Interference aware vertical handoff decision algorithm for quality of service support in wireless heterogeneous networks

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\textbf{A B S T R A C T}

Next generation wireless networks concept aims at collaboration of various radio access technologies in order to provide quality of service (QoS) supported and cost efficient connections at anywhere and anytime. Since the next generation wireless systems are expected to be of heterogeneous topology, traditional handoff (horizontal handoff/handover) mechanisms are not sufficient to meet the requirements of these types of networks. More intelligent vertical handoff algorithms which consider user profiles, application requirements, and network conditions must be employed in order to provide enhanced performance results for both user and network. Moreover, frequency reuse of one (FRO) seems to be the strongest candidate of deployment options for next generation wireless networks; therefore, interference conditions gains a significant attention in vertical handoff decision making process. In this study, a fuzzy logic-based handoff decision algorithm is introduced for wireless heterogeneous networks. The parameters; data rate, received signal strength indicator (RSSI), and mobile speed are considered as inputs of the proposed fuzzy-based system in order to decide handoff initialization process and select the best candidate access point around a smart mobile terminal. Also, in contrast to the traditional fuzzy-based algorithms, the method proposed takes ambient interference power, which is referred to as interference rate, as another input to the decision process. The results show that the performance is significantly enhanced for both user and network by the method proposed.

\section{1. Introduction}

As wireless communication evolves, many different signaling schemes and methods emerge and are standardized. Despite the obvious dominance of some specific types of networks in daily life such as cellular mobile networks, emergence of new standards forces different types of networks to coexist. Therefore, the concept "next generation networks" needs to allow for heterogeneous structure and to aim at collaboration of these various wireless technologies in order to provide quality of service (QoS) supported and cost efficient connections at anywhere and anytime.

Even though heterogeneous network structure is a very big concern by itself, terminals within the networks bring about some other issues for the next generation wireless networks. In this regard, it can be said that the next generation wireless networks need to include terminals that are able to: (i) be aware of the existence of heterogeneous networks around, and (ii) manage seamless transitions between existing networks when necessary. Considering (i) and (ii) together, one can deduce that recently emerging technology called cognitive radio (CR) can be a remedy for both, since CRs are able to be aware of, learn about, and adapt to the changing conditions in radio environment...
Here, note that the term “radio environment” has many aspects such as physical propagation environment, radio frequency spectrum, available networks and terminals around, and so on. Because these aspects are highly dynamic, capabilities of CRs become crucial from the perspective of both individual terminals and networks including them. Along with CR, cooperative networks concept should also be considered in the context of next generation wireless systems. The cooperative networks concept assumes that all of the wireless technologies such as cellular networks, wireless local/metropolitan area networks, wireless personal area networks, short range communications, and digital video/audio broadcasting can coexist in a heterogeneous wireless-access infrastructure and cooperate in an optimal way in order to provide high speed and reliable connectivity anywhere and anytime [2].

In addition to the considerations related to the capabilities of both terminals and networks, next generation wireless networks should also provide high data rate transmission despite their heterogeneous topology and complex structure. Moreover, they are desired to perform as close to wired networks as possible over wireless medium in terms of cost efficiency and of supporting highly sophisticated services that imply seamless transmission of different traffic types such as voice, data, and video.

Handoff is described as a process of transferring an ongoing call or data session from one access point to another in wireless networks. When all of the aforementioned aspects are contemplated, it is not difficult to conclude that handoff will be one of the vital mechanisms for next generation wireless networks. Traditional handoff process, which is called horizontal handoff, takes place to provide an uninterrupted service when a user moves between two adjacent cells. Generally, horizontal handoff process is initialized when the link quality condition parameters such as received signal strength indicator (RSSI), signal-to-noise ratio (SNR), and so on drop below a specified handoff threshold. Because the next generation wireless systems involve a heterogeneous topology, traditional handoff mechanisms will not be sufficient. Therefore, a new type of handoff, which is known as “vertical handoff,” is introduced. Vertical handoff is defined as a process which transfers a user connection from one technology to another such as a transfer from Global Service for Mobile (GSM) to WLAN or to WiMAX. Vertical handoff requires more intelligent algorithms which evaluate more parameters such as interference power, monetary cost, QoS, remaining energy, and so on in addition to already existing link quality condition quantifiers. Among all of the parameters, interference must be treated in a separate place, since every wireless system is interference limited. In traditional cellular-based systems, harmful impact of interference is tried to avoid/minimize by reusing the available frequencies in distant cells, which is called “frequency reuse.” In the literature, frequency reuse is quantified by a factor called “frequency reuse factor” which represents the distinct number of frequency sets (or equivalently, number of cells) in a cluster. In this regard, minimum frequency reuse factor can be one and it is called “frequency reuse of one (FRO)” or universal frequency reuse. FRO implies that each cell is allowed to use the entire spectrum available. Although frequency reuse is a very effective method in combating interference, it comes at the expense of inefficient spectrum usage and of expensive design processes. In contrast to traditional systems, FRO seems to be the strongest candidate in order to avoid expensive planning process and to overcome the problem of under utilized resource use in next generation wireless networks. It must be noted that FRO causes significant interference levels especially in the vicinity of cell borders in return. This renders interference one of the most critical parameters in handoff process for next generation wireless networks.

In the light of discussions given above, it is clear that interference, data rate, and mobility constitute the three prominent aspects of the next generation wireless networks. In this study, a new smart mobile terminal (SMT) is proposed. The proposed SMT is assumed to have cognitive capabilities such as sensing the environment periodically for available radio access technologies (RATs), evaluating their working conditions using its fuzzy logic-based algorithm, triggering handoff process if necessary, and deciding the best access point (AP) to camp on. The decision is based on interference rate, data rate, and RSSI due to the following reasons: Interference rate quantifies how severe the ambient co-channel interference power level, data rate takes into account the available transmission rate for applications carried out, whereas RSSI roughly helps to evaluate the mobility. The proposed SMT is modeled and simulated using OPNET Modeler Software for performance evaluation. Besides, the fuzzy logic-based handoff algorithm incorporated in SMT is implemented in MATLAB Software. The contributions of this study can be summarized as follows:

- Considering the fact that most of the wireless communication systems are interference limited, in contrast to the most of the fuzzy-based algorithms, the decision mechanism in the method proposed takes into account interference rates from different base stations as input to its fuzzy logic system in order to make a more reliable handoff.
- A new adaptive multi-criteria handoff decision system, which has the ability to adapt its structure according to the application requirements and network conditions, is proposed.
- A new cognitive smart terminal, which senses the environment for available APs and changes its working parameters such as frequency band, bandwidth, modulation scheme, medium access control (MAC) protocol and so on in order to camp on an appropriate AP, is developed.

The remainder of the paper is organized as follows: Section 2 presents related works to the vertical handoff in the literature. Section 3 provides the proposed models for SMT, handoff, and base station (BS). Section 4 includes example heterogeneous network scenarios which have overlapping RATs with different working parameters as well as proposed SMT, followed by performance evaluation. The paper is concluded with Section 5 providing final remarks and a discussion.
2. Related works

Although the vertical handoff concept is relatively new, several studies can still be found in the literature. In [3], the authors discuss different factors and metrics which are considered when triggering handoff. Besides, they describe a vertical handoff decision function (VHDF) which enables devices to assign weights to different network factors such as monetary cost, QoS, power requirements, personal preference, and so on.

A novel fuzzy logic-based handoff decision algorithm for the mobile subsystem of tactical communications systems is introduced in [4]. Handoff decision metrics used in [4] are: RSSI, the ratio of the used capacity to the total capacity for the access points, and relative directions and speeds of the mobiles to APs. The authors compare their algorithm with the RSSI-based handoff decision algorithm as well. Note that in [4, Eq. (3)], ambient interference power is embedded into the parameter of capacity, rather than being used as a direct input to the decision process.

In [5], the author presents a review on the proposed vertical handoff management, and focuses on the decision making algorithms in vertical handoff. The article [6] presents a tutorial on the design and performance issues for vertical handoff in an envisioned multi-network fourth-generation environment. In [7], the authors give a fuzzy logic-based vertical handoff scheme involving some key parameters and the solution of the wireless network selection problem using a fuzzy multiple attribute decision making (FMADM) algorithm.

It is considered that adaptation is crucial for next generation wireless networks from every aspect, such as handoff management and scheduling, since FRO seems to be one of the strongest deployment candidates [8–10]. Because interference is a very dynamic phenomenon, success of the adaptation of next generation wireless networks depends on being aware of the factors affecting it [11,12]. Therefore, the traditional fuzzy-based algorithms might not be able to meet the requirements of next generation wireless networks unless they take into account interference in their decision procedures. To the best knowledge of authors, none of the fuzzy-based handoff algorithms considers ambient interference power level as a direct input to their decision mechanisms.

3. The proposed models and algorithms for vertical handoff

Vertical handoff is a process issue compared to horizontal handoff as explained earlier. The cognitive smart terminal proposed in this study is in complete charge of managing the handoff process as well as its other functions. It scans the environment periodically for available APs, obtains the operating parameters, combines and processes all necessary parameters using its fuzzy logic-based classifier, initializes handoff process, and chooses the best candidate AP. The following subsections include the proposed models and algorithms implemented using OPNET Modeler simulation tool and MATLAB software.

3.1. Smart terminal process model

The proposed smart terminal process model has a cross-layer design and is developed using OPNET Modeler software. It includes physical, MAC, and some upper layer functions. It has a carrier sense multiple access/collision avoidance (CSMA/CA) MAC module for the wireless fidelity (WiFi) capability and a GSM module to handle GSM operations. Besides, it has a fuzzy logic-based smart handoff decision unit which is in charge of managing all of the handoff operations.

Fig. 1 outlines the state transition diagram of the SMT process model. The process starts with the Init state. This state performs a delay until the other processes in the simulation are initialized and loads the control variables. Then the process enters the Spectrum Scan and Handoff...
Decision states which are responsible for scanning the environment for available APs and managing the entire handoff process exploiting the proposed fuzzy logic-based handoff algorithms. The WiFi Mode and GSM Mode states stand for WiFi and GSM functionalities, respectively.

During the spectrum sensing phase, SMT listens to wireless medium for any handoff broadcast packet which might be sent by potential APs for a specified time span. All of the GSM APs have a broadcast control channel (BCCH) which is the first channel of allocated spectrum and is used for broadcasting network information periodically for possible handoff process in addition to its other functions. The detailed information about GSM technology can be found in [13]. The WiFi APs broadcast a handoff information packet periodically for this purpose as well. During the listening period, the SMT changes its working parameters such as frequency, modulation, data rate, and bandwidth in order to adapt to any possible AP and to receive handoff broadcast packet.

When any AP is available, SMT receives the handoff broadcast packet and extracts the network working parameters. It then invokes fuzzy-based handoff decision algorithm which takes these parameters as inputs; processes them; and produces an output called AP candidacy value (APCV). APCV is generally defined by a real number in order to quantify the strength of the candidacy level of the AP found. For instance, APCV can be designed to vary between one and ten where one denotes the weakest, whereas ten represents the strongest candidacy level of quantification. Subsequently, all the aforementioned network parameters along with APCV are stored in the handoff decision table (HDT) for further usage.

All of these steps are repeated until the scan process is terminated. In each turn, SMT listens to the environment for potential APs, receives the handoff broadcast packet of the AP found, calculates the APCV using its adaptive fuzzy inference system, and stores all of the pieces of information required in the HDT.

The sequence diagram of the proposed handoff decision algorithm is outlined in Fig. 2. This schema is repeated in every 10 s throughout the simulation run time.

As soon as the scan process is completed, APCV of each available AP is compared with that of current APs. If the difference between the compared values is equal to or greater than the handoff resolution (HR)\(^1\), that is a value determined by user, then the second condition, i.e., mobile speed, is evaluated. The mobile speed 10 km/h is selected as a threshold value. Any speed value below this threshold is regarded as walking speed and in this case, either any GSM or WiFi AP can be chosen as a serving node. Otherwise, only GSM network can be preferred, since the WiFi AP might serve SMT only for a very short duration. When these conditions are satisfied, handoff process is initialized.

3.2. Proposed handoff decision algorithm

Sophisticated handoff decision algorithms should consider more than one criteria and a methodology to combine and process them. Different decision algorithms have been proposed in the literature for vertical handoff as mentioned earlier. Artificial intelligence-based systems such as fuzzy logic and artificial neural networks are good candidates for pattern classifiers due to their non-linearity and generalization capability [4,14]. Therefore, in the proposed handoff decision system a fuzzy logic-based approach has been adopted.

Vertical handoff decision algorithm should initialize handoff process considering available network interfaces (link capacity, power consumption, link cost, and so on), system information (remaining battery), and user/application requirements (cost, QoS parameters, and so on). The block diagram of the proposed handoff decision system is given in Fig. 3.

The algorithm combines the user/application requirements and network capabilities, and produces an output which is utilized to make handoff decision and to choose the best candidate AP.\(^2\) In the proposed handoff system, there are three inputs (data rate, interference rate, and RSSI) for fuzzy inference system. Membership functions of these inputs are given in Figs. 4–6, respectively. In the figures, the horizontal axis indicates the crisp values of the aforementioned handoff parameters, whereas the vertical axis (i.e., \(\mu\) values) stands for the membership value of related parameter. The crisp inputs are converted into the fuzzy variable by means of these membership functions. Trim and trapezoid shapes are chosen as fuzzy membership functions due to their capability of achieving better performance especially in real time applications.

The data rate (DR) input has the ability to change its structure according to the application requirements as well. For instance, if the DR requirement of an application is 9.6 Kbps (GSM data transfer), then the membership function is similar to the one given in Fig. 4a. On the other hand, when the application needs more bandwidth, e.g., 25 Kbps (GPRS Class 6 traffic), then it dynamically changes its structure to adapt the new working condition as seen from Fig. 4b.

The interference rate parameter is also obtained by each AP and sent to the SMT in order to be considered in handoff decision process. In the proposed algorithm, interference rate refers to a special fuzzy logic variable whose value is determined by the ambient CCI power level. In GSM, the specification regarding the CCI level (GSM 05.05) recommends that the carrier-to-interference ratio (C/I) is at least 9 dB in order to meet the bit-error rate (BER) requirement. This indicates that for a reference signal level of \(-101\) dB m, which is the standard value for a GSM mobile station, CCI power level should be less than \(-110\) dB m. However, in a typical GSM deployment, it is reported that

\(^1\) Handoff resolution (HR) value is used to introduce a hysteresis to the proposed vertical handoff algorithm. Mobile terminal takes into account the HR value in order to decide whether any handoff process is required or not. If the candidacy level of any potential AP is greater with an amount of specified HR value than that of the current AP, then the handoff process is initialized.

\(^2\) It is worth mentioning here that data rate and interference ratio calculations in Fig. 3 can be considered as parameters related to the user/application requirements, since there are certain values for these parameters mandated by the application (e.g., data transmission or voice services).
C/I is around 14–15 dB [15]. In this sense, interference rate parameter is designed in such a way that the power level difference between the desired signal and interference is lower than –14 dB is assigned to be a low fuzzy logic value, whereas a difference that is greater than 14 dB is selected to be a high fuzzy logic variable. The corresponding membership function for the interference rate parameter can be seen in Fig. 5.

The RSSI input of the fuzzy system has also the ability to change its structure according to the network requirements. The RSSI membership function for GSM and WiFi networks are different as shown in Fig. 6a and b, respectively.

As stated earlier, according to the inputs of available APs the fuzzy inference system produces an output value between one and ten which describes the candidacy level of related AP. Any handoff initialization process is decided upon this value. One of the most crucial parts of this study is the new adaptive fuzzy inference system which is developed in order to make handoff decision. A fuzzy logic system consists of three main parts: Fuzzifier, Inference Engine, and Defuzzifier. Fuzzifier converts a crisp input into a fuzzy variable where physical quantities are represented by linguistic variables with appropriate membership functions. These linguistic variables are then used in rule base of Fuzzy Inference Engine. Since there are three
input variables each has three levels (i.e., low, medium, and high), there are 27 rules used for producing a new set of fuzzy linguistic variables. Some of the fuzzy rules in the rule base are tabulated in Table 1. For instance, Rule 1 corresponds to the following IF–THEN structure: if the potential AP supports low data rate, it is in a bad interference condition, and its RSSI is weak, then the APCV of the AP is 1, which means it is not a strong candidate. On the other hand, Rule 21 outputs a greater APCV value, i.e. 10, which implies the APs candidacy level is quite high.

Defuzzifier is responsible for converting this fuzzy engine output into a number called APCV. The output of the fuzzy system, APCV, is then combined with the mobile speed parameter to make handoff decision.

The analytic model of the fuzzy inference system is as follows [4,16]. Three dimensional pattern vector (input of the fuzzifier) for candidate access points is:

$$ PV_c = [\text{DR}_c; \text{IR}_c; \text{RS}_c]. $$

where DR is data rate, IR is interference rate, and RS is RSSI value of available AP. Three dimensional fuzzy pattern vector (output of fuzzifier and input of inference engine) for candidate access points:
Since product inference rule is utilized in the fuzzy inference engine then, for a new pattern vector, contribution of each rule in the fuzzy rule base is:

\[ C_r = \prod_{i=1}^{3} \mu_{F_i}(P_i), \]  

where \( \mu_{F_i}(P_i) \) is the membership value of the \( P_i \) for fuzzy set \( F_i \), and obtained from the aforementioned membership functions. There are 27 rules in the proposed system and a center average defuzzifier is used. Hence, the output of the defuzzifier (i.e., APCV) becomes:

\[
M_a = \frac{\sum_{l=1}^{27} y^l \left( \prod_{i=1}^{3} \mu_{F_i}(P_i) \right)}{\sum_{l=1}^{27} \left( \prod_{i=1}^{3} \mu_{F_i}(P_i) \right)},
\]

where, \( y^l \) is the output of the rule \( l \).

### 3.3. GSM base station

In GSM, each BS periodically broadcasts handoff decision packet using its BCCH in order to convey network information to any terminal in the vicinity for a possible handoff. In addition to this, in the proposed method, BS is in charge of both determining its interference rate and conveying this information to the SMT with the aid of its handoff broadcast packet. Fig. 7 shows the proposed GSM process model realized using OPNET Modeler.

As in the former process model, the process starts with the **init** state as well, then enters the **idle** state, and waits there until a specific interrupt arrives. The **fromRx** state machine delivers arriving packets to the next state machine, which can be either **bwRequest** or **data** state machine depending on the packet formats. If the **bwRequest** state machine is selected, then connection establishment/termination requests are handled. In case the **data** state machine is selected, then the received data is delivered to its destination. The interference state machine determines the interference rate of the BS and inserts this information into the related field of handoff broadcast packet. Finally, the handoff broadcast packet is created, provided with all of the required information, and then broadcasted to the environment in the handoff state machine.

### 4. Numerical results and discussions

#### 4.1. Assumptions

In this study, two different simulation scenarios are evaluated in order to investigate performance of the developed models and algorithms. The first one, which is illustrated in Fig. 8 and referred as “Scenario 1” in the remainder of the paper, has a higher interference rate, whereas the second one, which is given in Fig. 9 and referred as “Scenario 2” in the remainder of the paper, has a lower interference rate. Having these two scenarios in hand, the impact of interference can be extracted and interpreted from the simulation results. Three wireless networks are considered in the simulation scenarios. One of them is a WiFi network and the rest are GSM networks each of which has specific working parameters. GSM–WiFi pair is selected due to the following reasons: Both GSM and WiFi are very well-established and vastly deployed standards that are currently being used; therefore, they consti-
tute an appropriate case study for vertical handoff performance evaluations. In addition, GSM is a cellular standard in which handoff is one of the default network facilities, whereas WiFi does not have the concept handoff in the first place. From this perspective, handoff becomes a more challenging problem compared to other possible network pairs, such as GSM–CDMA pair, since CDMA contains the handoff concept as well. Also, in spite of the fact that many GSM deployments are not of FRO mode, GSM specification allows FRO mode of operation. Note that it is always desired to see how the proposed method performs in the worst case scenario. Since the method proposed makes a decision in regards to CCI present in the environment, studying a scenario which poses the harshest interference condition would be a reasonable approach. Because FRO introduces significant interference power levels especially in the vicinity of cell borders, a deployment that is based on FRO would be an appropriate scenario in order to evaluate the performance of the method proposed. Therefore, a GSM deployment of FRO is considered in the simulated scenarios. This way, it is also possible to get a clue about the performance of the method proposed in next generation wireless networks which are expected to deploy FRO.

Beside the networks, there are two mobile terminals which are served by GSM networks individually along with a smart terminal (SMT1) which has the capability of generating time sensitive voice traffic (13 Kbps), GSM data traffic (9.6 Kbps), and Class 6 GPRS data traffic (25 Kbps). In both scenarios, MTi denotes the ith mobile terminal served by base station labeled with BSi. These mobile nodes are of crucial importance for the method proposed, because they generate wireless traffic which causes interference to SMT1 and affects the decision regarding the handoff. It is worth mentioning that since interference spilled over SMT1 is a function of time and space, directions of motion of mobile terminals are important in terms of performance evaluation of the method proposed. Note that SMT1 moves along the trajectory shown in Figs. 8 and 9 of a specified speed during the simulation run time, senses the environment continuously for candidate APs, and has the aforementioned adaptive fuzzy logic-based handoff decision.
system as well as the capability of performing both WiFi and GSM functionalities.

In this sequel, one might wonder about the impact of traffic loads of APs present in the environment on the performance of the method proposed. In both of the scenarios considered in this study, it is assumed that one of the GSM base stations can provide less data rate compared to the other. This assumption is actually the common consequence of the following two items: Either (I) applications of the user of interest require different bandwidths, such as 9.6 Kbps for voice application and 25 Kbps for data transmission, or (II) regardless of the application requirements of the user of interest, GSM base stations can offer different data rates for a newcomer due to their different traffic loads. In other words, one of the GSM base stations can offer less data rate, because it cannot offer higher data rate due to its high traffic load present. From this point of view, results for the scenarios considered in this study already include the impact of traffic loads of APs present in the environment.

Diameter of the cluster which constructs the overall network topology is chosen to be four kilometers. The simulation was run for 3600 s and other relevant parameters are tabulated in Table 2.

In addition to the scenario assumptions given above, due to its importance, interference assumptions need to be explained further for the sake of completeness. Considering the fact that dynamic condition of the mobile radio propagation environment changes very rapidly, the received signal at a receiver can be defined for mobile radios by the following two processes:

\[ r(t) = m(t)s(t), \]

where \( m(t) \) is the fast fading (i.e., short-term multipath fading) component and \( s(t) \) is the local mean (i.e., long-term shadow fading) of the received signal [17,18]. Generally, \( m(t) \) and \( s(t) \) are identified in terms of probability distributions, since both are random processes. In the literature, Rayleigh and Rice distributions are frequently used, since both are random processes. In the case of non-line-of-sight (NLOS) and line-of-sight (LOS) cases, respectively. Field measurements reveal that shadowing process follows a log-normal distribution with a standard deviation \( \sigma \) which is defined, again, in linear scale [18]. Hence, the following formal model is adopted for representing \( s(t) \):

\[ s(t) = e^{q(t)}, \]

where \( \sigma \) is the standard deviation of the shadowing and \( q(t) \) is a normal process with \( N(0, \tau^2) \). It is also important to note that \( m(t) \) and \( s(t) \) are statistically independent processes [18,19].

In regard to shadowing processes, empirical studies show that there is a correlation in shadowing with respect to distance between two points in the space. Spatial correlation of shadowing is reported to be of an exponentially decaying form [20]. Considering practical purposes, there are several models proposed in the literature. For instance, [21] defines the normalized relationship between shadowing and its spatial correlation as:

\[ \rho(\Delta d) = e^{-\frac{\Delta d}{\sigma}}, \]

where \( \Delta d = 5 \text{ m for indoor and } \Delta d = 20 \text{ m for outdoor environments exemplifying practical scenarios.} \]

Before proceeding to the performance results and related discussions, it is appropriate to evaluate how well the Gauss–Markov assumption can capture the shadowing process introduced in Section 4.1. In order to verify the validity of Gauss–Markov assumption, the settings given for a suburban area in [23] are adopted with the following

\[ a = b^{(\alpha/d_p)}, \]

In this sequel, it must be stated that (5) actually contains a constant representing the impact of path loss for the received signal at the instant \( t \). However, the impact of path loss can be neglected under appropriate assumptions, such as pedestrian speed of motion.

### Table 2 Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message size*</td>
<td>13 Kb/s, 25 Kb/s, 9.6 Kb/s</td>
</tr>
<tr>
<td>Data rate</td>
<td>WiFi = 1 Mb/s, GSM = 270, 833 b/s</td>
</tr>
<tr>
<td>Frequency band</td>
<td>WiFi = 2.4GHz, GSM = 890–935 MHz (with FRQ)</td>
</tr>
<tr>
<td>Handoff resolution</td>
<td>3</td>
</tr>
<tr>
<td>Handoff threshold</td>
<td>WiFi = –80 dBm</td>
</tr>
<tr>
<td>Transmitter power</td>
<td>WiFi = 100 mW, GSM = 1.5 W</td>
</tr>
<tr>
<td>Speed of mobile</td>
<td>10 km/h</td>
</tr>
<tr>
<td>Area size</td>
<td>4 km x 4 km</td>
</tr>
<tr>
<td>Scan period</td>
<td>10 s</td>
</tr>
</tbody>
</table>

* Generated using exponential distribution function exp (Mean).
variables: \( b = 0.82 \), \( v = 3 \text{ m/s} \), \( \Delta t = 1 \text{ s} \), and \( d_p = 100 \text{ m} \). Within the decorrelation distance, each value of the shadowing process is obtained with the aid of (7) for the aforementioned parameter set. The process is initiated by an initial value which comes from the normal process \( \mathcal{N}(0,1) \) similar to that in (5). Fig. 10 plots the correlation coefficients versus displacement for both the theoretical and the simulated cases. It is clear that simulated values follow the theoretical ones very closely implying the suitability of the Gauss–Markov assumption for shadowing process generation. Note that the logarithm of the shadowing process is a normal process; therefore, it can completely be described in terms of its mean and variance. If (7) is analyzed, one can easily verify that the generated process meets the requirement of the shadowing process as well.

The first performance simulation set focuses on the case in which SMT1 moves along with the trajectory as illustrated in Figs. 8 and 9 of a specified speed. The simulation of the example scenarios has been run for different applications and working conditions, i.e., voice transfer and data transfer (9.6 Kb/s and 25 Kb/s), in order to evaluate the performance of the proposed approach comparatively. The performance metrics examined are; APCV of each available AP, number of handoff(s), and average end-to-end (EED) delay between SMT1 and APs.

Fig. 11 illustrates the outputs of adaptive fuzzy logic-based handoff decision algorithm for a voice transfer application in Scenario 1. APCV of each available AP is computed once in every 10 s during the spectrum sensing process by the proposed fuzzy logic-based algorithm employed in SMT1. As can be seen from the figure, the APCV of the WiFi hot spot is greater than those of the others when the simulation starts. At 300 ms, WiFi is not able to provide higher data rates anymore causing a decrease in the output of the proposed fuzzy system. Furthermore, because SMT1 moves out of the coverage area of WiFi, a rapid attenuation in RSS is experienced. Hence, the APCV is reduced once more between simulation times 1550 and 2000 s. When producing APCV, in case two candidate GSM BSs are of interest, the interference rate becomes the determinant input stemming from the fact that GSM BSs have approximately similar RSSI and DR values. The APCV of the candidate GSM BSs varies between 5 and 9.25 as can be seen from Fig. 11. Note that, for the GSM BSs, behavior of the interference rate looks similar to each other due to the motion of both mobile terminals in the vicinity of cell borders. These random movements cause random fluctuations in the interference rates observed as well. As a consequence, determining the candidate BS depends on the instantaneous interference rate values.

Fig. 12 presents the number of handoffs as a function of HR value for Scenario 1. As expected, the number of handoffs increases when SMT has a lower HR value. Hence, the lower the HR, the higher the number of handoffs. In order to determine an optimum HR value, user preferences, application requirements, and/or network conditions need to be taken into account.

Fig. 13 illustrates the outputs of adaptive fuzzy logic-based handoff decision algorithm for Scenario 2 along with the same procedure carried out in Scenario 1. Note that in Scenario 2, the behavior of APCV for WiFi behaves exactly the same as in Scenario 1. When producing APCV, in case two candidate GSM BSs are considered, the interference
rate is still the determinant input because GSM BSs have approximately similar RSSI and DR values. In general, APCV of GSM1 is greater than that of GSM2 most of the times during the simulation. Especially after 1000 s of the simulation run time, the dominance of the APCV value of GSM1 is obvious. This stems from the motion of MT2 towards GSM2 implying a diminishing interference power observed by GSM1. Therefore, the probability of selecting GSM1 as serving BS increases in time.

**Fig. 11.** APCV output of the proposed handoff decision algorithm for voice transfer application in Scenario 1.

In order to evaluate the performance of our proposed algorithms comparatively, **Fig. 15** can be examined. **Fig. 15** illustrates the measured GSM and WiFi RSSI results as a function of the simulation run time. If any RSSI-based horizontal handoff algorithm considered, which is alternative to the proposed multi-criteria approach, the following two conclusions can be drawn from the performance figure: (i) Since the RSSI values of the GSM are greater than those of WiFi along with the simulation run time; the SMT always prefers the GSM base station to camp on. However, this truth is not indicated in our study, it means additional monetary cost, since the WiFi is less expensive than GSM network. (ii) According to our scenario (i.e., Scenario 2), the supported bandwidth by the WiFi is greater than GSM from simulation starting time to the 300 s. Dur-

**Fig. 12.** Number of handoffs versus HR for Scenario 1.
ing this time proposed scheme chooses the WiFi AP, whereas the RSSI-based traditional algorithms chooses the GSM BS due to its greater RSSI values, which can be raised unexpected results in terms of QoS parameters.

In Fig. 16, average EED results (between SMT1 and APs) of different application traffics are presented as a function of the simulation run time. The EED results are obtained for Scenario 2 which represents the better interference rate conditions. Note that although all of the settings used for Scenario2 are the same as those for Scenario1, the mobility behavior of MTs in Scenario 2 is different than that in Scenario 1. A different mobility behavior with the same settings, as will be discussed here, will affect the results due to changing interference conditions; therefore, it will form a different simulation environment from the perspective of decision process proposed. In the light of this, SMT1 firstly camps on WiFi hot spot since it has a sufficient data and lower interference rate along with a high RSSI. After 300 s, the data rate supported by the WiFi AP dramatically decreases. Even though both RSSI and interference rate are appropriate, fuzzy-based handoff decision scheme decides to change the AP considering inadequacy in the DR offered. As can be seen from the Fig. 9, there are two alternative APs. For data transfer application with 9.6 Kb/s and voice transfer application GSM1 is selected as the new AP since both the DR and RSSI value meet the QoS requirements along with a relatively lower interference rate. The latency results of voice transfer are lower than those of data trans-
fer with 9.6 Kb/s. This is not surprising, because one slot is guaranteed for voice transfer application, whereas even reserving one slot might not be possible for data transfer due to dynamic network load conditions.

Fig. 15. RSSI-based performance evaluation chart.

Fig. 16. EED results (SMT1-APs) for different application traffics.
When the data transfer application with 25 Kb/s is running on SMT1, a conflict between data and interference rate arises. On the one hand, GSM1 observes a lower interference rate compared to GSM2. On the other hand, GSM2 can provide a higher DR compared to GSM1. Results show that GSM2 AP is selected after the decrease in DR offered by WiFi at 300 s of the simulation run time. This stems from the fact that fuzzy logic system weights the data and interference rate inputs differently because of QoS requirements of the application running on SMT1. As can be seen from Fig. 16, the average delay for this application is lower than those for the other applications, since GPRS Class 6 traffic type can be assigned up to four slots.

5. Conclusions

Vertical handoff is defined as a process which transfers a user connection from one technology to another. It is expected that the next generation wireless systems will include several different network technologies cooperating with each other; therefore, vertical handoff mechanisms should be investigated in detail. In general, handoff mechanisms allow for many parameters including user profiles, application requirements, and network conditions. In this work, an adaptive fuzzy-based handoff decision system which combines data and interference rate, RSSI, and speed parameters is proposed in order to satisfy both user and network requirements for next generation wireless heterogeneous networks.

Simulation results show that the proposed fuzzy logic-based vertical handoff decision algorithm is able to determine the most appropriate access network under different dynamic working conditions. Moreover, this study reveals that interference plays a crucial role in making vertical handoff for next generation wireless networks.

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