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A Multi-criteria based handover algorithm for vehicle-to-infrastructure communications

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ABSTRACT

Maintaining seamless quality of service (QoS) requirements for ongoing delay sensitive applications during handover processes for Vehicle-to-Infrastructure (V2I) communication over heterogeneous networks is a challenging task. The situation becomes even more challenging to deal with for multi-tier heterogeneous networks with various network sizes. To overcome the above challenges, we propose a multicriteria-based handover algorithm for V2I communications (V2I-MHA) to be used in multi-tier heterogeneous network environments. V2I-MHA selects the most appropriate underlying target network for handover based on QoS profiles of the ongoing applications and services. Moreover, our proposed algorithm filters out the inappropriate candidate networks using a multi-criteria decision-making technique based on Simple Additive Weighting (SAW) approach. However, our approach ensures that the most appropriate candidate network for handover processes is selected not only based on QoS requirements of the ongoing applications, but also on the knowledge of candidate network parameters (e.g. bandwidth, packet latency, packet losses, and service pricing). A multi-mode vehicle On-Board Unit (OBU) containing Long Term Evolution-Advanced (LTE-A) and Wi-Fi network interface cards is developed in the Riverbed (previously OPNET) simulator for system performance evaluation. The simulation results show that the proposed V2I-MHA outperforms (in terms of handover failure rate and packet losses) the existing handover methods.

1. Introduction

Recently there has been enormous demand for wireless applications and services due to the need for accessing information from anywhere and anytime. This requires wireless communication networks to offer higher data rate [1]. However, the plethora of emerging delay sensitive vehicular network applications, such as, road safety, traffic management, and infotainment applications, have exacerbated the need for having higher data capacity and bandwidth. Such vehicular network applications require seamless connectivity for moving vehicles.

Two of the most common modes of vehicular communications include the vehicle-to-vehicle (V2V) communication in which vehicles connect to each other and exchange information in an ad hoc mode, and the vehicle-to-infrastructure (V2I) communication, in which vehicles connect to fixed roadside infrastructures for communications. With the advent of Fifth Generation (5G) networks [1], layered (multi-tier) network structures having array of cells of different sizes are getting deployed to increase coverage and capacity. In a typical multi-tier network, a wide macro-cell may overlay multiple small cells of different sizes (femto or pico) to support increased capacity and also to offload network traffic when needed [2].

Despite the different advantages of V2I applications, providing seamless connectivity to moving vehicles remain as one of the main challenges for V2I communications. Currently, the vehicular network infrastructures offer limited coverage, thus preventing in-vehicle users from accessing internet content such as news and weather information while on the move. Standardization efforts in vehicular networks have resulted in Wireless Access for Vehicular Environment (WAVE) protocol. The WAVE protocol integrates the IEEE802.11p at MAC and physical layers; hence, its main limitation is linked to scalability issues [3]. On the other hand, the automotive industry has been building fully featured vehicle On-Board Units (OBU) aiming to integrate different heterogeneous communication technologies such as WiFi, UMTS, LTE, and WiMAX to solve the scalability issue and reinforce the communication systems of vehicles [4]. As shown in Fig. 1, the multi-homing vehicle OBU will have different channels (from different radio

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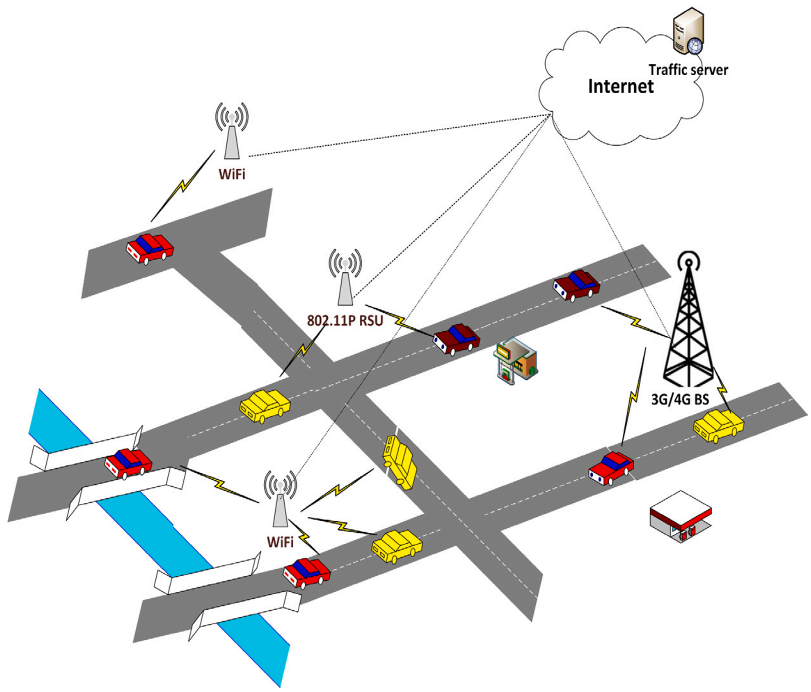

Fig. 1. Integration of WAVE protocol and evolving RATs to support V2I communication.

technologies) for communications. However, one of the key challenges in this case will be an increased number of frequent but unnecessary handovers [5].

The research community has been making considerable progress towards the convergence of the different radio access technologies. Consequently, numerous proposals addressing heterogeneous networks in terms of handover management, procedures, and protocols have emerged. Furthermore, in its Release 8 version, the Third Generation Partnership Project (3GPP) has introduced the Access Network Discovery and Selection Function (ANDSF) to enable a 3GPP compliant user equipment (UE) to discover non-3GPP access networks (e.g., WiFi and WiMAX). In latter 3GPP releases (10 and 12) this has advanced to the extent of supporting the UE to discover, select, and connect to both non-3GPP and other 3GPP access networks, like the UMTS Terrestrial Radio Access Network (UTRAN), LTE, and High Speed Packet Access (HSPA). In the recent 3GPP release 15, 5G New Radio (5G NR) [6] provides a number of advanced features for vehicular communication to support high mobility and capacity. For example, 5G NR intends to support seamless communications up to 500 km/h, and an area capacity of 10 Mbit/s/m2 with up to 106 connections per sq. km [7].

For effective V2I communication in an urban multi-tier heterogeneous network environment, vehicles on the move will need to perform fast and successful handovers between macro and small cell networks, as well as between different small cell networks to ensure seamless mobility and communications. While various studies on handover in heterogeneous networks have been published in the networking literature, most of them focused on low-speed mobile users with limited processes and parameters. This paper presents a Quality of Service (QoS)-aware handover method to facilitate seamless handover activities for V2I communications over multi-tier, heterogeneous networks. We call this a Multi-criteria based Handover Algorithm for V2I communication or V2I-MHA. V2I-MHA applies a multi-criteria decision-making (MCDM) algorithm to select the most appropriate network for handover to meet the requirements of end-user connectivity based on criteria, like, guaranteed bandwidth (GB), packet latency (PL), packet loss ratio (PLR) and the usage cost of services offered by different networks. Thus, selection of the target network for handover is mostly based on the QoS requirements of the ongoing services in an UE. V2I-MHA is built on top of its predecessor handover algorithm, V2I-MoLoHA (Mobility and Network Load-aware Handover Algorithm for V2I communications) [2], which selects the most appropriate underlying network for handover based on factors like, real-time geographical location of the vehicle, its movement direction and speed, and load of the different candidate networks measured in real-time. In this paper, the terms mobile device/device, UE and OBU are used interchangeably to imply an equipment in a moving vehicle connected to the roadside network infrastructure.

The rest of the paper is organized as follows. Section 2 reviews literature on V2I Handover methods in Multi-tier Networks. The proposed V2I-MHA algorithm is described in Section 3 and its performance evaluation is presented in Section 4. Simulation results are presented in Section 5, and Section 6 concludes the paper.

2. Vehicle-to-infrastructure handover in multi-tier networks

In this section, we mainly focus on handover methods proposed for V2I communications. A significant number of handover decision methods for high speed mobile nodes such as V2I communications can be found in the recent literature [2,8–11]. The common research problem for these studies is to overcome the issue of selecting a wrong candidate network for an anticipated handover, as result of the duration that a vehicle spends in the service area of the selected network and insufficient information mostly at the terminal side. A mobile node moving across a multi-tier network at a moderate to high speed may cross the coverage area of a serving small cell eNb/gNB (it is a base station for LTE-A/5G New Radio) before a handover is completed. Thus, it may result in the radio link failure (RLF) with the current serving cell and the node tries to establish its radio link to another base station. Thus, not only handover failures but unnecessary handovers also occur. On the other hand, the insufficient information mostly at the terminal side could lead to unsuccessful since the traditional handover is triggered when the target network shows Reference Signal Received Power (RSSP) greater than default threshold value. This section presents remarkable handover decision approaches proposed in the recent literature.

In our previous work [2,8] we proposed handover decision methods for minimizing the number of unnecessary handovers by considering the distance between the vehicle and the target network [8] and vehicle mobility as well as available network resources [2]. The primary objective of Distance-based Handover Algorithm for V2I communications (V2I-DHA) [8] was for reducing the number of unnecessary handovers by considering the distance between the vehicle and the target Base Station (BS). The short-list of the potential target networks includes only those lying in the direction of movement and are determined based on the Geo-location of both vehicle and the candidate network BSs. Certainly, the better network performance is achieved by reducing the scanning time of the candidate networks. V2I-DHA pro-actively evaluates all candidate networks, first based on their geo-locations relative to the movement direction and secondly based on their proximity to the vehicle trajectory (road). The shorter the distance between AP and the vehicles movement trajectory, the higher the selection probability of a candidate network. The contribution of this algorithm is twofold: it reduces the number of unnecessary handovers and also improves the overall handover delays by limiting the number of candidates AP/BS to be scanned.

In [2], we extended the idea of network selection presented in [8] by considering both UE mobility and network resources available before sending a handover request. Moreover, this method considers both downward (vehicle switches its connectivity from a large scale to small-scale network) and upward (vehicle switches its connectivity from a small scale to a wide scale network) network selections. For downward network selection, the method considers the dwelling (residence) time (the time a UE spends within the coverage area of the selected BS), the network load, which represents the capability of the target AP/BS to accommodate handed sessions, and the RSSP value of the target BS. On the other hand, an upward handover is mandatory to prevent the UE from losing its ongoing connection as it moves out of the coverage area of the serving small cell BS. This algorithm reduces the handover dropping probability, by limiting vehicles to select the candidates with an increased load. The key concept as well as the implementation of V2I-MoLoHA can be found in [2].

In V2I communication, a vehicle on the move must select the most suitable underlying network in real-time. In the urban regions, V2I communications serves either to disseminate data to a dense capacity of users, or to exchange low latency emergency messages with the road side units or for running safety applications. It is very important to consider multiple parameters to make the network selection. This can be implemented using multi-criteria decision making (MCDM) algorithms. A significant number of MCDM-based handover decision methods can be found in networking literature [9–11].

Authors in [9] applied the MCDM algorithm to develop a QoS-aware handover method that selects the suitable candidate network in a heterogeneous network that includes LTE and WLAN RATs. The most appropriate target network is selected based on estimated user dwelling time. The study in [10] applied the technique order preference by similarity to ideal solution (TOPSIS) for selecting the most appropriate candidate network based on a single application or multiple applications. This method considered different criteria, including, maximum data rate, security, delay, battery power consumption, and cost. Although these proposals provide effective handover decision methods (compared to the conventional RSS-based handover), they are inaccurate in terms of selecting parameters (criteria) involved in handover decisions. A typical example is the dwelling time utilized in [9], where it is assumed to be received from the candidate network BS, but it is not clearly explained how this parameter should be calculated. The authors in [11] developed a MCDM-based handover decision method that relies on a media independent handover (MIH) protocol. This method considers the information from on-going applications including Throughput (T), Data rate (DR), Jitter (J), Delay (D) and Packet Loss (PL) to select the most suitable candidate network in a heterogeneous network environment. Among reviewed handover approaches, only authors in [9] has considered the type of user applications for deciding the best candidate BS. Unlike the above network selection methods reviewed in this section, the primary objective of the network selection method proposed in this paper focuses on preserving network resources. This is achieved by allocating mobile users to BSs/eNb/gNB available in the Ultra dense network (UDN) in 5G environment based on the QoS requirement of the user traffic. Next, we discuss the concept of Multi-criteria based Handover Algorithm for V2I communication (V2I-MHA).

3. Proposed V2I-MHA: A multi-criteria based handover algorithm

In this section we describe our proposed V2I-MHA handover algorithm for a vehicle moving from its source to destination. V2I-MHA selects the most appropriate target network for handover in its movement trajectory based on the QoS requirements of the ongoing services/applications to maintain the service continuity after the handover, and on the usage cost of services offered by the different networks. We consider a V2I communication scenario in which the vehicle passes through multi-tier heterogeneous networks in an urban environment consisting of macro cells and micro cells (networks) of different sizes. Fig. 2 illustrates the scenario.

V2I-MHA applies the multi-criteria decision-making (MCDM) algorithm to select the most appropriate target network for handover as mentioned above. It considers various application profiles (based on services) profiles while selecting the target network for handover (Please refer to Section 3.1 for more explanation). The proposed algorithm considers both downward and upward handovers.

We assume that the vehicle maintains network connectivity through an OBU, which is initially connected to a macrocell BS and there exist multiple m small cell candidate networks enroute the destination, i.e., there are m SAPs (Small cell Access Points): $SAP_1, SAP_2, .., SAP_m$, where all candidate SAPs for the user(vehicle OBU) can be indexed by 1 to m in a set C: $C = [SAP_1, SAP_2, \dots, SAP_m]$ For each handover event, the suitable SAP from the candidate set C will be determined by the proposed V2I-MHA algorithm based on the following criteria: guaranteed bandwidth (GB), packet latency (PL), packet loss ratio (PLR) and the usage cost of services offered by different networks (i.e, by service providers of networks), which varies between operators. The proposed V2I-MHA is based on the Simple Additive Weighting (SAW) method [12] and the weighting vector of the decision element is calculated by the Eigenvalue method of Analytical Hierarchical Process (AHP). While there are numerous methods used for multi-criteria decision making, we selected SAW because of its simplicity and less processing time, which is a key requirement for a good decision mechanism, particularly in vehicular networks that experience frequent handover decisions. In contrary to its predecessor Mobility and network Load aware Handover Algorithm (V2I-MoLoHA)) algorithm [2], the current algorithm focuses on the quality of service (QoS) requirement for the ongoing applications. Moreover, the V2I-MHA also considers the network usage cost that specifies how much money the user pays for the service.

V2I-MHA aims at maintaining acceptable QoS levels to different user during handover event. To achieve this, we define application profiles that classify user preferences into different sets. These application profiles are defined based on application requirements and the tariff to be paid for accessing those applications on selected networks that meet the requirements. Subsequently, for each application profile, a weight vector is developed based on the importance of weight of attributes. In terms of computing weights, the judgement of assigning weights must be consistent. For example, if $B > A$ and $A > C$ then for consistency, B should be greater than C ($B > C$). This is also known as transitive property. The consistency ratio (CR) is calculated to verify the consistency of the considered weighting matrices. To prove that the judgement was consistent, the calculated consistency ratio (CR) should be less than 0.1 ($CR < 0.1$).

A weight vector is acceptable when the calculated CR is less than 0.1 [13]. Next we discuss the different application profiles.

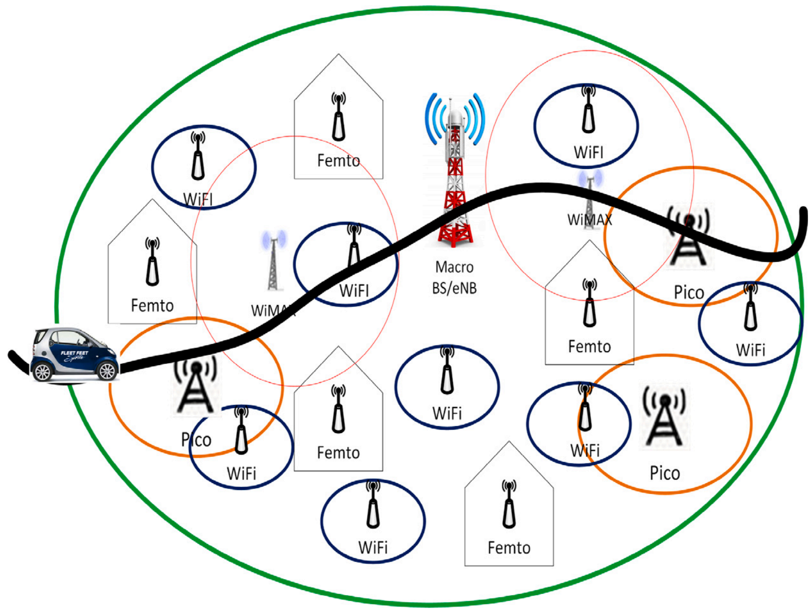

Fig. 2. V2I communication over multi-tier heterogeneous wireless networks (constituting of LTE-Macro, LTE-Pico and Femto, and WiFi).

3.1. Application profiles

The application profiles are designed to meet application-specific requirements based on different parameters and we assume that these application profiles are stored on the OBU of the vehicle. For instance, if the user is making a phone call while on the move, the ongoing voice application will require uninterrupted communication and the OBU may choose to connect to a network that provides less packet latency and less packet loss ratio. With respect to V2I communications, we consider the following five application profiles.

- **Maximum Quality:** In this profile, the V2I-MHA algorithm selects the best performing network (in terms of multiple parameters like throughput, packet latency, handover failure rate, packet losses) for handover among all underlying candidate networks, irrespective of the network access tariff (cost). In context to V2I communications, this profile is applicable for road safety-related applications such as accident warnings.
- **Guaranteed VoIP**: The most important parameters associated with this profile are packet latency and packet loss. Latency is a key issue as a conversation must be processed in real time. We also consider a reduced number of handovers to avoid an increased packet loss ratio. Moreover, the usage cost/tariff should be reasonable since the call may take time. In the context of V2I communications, this profile can also include any kind of data calls made by the user while on the move. Also, this profile can include traffic management applications where traffic authorities may directly communicate to vehicle drivers through OBU via VoIP.
- **Guaranteed streaming:** This is a typical profile for streaming applications. To cater for this application profile, the V2I-MHA algorithm selects the target network for handover that offers not only a high throughput but also a low packet loss ratio. In V2I communications, vehicles may send/receive video data (on-road traffic calculation) to/from a traffic server. Generally, the traffic server represents all servers that could be maintained in the cloud or in the back office of the ISP, which may provide V2I connections.
- **General:** This is the most general possible profile, where the ongoing vehicle user communication does not specify any constraint for the QoS parameters. In V2I communications, this profile may represent entertainment and personalized applications. Examples of such applications include searching for the nearest gas station or looking for the nearest McDonalds restaurant. These applications do not usually suffer from stringent communication constraints, like restricted latency or packet loss, although high data throughput may be occasionally required.
- **Profile Level**: A vehicle OBU can have pre configured profile levels in terms of type of subscribed services and each profile level can have different pricing associated to avail the respective subscribed service for that profile level. Choice of the profile level to avail the subscribed service will depend on the budget of the user while making the network selection decision. Current networks have become highly ubiquitous in nature and in recent years a paradigm shift has occurred to offer more user-oriented access to different services (e.g., VoIP, high speed media streaming, Internet browsing, application usage, content-oriented access scenarios etc.). While, users nowadays are expected to roam seamlessly and avail different services, as and when needed, offered by the telecommunication service providers with whom they have got long-term contracts, in near future, users will have the option to choose the best-possible connection offered by any telecommunication service providers that can satisfy their requirements (as and when required) at an affordable price while on the move [14,15].
One of the key criteria to choose the best-possible connection will be dynamic service pricing, which implies that pricing for availing different services, offered by different service providers (for different network technologies, like LTE/WiMAX/5G NR or for same technology, like LTE for macro networks/micro networks), can be dynamic in nature (dynamic pricing over static pricing) and may change according to context and user demand. Users may not have to be bind to a particular service provider under any long term contractual agreement but can enter into spot-agreements with different service providers of their choice, depending on the pricing and QoS offered, to avail different services at low price [16].
Very recently GSM Association (commonly referred to as GSMA or Global System for Mobile Communication Association), which is the international association of cellphone network operators/service providers and related businesses, has released the specification and standard for eSIM or embedded SIM for a mobile devices. An eSIM is a tiny chip directly soldered into

the mobile device's circuitry, fully programmable in nature, and enable the mobile device to sign on with whoever service provider is offering the best deal. eSIM has an element called eUICC (Embedded Universal Integrated Circuit Card) inside, that can accommodate multiple operator profiles and subscriber data [17]. An eSIM can be a big leap towards making the above-mentioned concept of dynamic pricing a reality very soon.

The Profile Level in terms of type of subscribed service in this proposed handover algorithm is based on the above discussions. While on the move, the vehicle OBU presumably with a fitted eSIM, will be able to choose for handover the LTE-A service provider (i.e., the target network) that can provide resources for the required profile level (for the required type of service) at the lowest pricing option such that the quality of experience after handover is not hampered. The overall usage price for availing the service will thus be the lowest as well. Different networks (heterogeneous technologies or same technology) can be controlled by different service providers and it will not be unrealistic here to presume that service providers will share their service pricing structure and plans (price ($/MB) of data) with the users [16]. This information about the profile level pricing (to avail the service offered) can either be stored in the vehicle OBU or can be obtained while on the move and can serve as the service pricing parameter (with respect to different profile levels) used in V2I-MHA. The higher the weight of the service pricing parameter, the algorithm will select the cheapest candidate access network for handover. However, while on the move, if the vehicle has the option to choose between an LTE-A network and a free public WiFi network (public hot spot) for handover, with both offering comparable satisfactory quality of experience for a particular profile level (and service) of interest, then the vehicle may choose the free WiFi over the LTE-A network, which may charge very less but will not be completely free. In near future, while there may be possibilities of also considering personal protected WiFi hot spots for such handovers (depending on the discretion of the owners of those personal hot spots), that will come with its own complications and will not be free unlike current public WiFi hot spots. However, free public WiFi networks may suffer from lack of adequate security measures in comparison to LTE-A network and personal protected WiFi networks, which could be an issue to consider. So, there is trade off involved in considering free public WiFi networks for handover over protected WiFi networks and LTE-A networks. Security aspects of underlying access networks, however, has not been considered in this work when choosing the appropriate target network for handover.

3.2. Application requirements

Application requirements for the different profiles discussed in the previous subsection are based on key QoS parameters and price of service.

- **Guaranteed bandwidth (GB)**: This parameter is given higher weightage for bandwidth-hungry applications, such as video streaming. Thus, each vehicle OBU selects the appropriate underlying candidate network based on the required bandwidth for the ongoing application.
- **Packet latency (PL)**: This parameter specifies the latency that the ongoing application can tolerate before decreasing its performance deteriorates.
- **Packet loss ratio (PLR)**: This implies the fraction of dropped packets that the application tolerates in order to guarantee effective performance.
- **Service Pricing**: As explained in the previous subsection, this parameter defines user preferences in terms of pricing to avail a service (with respect to the profile level). For a profile that requires maximum quality, this parameter is given the lowest value, while it is given the highest value for the profile level requiring the lowest pricing option to avail the service.

Table 1 shows the mapping of profiles with applications with QoS requirements to select the appropriate target network.

3.3. MCDM-based network assessment function

As mentioned early in this Section, the proposed V2I-MHA applies multi-criteria decision making (MCDM) technique for selecting the most appropriate target network for handover. While there are multiple MCDM techniques, we have used the simple additive weight (SAW) decision method to select the most appropriate target network. SAW was selected because of its simplicity and hence the proposed analytical model does not suffer from processing delays due to computation overhead [12,13].

3.4. Simple additive weighting

Simple Additive Weighting (SAW) selection method is probably the most broadly utilized MCDM method [13]. Also known as the weighted sum method (WSM), SAW is one of the simplest type of multiple attribute decision making methods. It fundamentally tries to obtain a weighted sum of performance ratings of each alternative over all the different attributes. SAW selects the best alternative in five simple steps as discussed below. By alternatives, in this paper, we mean all candidate radio access technologies (RAT_i) at the time of handover. Let us consider that A be a set of alternatives that can be denoted as

$$A = (a_1, a_2, a_3, \dots, a_n) \tag{1}$$

Let us also consider that C be a set of Criteria. Criteria implies application requirements in this proposal, such as guaranteed bandwidth (GB), packet latency (PL), packet loss ratio (PLR), and the usage cost of services offered by different networks. C can be denoted as

$$A = (c_1, c_2, c_3, \dots, c_n) \tag{2}$$

- **Step 1:** Constructing the decision matrix.

$$M = \begin{array}{c} \\ RAT_1 \\ RAT_2 \\ . \\ . \\ . \\ RAT_n \end{array} \begin{array}{c} \begin{array}{cccc} \textbf{GB} & \textbf{PL} & \textbf{PLR} & \textbf{Cost} \end{array} \\ \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} \\ X_{21} & X_{22} & X_{23} & X_{24} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ X_{n1} & X_{n2} & X_{n3} & X_{n4} \end{bmatrix} \end{array}$$

  The decision matrix (M) displays all candidate radio access technologies (RAT_i) at the left and the matrix elements (X_{ij}), which are the ratings of alternative Ai with respect to criterion Ci.
- **Step 2:** Constructing the normalized decision matrix for both beneficial attribute (criteria of benefit) and non beneficial attribute (criteria of usage cost). Benefit criteria refers to the parameters for which a high value is better ($Guaranteed\,Bandwidth$) while the usage cost criteria refers to those parameters for which a low value is better ($Cost, packetlatency, Packetlossratio$. The normalized decision matrix is calculated in .

$$r_{ij} = \begin{cases} \frac{X_{ij}}{X_{ij}^{max}}, for \;\; benefit \;\; criteria \\ \frac{X_{ij}}{X_{ij}^{min}}, for \;\; cost \;\; criteria \end{cases} \tag{3}$$

- **Step 3:** Constructing the weighted normalized decision matrix.

$$Y_{ij} = \sum_{i=1}^{n} W_i * r_{ij}, \sum_{i=1}^{n} W_i = 1 \tag{4}$$

  where, W_i denotes the weight of a criterion i. The computation of weight vector is presented in the next subsection.

Table 1
The mapping profiles with applications with QoS requirements.

Application profiles	Application requirements	QoS requirements to choose the appropriate target network
Maximum quality	Guaranteed bandwidth (GB), Packet latency (PL), Packet loss ratio (PLR)	To select the network offering the best QoS performance among all the possible choices, irrespective of the associated network usage cost.
Guaranteed VoIP	Packet latency (PL), Packet loss ratio (PLR)	To select the network that offers low PL, and low PLR. Throughput and costs are not so important here.
Guaranteed streaming	Guaranteed bandwidth (GB), Packet loss ratio (PLR), Network usage cost	To select the network that offers a high throughput and a low PLR.
General	Packet latency (PL), Packet loss ratio (PLR), Cost	There is no constraint on the QoS parameters.
Minimum cost	Network usage Cost	To select the network that offers the lowest cost of usage irrespective of the offered Bandwidth, PL, and PLR.

Table 2
Weight values optimized for application profiles.

Requirement parameter	Maximum quality	Guaranteed VoIP	Guaranteed video	General	Minimum cost
Guaranteed bandwidth	0.321429	0.237245	0.375141	0.250000	0.161797
Packet latency	0.321429	0.386297	0.271775	0.250000	0.142400
Packet loss ratio	0.321429	0.211662	0.271775	0.250000	0.212937
Cost	0.035714	0.164796	0.081309	0.250000	0.419058
CR	**0**	**0.038227**	**0.029161**	**0**	**0.096453**

- **Step 4:** Calculating the score of each alternative.

$$S_i = \sum_{j=1}^{m} Y_{ij}, i = (1, 2, 3, \dots, n) \tag{5}$$

- **Step 5:** Selecting the best alternative.

$$BA_i = max_{i=1}^{n} S_i \tag{6}$$

3.5. Computing the weight vector

The weight value shows the relative importance of criteria in a decision matrix. In this research work, the appropriate weight vector for each application profile is calculated based on the Analytical Hierarchy Process (AHP) method. The AHP method is decision-making framework developed by Saaty [18]. The AHP is a structured technique for analysing complex decisions, especially when the number of criteria of alternatives is less than seven. We have used AHP for V2I-MHA, which has only four criteria. Table 2 presents the weight values optimized for all application profiles considered in this research work. Values in Table 2 were obtained by applying Analytical Hierarchical Process (AHP) technique. The details for calculating weights with AHP are explained in [19]. For each application profile, the decisions where done from a subjective point of view, considering all the requirement parameters. The consistency of the calculated weight vectors is justified by the consistency ratio (CR). As presented in the last row of Table 2, for each application profile, the consistency ratio is less than 0.1 [19], thereby indicating sufficient consistency.

We now describe the following three steps that lead to the weighting vector.

- **Step 1:** This involves developing the pairwise matrix that establishes the relative priority of each attribute against every other attribute. This pair-wise comparison is based on Saaty's 1–9 scales of pairwise comparison and utilizes index values from 1 to 9 [18]. Here, two criteria are evaluated at a time based on their relative importance. If a criterion A is equally preferred as criterion B, the pair receives an index value of 1. If criterion A is highly preferable than criterion B, the index value of 9 is used. Moreover, the reciprocal relationships are also applied when appropriate. For instance, if A is extremely non-preferred to B, this pair receives an index value of 1/9. Table 3 presents Saaty's 1–9 scales of pairwise comparison [18,20]. Saaty's 1–9 scales has been used in various research works such as [21].
- **Step 2:** The weights of the individual criteria are computed in this step. It starts with multiplying the values in each row and calculating the *n*th root of the product. Then the calculated product root is normalized to get the appropriate weight. The normalization is done by dividing each entry by the sum of the column.
- **Step 3:** Finally, the consistency of the pair-wise matrix is assessed by calculating and checking the CR value. The developed pair-wise matrix is consistent when the CR value is less than 0.1. CR is calculated as follows:

$$CR = \frac{CI.}{RI} \tag{7}$$

$$CI = \frac{Lambda_{max} - n}{n - 1} \tag{8}$$

where, $Lambda_{max}$ is the maximum eigen value of matrix A [22], and n is the number of criteria. The amount of random index (RI) depends on the number of criteria being compared and its value can be obtained from Table 4.

3.6. V2I-MHA for upward and downward network selection

Generally, for a handover activity, a network selection in multi-tier networks can be of two types: upward selection and downward selection. While, in the former an UE moves from the coverage area of a small cell (pico/femto) to the coverage area of a large cell (macro), in the latter it moves from a macro cell to a small cell. V2I-MHA supports both as explained below:

- Downward selection: The V2I-MHA for downward selection method is presented in Fig. 3. Initially, it is assumed that the UE is connected to the macro-cell BS. During its stay in the macro-cell service area, it sends an ANDSF request to the ANDSF server and the ANDSF response includes a list of all small cell networks available in the service area of the serving macro-cell BS. As shown in Fig. 3, the proposed V2I-MHA for downward network selection is composed of two main asynchronous stages: data collection and decision process. While, the UE collects information of the list of potential candidate networks for handover in the data collection stage, the decision processing stage involves the execution of the MCDM mechanism. If none of the candidate small cells meets the service demand of the ongoing application and the user's requirements, the UE stays connected to the macro

Table 3
Saaty's 1–9 scales of pairwise comparison.

Definition	Index value	Explanation
Equally preferred	1	Two activities contribute equally to the objective
Weak or slight	2	
Moderately preferred	3	Experience and judgement slightly favour one activity over another
Moderate plus	4	
strongly preferred	5	Experience and judgement strongly favour one activity over another
Strong plus	6	
Very strongly preferred	7	An activity is favoured very strongly over another
Very, very strong	8	
Extremely preferred	9	The evidence favouring one activity over another is of the highest possible order of affirmation

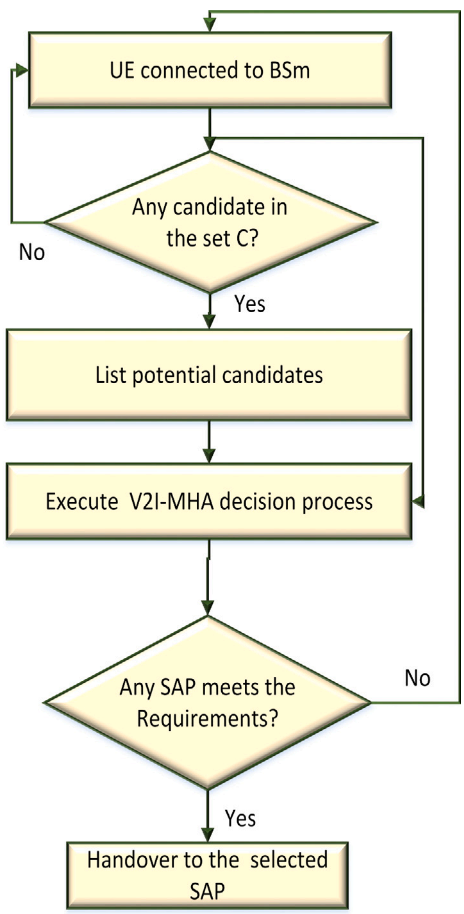

Fig. 3. Illustrating V2I-MHA algorithm for downward network selection.

cell. Otherwise, the UE selects an appropriate small cell and executes the handover. There is also a lesser possibility of the UE selecting another candidate macro cell for handover. However, for a downward handover, a target macro cell will only be selected if it offers greater QoS and better resources as well as lower cost of service usage compared to other candidate small cells, and, generally, the possibility of small cells offering better handover resources are more than that of macro cell offering. Having said, an UE moving at a very high speed (e.g., in straight highways with little or no slow moving traffic and lesser turns) may choose to handover to another macro cell (and not to a small cell) to avoid frequent handovers.

- Upward selection: The UE performs upward selection when trying to move from the coverage of a small cell network to the coverage area of a large or macro cell BS. For this type of network selection, the candidate set includes the macro-cell BSs or eNBs and a number of small cells excluding the current serving small cell BS. Thus, the new set C_N becomes, $C = [BS_M, SAP_1, SAP_2, \dots, SAP_{m-1}]$
As it is presented in Fig. 4, the proposed upward handover can be triggered by either of two events: (a) a SAP availability event and (b) a call event. A SAP availability event occurs when the C_N is not empty. On the other hand, a call event may occur when an UE initiates a new application with different QoS requirement (that the current small cell BS may not be able to provide) that calls for a new session initiation by the vehicle OBU. The OBU then looks out for another appropriate underlying network to select for the handover that can serve the requirements of the new call. For instance, let us say that a UE initiates a delay sensitive call while connected to a small cell SAP. As the new call requires uninterrupted connectivity, this call event will instantly trigger the selection of an appropriate underlying network that can better service the call. Thus, it may turn out that the best choice could be to switch from the small cell network to a macro cell network that can offer better bandwidth for an uninterrupted continuity of the ongoing call.
In this work, we assume that the vehicle OBU will pre-store some common applications matched against the different application profiles and the proposed method will select the most appropriate candidate network based on the application with the highest priority.

Table 4
The average stochastic uniformity index target value of judgement matrix.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

4. Performance study

To evaluate the performance of the proposed V2I-MHA, we used the LTE-A and WiFi modules of the Riverbed simulator. In Riverbed simulator, we implemented various active application profiles in UE nodes as per the requirement of the V2I-MHA. We also modify the standard EPC module in the simulator to implement the handover decision activities based on application to user profile mapping. Please also note that since V2I-MHA is built on top of its predecessor algorithm, V2I-MoLoHA, as mentioned in Section 1. The simulation set up, by default, takes into account the current location, movement direction and speed of the vehicle as per the V2I-MoLoHA requirement (Please refer to [2] for detailed explanation of V2I-MoLoHA) and has built the V2I-MHA specific criteria (QoS requirements and pricing of services with respect to profile levels) on top of that.

Fig. 5 shows the urban scenario used for our studies in which a multi-mode vehicle OBU moves across a multi-tier HetNet environment consisting of LTE-A (macro and pico) and Wi-Fi radio access technologies. The simulated scenario consists of one standard macro-cell eNB

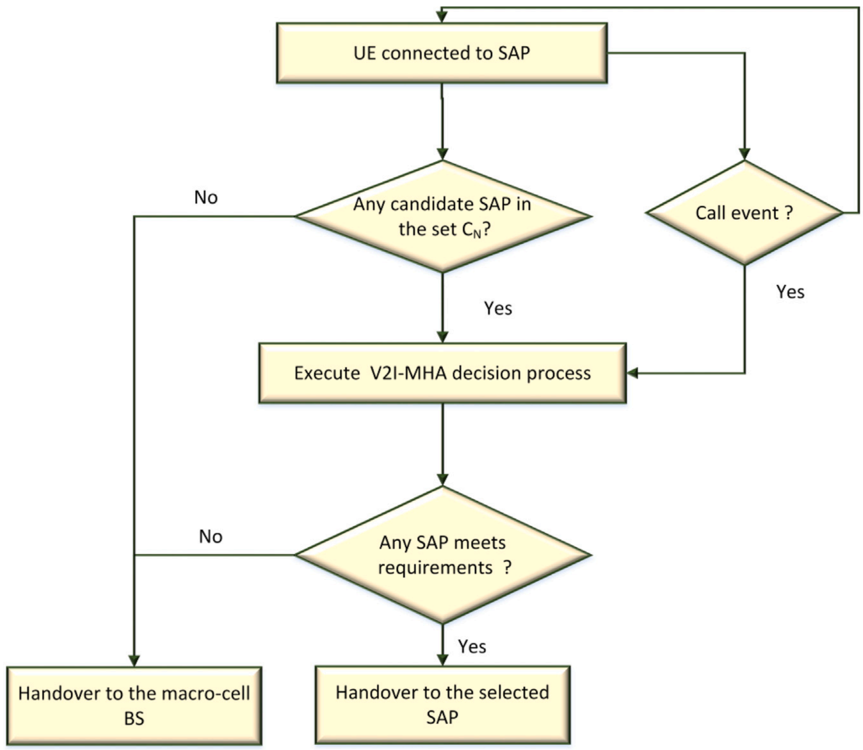

Fig. 4. Illustrating V2I-MHA algorithm for upward network selection.

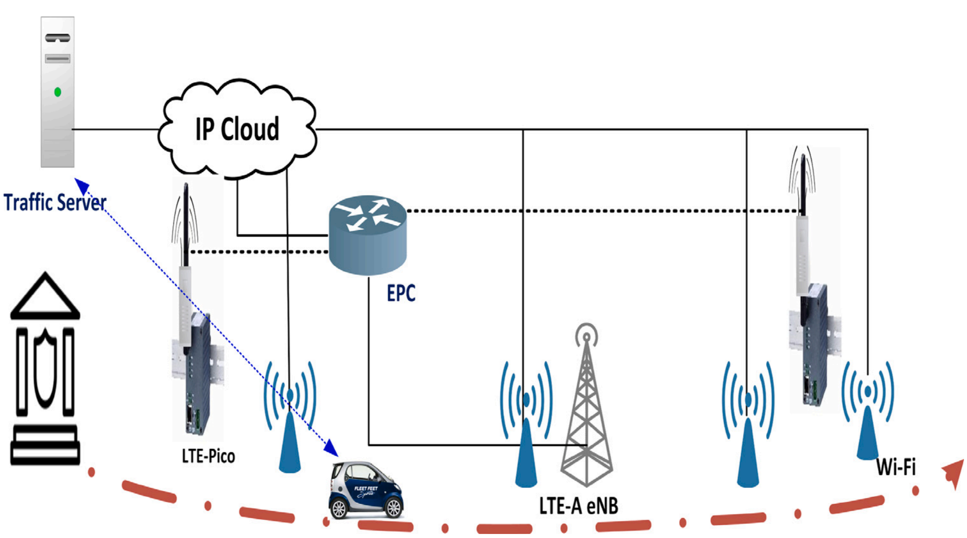

Fig. 5. Illustrating the simulation scenarios for V2I-DHA.

and two pico-cell HeNBs that are deployed at the edges of the macro-cell network. In addition, four Wi-Fi APs (IEEE 802.11p) are deployed at different locations (e.g., road intersections) in the simulated terrain.

Let us presume that, as per the proposed handover algorithm, the vehicle OBU is initially connected to the macro-cell eNB. It performs a handover activity only if one of the underlying candidate networks offer a higher selection probability or if the current network suddenly disappears thereby forcing the OBU to get connected to another network. The OBU in the simulation model is equipped with the Wi-Fi and LTE-A interfaces as well as the application client (Vehicle_App_Client). The vehicle moved across the simulation terrain across the movement path from source to destination (as shown in Fig. 7) at a speed range varying from 20 km/h to 120 km/h. Multiple simulation iterations were performed and in each iteration, the vehicle randomly chose its movement speed from 20 km/h–120 km/h across the different segments in the movement path. The SAPs and eNBs are strategically placed across the simulation terrain as per our simulation topology and the movement path from source to destination was strategically created such that the vehicle always remained under the coverage areas of one or more eNBs/BSs and the vehicle OBU remained connected to one of the eNBs for communication. The proposed algorithm filtered out any eNB or AP that either does not fall in the movement trajectory of the vehicle or offers very low strength of signal (e.g., AP4 in Fig. 7). Fig. 6 shows the simulated network architecture in the Riverbed Modeller. Simulations scenarios considered both delay-tolerant (e.g., HTTP and FTP) and delay-sensitive (e.g., voice and video conference) applications and the Riverbed Modeller allowed simulating multiple application profiles running simultaneously in each simulation run. For each simulation

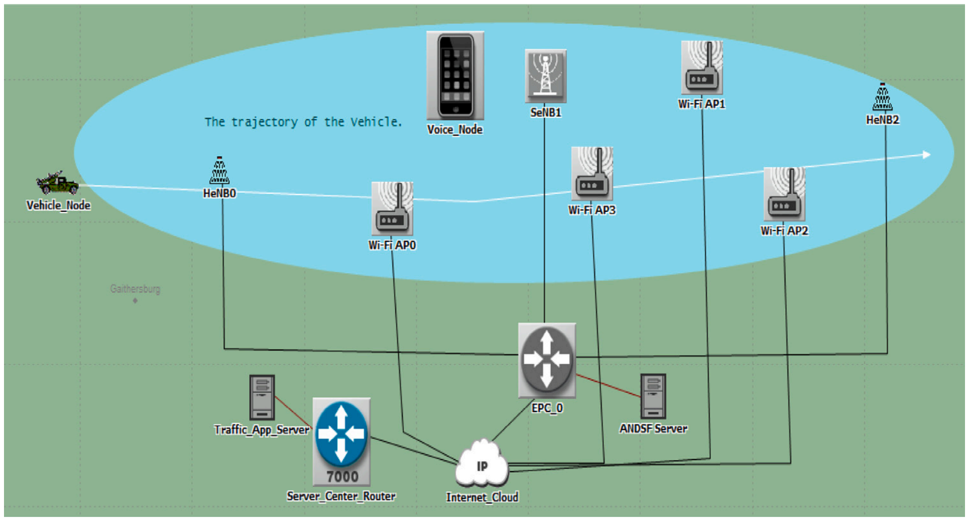

Fig. 6. The system simulated model.

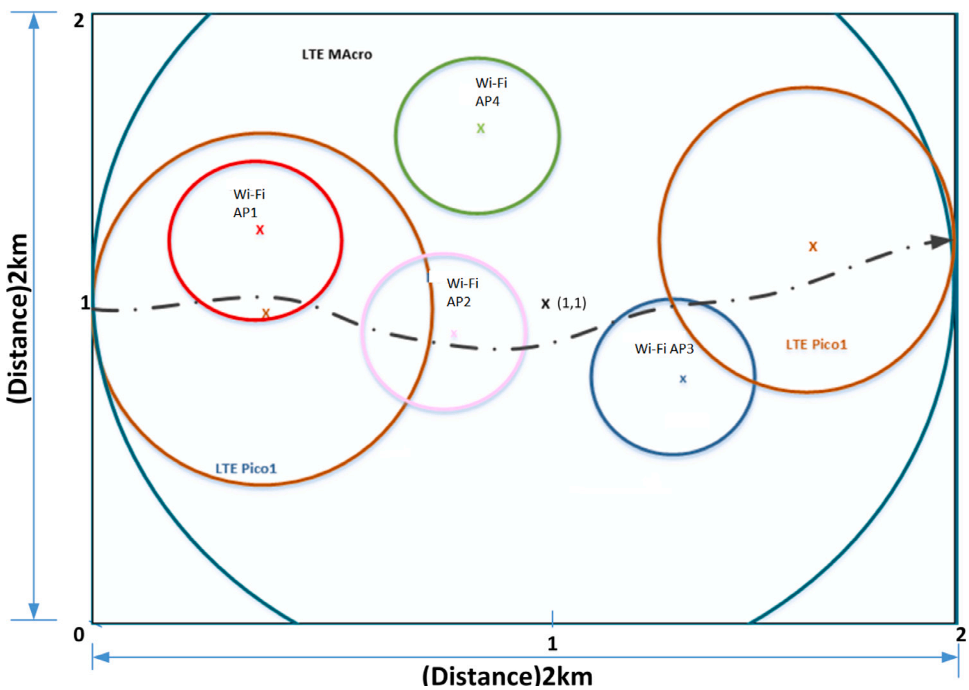

Fig. 7. Wireless technologies coverage areas in the simulated scenario.

iteration, results of each application profile were then collected and average of each profile for all the simulation iterations was calculated. Moreover, the Riverbed simulator allowed setting priorities for all defined application profiles and for the simulations, delay-sensitive applications were prioritized over others, which implies that in case of conflicting requirements, delay-sensitive applications were considered over other applications by the vehicle OBU.

For the performance evaluation of the V2I-MHA, we performed experiments varying different parameters affecting the performance of V2I communications such as, vehicle speed, the user request rate and the type of services of these requests. Simulation parameters are presented in Tables 5 and 6. These simulation parameters are commonly used for simulating handover performances [20,23,24]. In the simulation, the vehicle moves within the designed trajectory, crossing different coverage areas while executing both delay-sensitive and delay-tolerant applications. For handover, the vehicle OBU chooses the most appropriate underlying network, in its direction of movement, that is capable enough to satisfactorily fulfil the QoS requirements of the ongoing session at an affordable pricing of ongoing services.

5. Simulation results

The performance of the proposed algorithm V2I-MHA, is evaluated by Riverbed Modeller simulations. Depending on the application profile applied, the V2I-MHA behaves in a different manner. These behaviours are analysed based on the type of traffic considered against the proposed application profiles. For delay-sensitive applications, we consider both voice and video applications and the performance is evaluated based on a comparative study of the throughput, packet latency and packet loss ratio offered for each application profile. Moreover, we analyse the number of handovers performed per application profile. The results presented here are based on the method of multiple independent replications each of which continued until the vehicle stopped its movements at the end of the time frame for each simulation run.

Table 5
Simulation parameters.

Parameter	Values
Network area (m * m)	1000 * 1000
Transmit power of LTE Macro/SAP	0.5 W/0.1 W
LTE Macro/ SAP gain	14 dBi/5 dBi
WiFI SAP (IEEE 802.11p) transmit power	0.05 W
Vehicle speed (km/h)	20–120
Path loss	$L = (40(1 - 4 * 10^{-3}\Delta h_b)\log_{10} R - 18\log_{10}\Delta h_b + 21\log_{10} f + 80)$ dB
Radio propagation	Large-scale propagation
log-normal shadow fading	10 dB
LTE-A Channel bandwidth	1.4 MHz
WLAN data rate	11 Mbps
Mobility	Vector based trajectory
Simulating time	600 s

Table 6
Simulated Network parameters.

Technology	GB (Mb)	Packet E2E Latency (ms)	Packet loss ratio	Price/Mb
LTE-A Macrocell (eNB)	0.9360	48.8200	3.1510	0.9000
WiFi AP	3.5000	30.0800	0.9800	0.0800
LTE-A Small Cell (HeNB)	1.5000	41.8000	0.8600	0.0950

Table 7
Number of handover per profile.

Profile	Maximum quality	Voice	Video	General	Lowest Service Pricing Profile Level
Handover events	3	4	4	6	8

5.1. Throughput analysis

For the simulations, the vehicle ran both voice and video applications requiring a minimum guaranteed bandwidth of 64 kbps and 900 kbps, respectively. For a successful handover of the ongoing sessions of the applications for our proposed V2I-MHA, the target network needed to provide a minimum of 964 kbps to maintain the acceptable QoS for these two concurrent sessions.

Fig. 8 shows the throughput attributed to each application profile. The Maximum Quality (MaxQ) application profile and the video profile almost achieved 0.964 Mbps, which is the total required throughput. The throughput measured for the voice profile is slightly lower than that of MaxQ and the video profiles. This is due to the fact that the voice profile put less weight on the bandwidth attribute. We also observe that the general profile registered half of the required throughput as there is no service prioritization. V2I-MHA recorded the lowest throughput for the lowest Service Pricing application profile as this profile puts more priority to low pricing of services compared to better handover performance.

5.2. Packet latency and packet losses

As mentioned in Section 5.1, the vehicle OBU has two active applications, voice and video sessions, throughout the simulation duration.

Fig. 9 illustrates the packet latency experienced by the vehicle OBU for the voice application. The Packet latency parameter reports the total voice packet latency, called "mouth-to-ear" delay [25]. The higher value of packet latency affects the overall QoS of delay sensitive applications. The proposed V2I-MHA algorithm is compared with our previous handover algorithms (mentioned in Section 2) and another ANDSF-Assisted handover method proposed in [26]. We found that V2I-MHA reduces the packet latency by 8% compared to the V2I-MoLoHA, 14% compared to V2I-DHA, 29% compared to the ANDSF-Assisted handover method and up to 42% compared to the conventional handover method. This is achieved by selecting the best target radio access technology that provides the lowest latency for the delay-sensitive applications. For such applications, the packet latency (PL) parameter is given the highest weight.

In regards to packet losses, Fig. 10 shows that The proposed V2I-MHA has reduced packet losses by up to 3% for maximum quality, 29.5% for voice and video profiles, and 33% for general and service pricing profiles.

5.3. Handover failure rate

An increased rate of handover failures deteriorates the expected QoS. The handover failure ratio can be calculated as follows: the ratio of handover failure (HOF) indicates the number of HOF relative to the total number of handover attempted (both successful and failure) [27]. The HOFR is measured in percentage as shown in (9).

$$HOFR(\%) = \frac{N_{HOF}}{N_{SuccessfuHO} + N_{HOF}} \tag{9}$$

The simulation results presented in Fig. 11 exhibits how much the proposed handover algorithm reduces the percentage of HOFR for voice applications. Fig. 11 compares the performance of the proposed V2I-MHA with V2I-DHA [28] and V2I-MoLoHA [2], the ANDSF-Assisted handover method [29], and the conventional RSS-based handover method. The proposed V2I-MHA offers 16%, 51%, 57%, and 62% lower HOFR than V2I-MoLoHA, V2I-DHA, the conventional, and ANDSF-Assisted, respectively.

This reduction in the HOFR implies that V2I-MHA is choosing the most appropriate underlying target network based on the QoS requirements of the ongoing application. It also implies that there has been less handover ping pong activities.

5.4. Number of handovers

Table 7 compares the number of handovers performed by the vehicle, running the proposed V2I-MHA, for all the considered application profiles. The lowest number of handovers (only three) occurred when the vehicle was running the applications having the maximum quality profile, while the highest number of handovers (eight) is registered in case of the type of service (with respect to the Profile Level) for which the service pricing is the lowest. This is because, the vehicle OBU chose to remain within the same macro-cell network for the max quality profile until another network has offered similar or better QoS for the transferred call. So, the number of handovers performed is less. On the other hand, the number of handovers is much more for the Profile Level with the lowest service pricing as the vehicle frequently switched to the underlying network offering the lowest pricing to avail the required service (e.g., Wi-Fi networks), irrespective of the QoS. As per Table 7, higher the quality of the application profile, lesser has been the number of handovers.

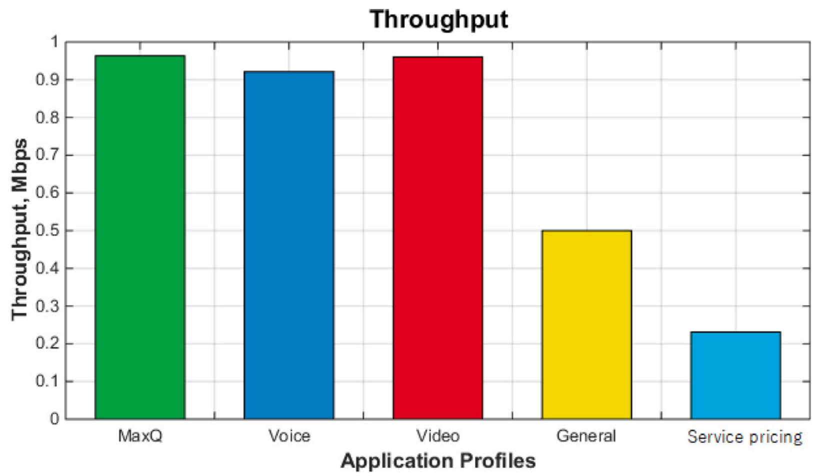

Fig. 8. User throughput comparison.

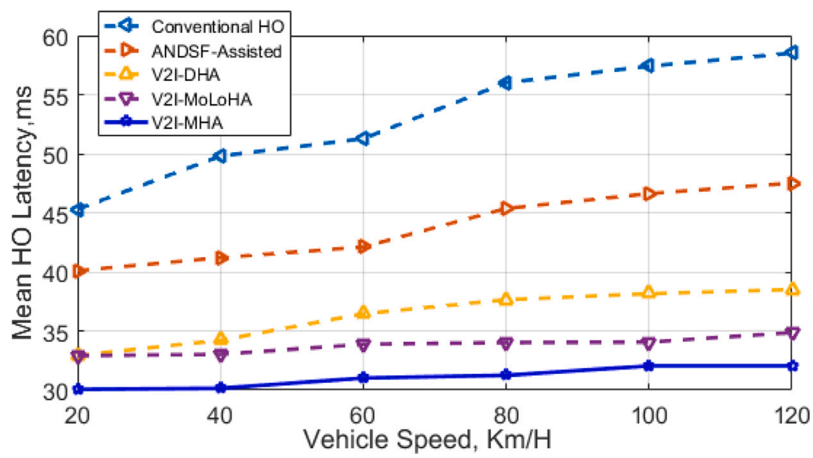

Fig. 9. Latency Comparison of conventional, ANDSF-Assisted, and the proposed methods.

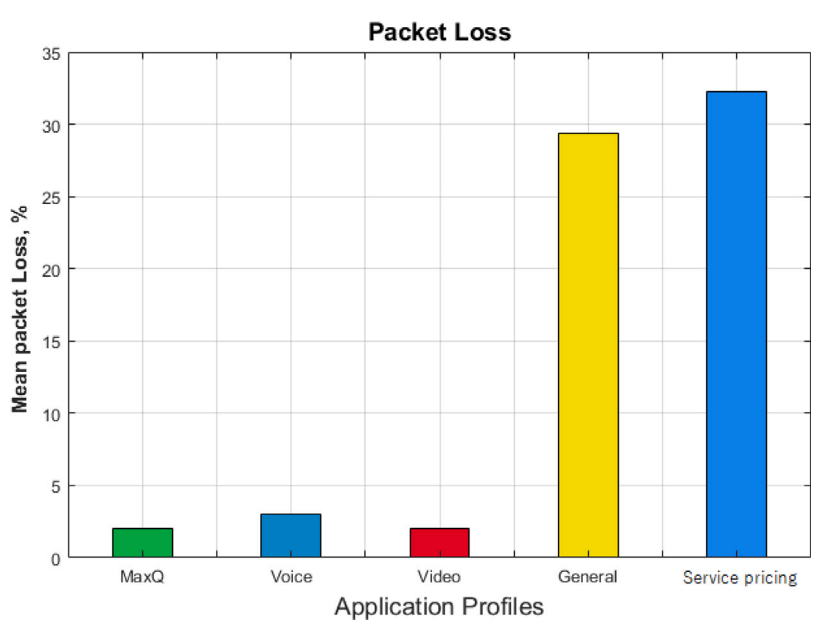

Fig. 10. Packet loss comparison.

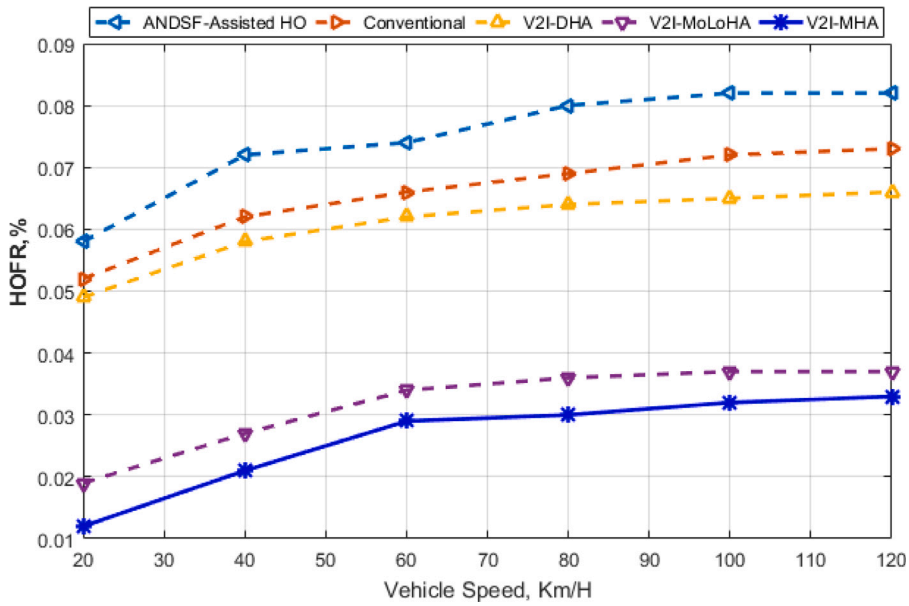

Fig. 11. Handover failure rate (HOFR) versus vehicle speed. Comparison of conventional, ANDSF-Assisted, and the proposed methods.

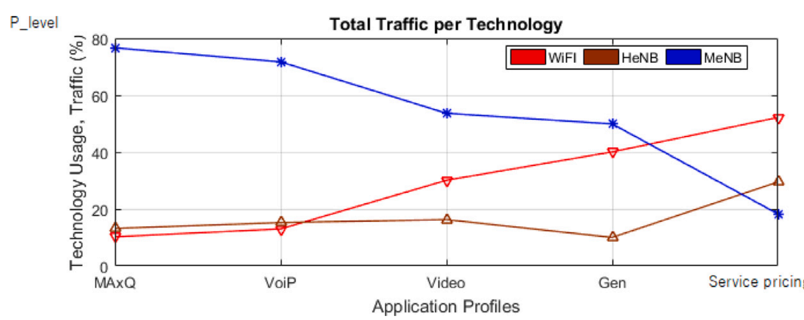

Fig. 12. Comparison of data traffic per technology.

5.5. Data traffic

Fig. 12 exhibits the total data traffic exchanged between the vehicle OBU and the different network technologies across the simulation terrain. We observed that for applications pertaining to the maximum quality profile, voice profile, and video profile, which demanded more resources to maintain the QoS of those calls, the vehicle, running V2I-MHA, has remained mostly within the coverage area of the macro-cell eNB compared to the coverage areas of the small cells. On the other hand, for general profiles and for the lowest service pricing profile levels that demand less resources to maintain the QoS of the calls, the vehicle has preferred to move to the small cells, mostly the Wi-Fi networks.

Although voice and video profiles portray similar performance in terms of the number of handovers, the data traffic received/transmitted per technology are different. For instance, the amount of data traffic transmitted and received via Wi-Fi SAPs for the video profile is higher than the voice profile data traffic. It is due to the fact that the video profile puts higher weight on bandwidth requirements than voice profile. It is also observed that the total data traffic for lowest service pricing profile level have mostly been received/transmitted through the Wi-Fi SAPs since Wi-Fi offers the lowest pricing to avail network services (see Table 6).

6. Conclusions

In this paper, we proposed a multi-criteria based handover algorithm for V2I communications (V2I-MHA) for use in heterogeneous multi-tier network environments. V2I-MHA is built on top of its predecessor V2I-MoLoHA which selects the list of potentials target networks based on the movement direction, speed of movement and the available bandwidth. V2I-MHA selects the most appropriate target network for a potential handover in meeting the QoS requirements for delay-sensitive applications. By defining five different application profiles associated with the knowledge of the underlying candidate network parameters, the most appropriate target network is selected for anticipated handovers. For system evaluation and comparison purposes, we implemented a multi-mode vehicle OBU containing Long Term Evolution-Advanced (LTE-A) and Wi-Fi network interface cards in the Riverbed (Modeller) simulator. The performance of V2I-MHA is evaluated by Riverbed simulator for voice and video applications in multi-tier heterogeneous network setting consisting of LTE-A macro, pico, and femto cells as well as Wi-Fi networks. We compared the performance of V2I-MHA (in terms of handover failure rate (HOFR), and packet losses) with the selected four existing handover methods (V2I-MoLoHA, V2I-DHA, conventional, and ANDSF-Assisted). Results obtained have shown that the proposed V2I-MHA algorithm out performs the existing handover methods. For instance, V2I-MHA offers 16%, 51%, 57%, and 62% lower HOFR than V2I-MoLoHA, V2I-DHA, conventional, and ANDSF-Assisted, respectively. We also found that V2I-MHA offers reduced number of handovers for delay-sensitive applications. The findings reported in this paper provide some insights into handover methods for V2I communications that can help network researchers to contribute further towards developing the next generation vehicular communication networks. The performance modelling of V2I-MHA in a mixed network setting, including 5G, LTE-A, and IEEE 802.11ac networks is suggested as future work.

CRediT authorship contribution statement

Emmanuel Ndashimye: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing - original draft, Writing - review & editing. **Nurul I. Sarkar:** Analysis and/or interpretation of data, Writing - review & editing. **Sayan Kumar Ray:** Conception and design of study, Analysis and/or interpretation of data, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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