reduction in probability of handover failure over the traditional SAW [9], TOPSIS [10], VIKOR [11], FAHP-PCA [21] and Fuzzy-SAW [5] schemes. Since the number of handover and decision delays are smaller for Fuzzy-SAW and FAHP-PCA,

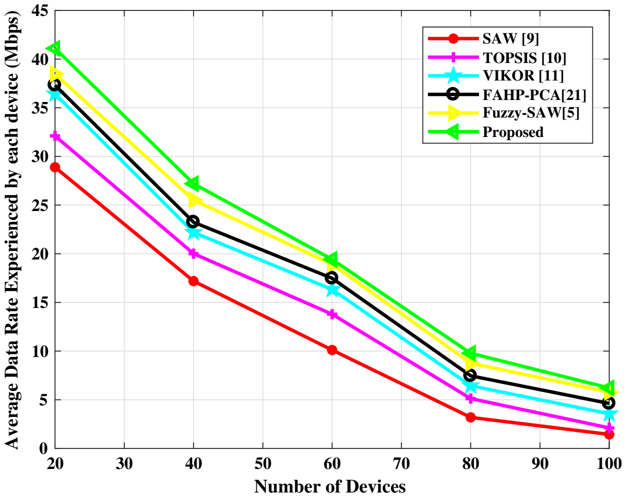


Fig. 20 Average data rate versus number of devices

they offer lower handover failure than the classical MADM schemes.

The average data rate experienced by each device (Mbps) versus number of devices is compared for various schemes in Fig. 20. The increase in the number of devices decreases the average data rate experienced by each device irrespective of the handover schemes. The shortage of radio resources and increased handover delays reduce the average data rate experienced by each device. Because of the fast and intelligent nature, the proposed scheme can offer more data rate than all other MADM schemes. For 100 devices, the proposed scheme offers 76.81%, 66.02%, 42.67%, 25.6%, 6.92% improvement in data rate over the traditional SAW [9], TOPSIS [10] and VIKOR [11], FAHP-PCA [21] and Fuzzy-SAW [5] schemes.

6 Conclusion

In this paper, we have developed a two-stage fuzzy-logic-based VHO scheme for D2D communication. In stage 1, the possible target network is selected based on the fuzzy logic. Based on the available bandwidth, the most suited network to handover is decided in stage 2. From the simulation results, it is observed that the decision delay of the proposed scheme is much lower for the increased number of inputs and the target networks than the traditional MADM approaches considered. It is also observed that the performance of FAHP-PCA and Fuzzy-SAW is closer to the proposed scheme. But the computational complexities associated with these schemes are higher than the proposed schemes. Because of the inclusion of bandwidth availability check, the average data rate experienced by each device and probability of handover failure performances of the proposed scheme become superior to the MADM approaches considered. Because of the fast, low complexity and intelligent nature, the proposed scheme becomes a most suitable candidate for D2D communication. As a future work, the algorithms used in the recommender system can be tested for VHO decision-making process.

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