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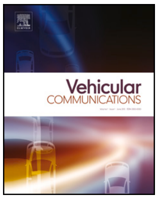

An intelligent path management in heterogeneous vehicular networks

Vadym S. Hapanchak [b,*], António Costa [a,b], João Pereira [b], Maria João Nicolau [a,c]

[a] *Department of Informatics, University of Minho, Portugal*
[b] *ALGORITMI Center, University of Minho, Portugal*
[c] *Department of Information Sistems, University of Minho, Portugal*

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ABSTRACT

Achieving reliable connectivity in heterogeneous vehicular networks is a challenging task, owing to rapid topological changes and unpredictable vehicle speeds. As vehicular communication demands continue to evolve, multipath connectivity is emerging as an important tool, which promises to enhance network interoperability and reliability. Given the limited coverage area of serving access technologies, frequent disconnections are to be expected as the vehicle moves. To ensure seamless communication in dynamic vehicular environments, an intelligent path management algorithm for Multipath TCP (MPTCP) has been proposed. The algorithm utilizes a network selection mechanism based on Fuzzy Analytic Hierarchy Process (FAHP), which dynamically assigns the most appropriate underlying network for each running application. The selection process takes into account multiple factors, such as path quality, vehicle mobility, and service characteristics. In contrast to existing solutions, our proposed method offers a dynamic and comprehensive approach to network selection that is tailored to the specific needs of each service to ensure that it is always paired with the optimal access technology. The results of the evaluation demonstrate that the proposed method is highly effective in maintaining service continuity during vertical handover. By tailoring the network selection to the specific needs of each application, our path manager is able to ensure optimal connectivity and performance, even in challenging vehicular environments, delivering a better user experience, with more reliable connections, and smoother data transfers.

1. Introduction

Over the past few years, there has been a surge in the development of vehicular network applications and services to meet the growing demand for ubiquitous access to information. This has led to the emergence of a diverse range of innovative solutions that enable vehicular users to access information from anywhere and at any time [1–3]. When it comes to fast-moving vehicles, meeting the performance requirements of different applications, such as throughput, latency, and reliability, poses a significant challenge for any single network technology. To meet these demands, a heterogeneous network architecture has become the key technology in vehicular communications that could guarantee continuous connectivity with an adequate quality of service (QoS) [4].

In the wireless network scenario, a heterogeneous system incorporates the characteristics of multiple radio access technologies (RATs), which enables it to improve the overall network performance [5,6]. Therefore, a vehicular user will be able to exploit the different properties of each wireless technology such as different spectrum bands, physical layer schemes and medium access control. Accordingly, there are several RATs adopted for vehicular communication, including ad-hoc and cellular wireless networks, that can overlaps the coverage of each other when deployed in the same area [7]. Nowadays, a vehicle's On-Board Unit (OBU) is equipped with multiple interfaces to access various technologies, such as Wi-Fi, Dedicated Short-Range Communication (DSRC), Bluetooth, LTE, Cellular V2X(C-V2X) and 5G, in order to enhance their communication performance. Integrating a heterogeneous RAT into a single communication device aims to address the scalability issue and strengthen the communication systems of vehicles [8]. Therefore, it is important to study the coexistence and interoperability between different architectures in order to ensure a certain level of QoS to a data flow offered by the underlying networks.

Providing always best connectivity in a vehicular network is a challenging task, due to rapid topological changes and random vehicle speed. Since the coverage area of the serving wireless network is limited, frequent disconnections are expected during vehicle movement. For effective communication, vehicles on the move will need to per-

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* Corresponding author.
E-mail address: vadim@di.uminho.pt (V.S. Hapanchak).

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form fast handovers between different heterogeneous networks to ensure seamless mobility. Vertical handover (VHO) occurs when a vehicle switches the current serving technology while moving among heterogeneous networks (e.g., from LTE to WiFi). Vertical handovers in vehicular networks pose several challenges, including issues such as, packet losses, high delay, and even service interruption during the handover process [9]. To provide a seamless handover experience for moving vehicles across networks, the design of an efficient VHO mechanism is critical. The handover process should not be perceptible to the user, and the ongoing connections should remain uninterrupted when transitioning from one access technology to another.

The current solutions for RAT selection strategy can be broadly categorized into two alternatives, namely *centralized* and *distributed* approaches. In the centralized approach, a particular vehicular user is assigned to the most suitable access technology based on the global view of the network status and application requirements. Conventional centralized handover mechanisms, such as those found in cellular networks, are not well-suited for vehicular networks, as vehicular users may frequently switch among different systems during their movement. Therefore, a large amount of literature focuses on Software-Defined Networking (SDN) paradigm to provide a seamless handover for mobile users [10–12]. SDN allows achieving network programmability and flexibility, making it an essential tool for managing mobile devices and resources. By separating the control and data planes, SDN allows for centralized management and configuration of network devices, simplifying network operations and improving resource allocation. However, a distributed RAT selection algorithm could be undesirable in vehicular communication for two primary reasons. Firstly, it creates a high amount of signaling and message passing overhead in the operator's network infrastructure. Secondly, it deteriorates the user experience by causing constant fluctuations in client throughput [13].

The advanced computation capabilities of recent vehicle OBUs enable the execution of a distributed VHO procedure. This allows each connected vehicle to independently select the most suitable underlying network based on their own requirements, without requiring coordination among different systems or involvement of the network core in the policy decision. Choosing the optimal access technology in a vehicular environment requires consideration of various factors, including user preferences, service type, vehicular mobility profile, and network characteristics [14]. In a vehicular environment, traditional network selection methods based solely on Received Signal Strength Indicator (RSSI) along are inadequate due to their linearity over fast network variance and frequent handovers. Additionally, having multiple networks available simultaneously means that the network with the highest RSSI may not necessarily be the best option for a particular service. Consequently, selecting the most suitable network for multi-RAT terminals in a vehicular scenario is essentially a complex optimization problem. So far, there have been works that focus on the network selection process by relying on fuzzy logic [15–17] multiple-attribute decision-making [18–23], markov chain [24], machine learning and game theory [25–27,13,28] techniques, taking into account many parameters obtained from the different information sources, i.e. network, mobile devices, and user preferences.

While there have been notable advancements in the integration of different radio access technologies, most of the research in the literature has concentrated on wireless environments with low mobility scenarios. Nevertheless, existing solutions in the context of vehicle communications rarely consider a multipath approach. Most of the research in vehicular heterogeneous networks has focused on seamless handover for data offloading, using only one RAT at any given time for communication. Furthermore, most decision-making techniques do not consider the unique QoS requirements of each ongoing service, which can result in suboptimal utilization of network resources. For example, in the case of real-time services like voice and video streaming, which are more susceptible to delay, the decision algorithm may prioritize networks with lower latency. However, for web and data traffic, the algorithm may choose an interface with the highest available bandwidth. Some works have suggested defining a service priority value to reflect the significance of the service to the user [29,11]. Consequently, lower priority services could be directed to use a non-optimal network to achieve consensus among multiple services.

In this paper, we introduce an innovative *path management (PM)* scheme that controls RAT usage to provide an optimal and seamless user experience in a multi-technology vehicular network. The proposed PM scheme differs from existing solutions as it focuses on dynamic network selection for each service individually by utilizing multipath communication and taking into account several factors, such as vehicle mobility, the communication context and the QoS requirements of the ongoing services. In particular, a Fuzzy Analytic Hierarchy Process (FAHP) was exploited to make the path management process fast and efficient. The main contributions and novelties of this article as follows:

- We propose a comprehensive technology-agnostic access selection algorithm, which considers cross-layer factors to make optimal network selection under the constraint of highly dynamic environments.
- The proposed PM strategy can fulfil the individual application requirements to support efficient and reliable V2I (Vehicle-to-Infrastructure) and V2N (Vehicle-to-Network) communication. Unlike previous solutions, the network selection is made in per-connection level. Thus, the decision is made for each service individually.
- The experimental results validate the efficacy of the proposed algorithm, which accurately selects the most suitable network, enhances the user's quality of experience (QoE), and improves the overall network performance in the heterogeneous vehicular system.

The rest of the paper is organized as follows: Section 2 reviews the literature on VHO and network selection methods in vehicular networks. Section 3 provides background on the system architecture and protocol stack used. The FAHP-based network selection mechanism is then described in Section 4, and its performance evaluation is presented in Section 5. Finally, Section 6 concludes the paper.

2. Related work

In recent years, there has been a growing interest in the use of multipath communication for vehicular networks [7,30]. This approach involves leveraging multiple RATs to enable reliable and uninterrupted vehicular communication, even in challenging heterogeneous environments [31]. For example, the redundant use of multiple access technologies was considered in [8] to improve the communication reliability of vehicular applications. The paper demonstrates the potential benefits of using multiple RATs in the context of a highway platoon scenario. In [9], a hybrid vehicular network architecture and protocol stack was proposed, which combines DSRC and C-V2X technologies. The paper addresses the problem of radio resource management, adaptive RAT selection and VHO algorithm in a highway environment. The effectiveness of the proposed architecture is shown using several simulations with different parameter settings. A multi-radio access technologies scheme for V2X communication have been introduced in [32], where two different radio access technologies (i.e., LTE-Uu and PC5) are combined in order to improve a system performance and meet high reliability requirement.

A discussion on the use of MPTCP in vehicular environments has become an urgent issue. Authors in [33], conduct a survey on the technical challenges and reviewed the existing studies regarding MPTCP, and the implementation of MPTCP in vehicular networks. In [34], the MPTCP was used to seamlessly switch between 802.11 and satellite connections for non-safety related vehicular infotainment applications. A performance evaluation demonstrates the good performance of the proposed method in a vehicular scenario, in which both interfaces are used to transmit the video data. The combination of MPTCP and Software Defined Networking (SDN) to provide a seamless V2I connectivity was considered in [35]. The authors conducted experiments to evaluate the default performance of MPTCP in heterogeneous networks that employed both Wi-Fi and DSRC. They also presented an approach for installing rules to establish V2I connectivity in software-defined vehicular networks with centralized control. The problem of ultra-reliable low latency communication for Connected Autonomous Vehicles (CAVs) has been addressed in [36]. A novel framework based on MPTCP was introduced, which employs coding techniques and efficiently distributes packets across multiple wireless network links that may dynamically change. Based on mathematical modeling and performance evaluations, it was demonstrated that the proposed approach effectively optimizes resource utilization and enhances throughput. Authors in [37] proposed a mobility-aware multimedia data transfer mechanism using MPTCP in vehicular networks. MPTCP was adopted for aggregating bandwidth and improving transmission rate for video streaming services. To measure the quality of subflows and dynamically allocate data to different paths, a quality-aware data distribution technique is utilized. Furthermore, the VHO mechanism was tested for continuous data transmission. The simulation results indicate that the mobility-aware data transmission mechanism effectively enhances throughput while reducing transmission delays. A novel MPTCP scheduling scheme that dynamically enables packet duplication across parallel paths have been recently introduced in [38]. The proposed scheme can adaptively turn to redundant scheduling in the presence of HoL blocking in order to achieve the best bandwidth performance for high-speed vehicles. Experimental results show that the proposed solution can improve the bandwidth aggregation under fast mobility scenarios.

The VHO challenges in vehicular networks have received considerable attention, with research efforts primarily focused on the lower layers of the protocol stack. However, there has been limited investigation into the multipath approach to this problem. Authors in [39,40] presented and implemented a path management scheme for MPTCP that utilizes cross-layer analysis of attributes such as MAC-layer information to manage path usage and address quality changes in heterogeneous networks. In our earlier work [41,42], we evaluated the feasibility of MPTCP in supporting efficient and resilient V2I communication over heterogeneous networks. Initially, we discussed various challenges associated with multipath communication and demonstrated the impact of handover events on application performance. We also proposed a cross-layer PM scheme to enhance the effectiveness of multipath vehicular communication and enable a seamless handoff for end-users. However, the presented VHO algorithm relies on a single criterion, which may not always provide a comprehensive solution. Therefore, a more advanced PM method is needed with more sophisticated policies that take into account real-time network attributes and user preferences. This would require a more complex decision-making algorithm that can dynamically adapt to changing network conditions and user requirements.

Machine Learning (ML), a prominent subfield of Artificial Intelligence (AI), has emerged as a promising research direction to tackle the network selection problem in vehicular networks by using a data-driven approach. ML offers a flexible toolkit to leverage non-linear parameters and support accurate decision-making in a variety of applications. Typically, ML involves two stages: training and testing. During the training stage, a model is developed using training data, while during the testing stage, the trained model is used to generate predictions. However, selecting the appropriate ML method is crucial to achieve optimal speed, accuracy, and memory utilization, especially in a dynamic network environment. For a comprehensive classification of the related AI approaches for traffic management in MPTCP, please refer to the survey in [43].

Despite significant progress in the convergence of various radio access technologies, research in the literature has mostly focused on low mobility scenarios in wireless environments [27,13]. However, there have been studies to solve access selection challenges in heterogeneous vehicular environments. For example, the works proposed in [16] and [17], relies on fuzzy logic to estimate the suitability of each RAT to support the QoS requirements of the various applications. The experimental results demonstrate that the combination of fuzzy logic and MCDM components is effective in tracking changes in the operating conditions of different RATs and implementing an adjustable context-aware strategy for selecting the optimal underlying network. Two different models were considered in [44] to model the network selection process. The first model is based on MCDM techniques of order preference by similarity to ideal solution (TOPSIS), whereas the second model is based on the Markov decision process (MDP). Authors have proposed a framework, called VECOS, consists of a complete protocol that includes various modules to be deployed at the network control plane and at the user equipment. The framework enables the selection of the most suitable radio access technology for connected vehicles based on various criteria, including service type, the mobility feature, and traffic dynamics. The simulation models were used to evaluate the performance of the proposed framework, considering two heterogeneous wireless technologies, namely, WiFi and cellular networks. The multi-criteria based handover algorithm for V2I communications have been recently introduced in [45] for use in heterogeneous network environments. An MCDM algorithm was utilized to determine the optimal network for handover by considering the QoS needs of the ongoing services, such as guaranteed bandwidth, latency, PLR and the usage cost. The proposed algorithm utilizes the Simple Additive Weighting (SAW) method, with the weighting vector of the decision element determined through the eigenvalue method of AHP. Furthermore, a weight vector is developed for each application profile to enable the selection of the most appropriate network for handover, based on the QoS requirements of the ongoing services. The problem of seamless handover between light fidelity (LiFi) and wireless fidelity (WiFi) networks has been addressed in [46], in which an adaptive cross-layer handover algorithm based on MPTCP was demonstrated. According to this algorithm, the MPTCP can switch dynamically from ‘Default’ to ‘Fullmesh’ operational mode based on the mobility level of users, which is determined using the FAHP-TOPSIS method. In an indoor wireless network scenario, a central controller was utilized to constantly monitor the entire network and gather channel status information periodically. The simulation results demonstrate that the proposed algorithm can reduce the handover times and improve throughput and service continuity of users. Authors in [47] investigates a new MCDM weighting technique to improve VHO decision in V2I network for multimedia services transmission. The proposed approach is based on the combination of two main weighting techniques, the AHP technique and the Entropy technique, which takes into account the required quality of service metrics as well as the vehicle velocity. The effectiveness of the proposed VHO method was evaluated for both conversational and streaming services. The results demonstrate that it outperforms commonly used RSS-based techniques and is well-suited for future V2X applications.

3. System model

Future vehicular networks are expected to adopt a heterogeneous architecture that integrates multiple RATs with distinct characteristics [14,6,5]. This approach would allow various access technologies to coexist and collaborate, resulting in significantly improved communication performance. By leveraging the strengths of each RAT, this architecture promises to provide faster and more reliable connectivity, supporting a diverse range of use cases such as high-bandwidth applications, IoT devices, and low-latency applications [48].

The rapid and expansive growth of telecommunication systems, coupled with the widespread deployment of the Internet of Vehicles (IoV), has paved the way for the development and standardization of numerous novel communication processes and protocols. Within this landscape, the domain of VANETs has kept pace with this evolution and transitioned into the realm of IoV. In the realm of the IoV, intelligent interfaces play a pivotal role in seamlessly integrating heterogeneous networks. One of the primary objectives within IoV is achieving interoperability among diverse devices and systems.

The key idea is to tightly integrate multiple RATs available, allowing data messages to be sent over the network(s) that best suit the performance requirements and network conditions at any given moment. This approach enables the coordination of multiple RATs and ensures that vehicles maintain reliable and efficient connectivity by dynamically adapting to the changing vehicular environment and driving situation. Efficient utilization of heterogeneous vehicular wireless networks has the potential to yield several benefits, including cost savings through the utilization of free Wi-Fi, the facilitation of high-throughput applications by aggregating bandwidth, and the enhancement of network performance in the face of wireless communication's inherent dynamics and uncertainties.

The vehicular communication system encompasses not only vehicles but also other communication entities like roadside units, cloud and fog networks, the Internet and pedestrians. V2X communication, enabling seamless interaction between vehicles and their surrounding entities, using heterogeneous technologies like Wi-Fi, DSRC and LTE networks. This facilitates the dissemination of valuable information to drivers, passengers, the cloud, and even entities in proximity, such as pedestrians and cyclists. The purpose is to enhance safety and cater to both safety-critical and non-safety-related services and applications. The communication architecture of IoV encompasses not just vehicles and RSU but also a diverse array of communication devices. While this inclusion adds complexity, it aligns the architecture with market demands, distinguishing it from VANETs. As shown in Fig. 1, the heterogeneous network architecture of IoV includes different types of vehicular communications, which include Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), Vehicle to Network (V2N), Vehicle to Pedestrian (V2P), Vehicle to Device (V2D) etc

Recent advances in network technologies have led to the promotion of multipath connectivity as a means of enhancing network interoperability [49]. This novel paradigm enables the simultaneous use of multiple RATs, improving network performance and reliability. To achieve this goal, Multipath TCP [50–52] is being recognized as a promising solution for future mobile networks. It enables the aggregation of parallel connections at the flow level, resulting in enhanced user experiences through increased throughput and seamless connections. MPTCP can support various types of vehicular applications, including infotainment, real-time navigation, and remote diagnostics, which makes it particularly valuable for V2N communication [7,33]. As shown in the Fig. 1, each vehicle can utilize several communication paths to connect with a remote host on the internet while moving on the road. MPTCP is capable of maintaining multiple parallel connections, also known as *subflows*, and dividing a single data stream into several segments that can be transferred concurrently through different available interfaces, which enables applications to remain active during VHO, whereas conventional TCP connections would terminate. In addition, the subflow creation and the data allocation to different subflows occurs transparently to the application.

Unfortunately, the frequent handovers across heterogeneous networks, the unstable wireless connection caused by the user mobility, and rapid topology changes can substantially impair the performance of MPTCP connections [53,54]. The frequent handovers across heterogeneous networks can result in latency on data delivery, interruptions and head-of-line (HoL) blocking that is especially problematic for real-time applications such as video conferencing or online gaming, where even small delays can negatively impact the user experience [55]. In our earlier research [41], we demonstrated that the default MPTCP path management scheme is not well-suited for vehicular networks due to its latency in detecting link failures and lack of dynamic subflow control. Consequently, the protocol could not ensure service continuity in vehicular scenarios, as we show in our results. In order to reduce the impact of frequent VHOs, we designed an adaptive cross-layer assisted path manager tailored for vehicular networks [42], which leverages MAC-layer information to control subflow utilization based on real-time network performance. By adopting a cross-layer strategy, our PM aims to accurately gauge path quality and promptly control the MPTCP connection from the application layer, i.e., create or remove MPTCP subflows as needed. While the proposed strategy yields significant improvements in data delivery latency and throughput, it employs a PM algorithm based on a single criterion (i.e., RSS), which may not be sufficient for providing a comprehensive solution. Network parameters such as available bandwidth, packet loss rate, packet sending delay and jitter are crucial factors influencing the performance of any connection and should be considered in the decision-making process. MPTCP is highly sensitive to the state of the network, and thus, these factors play a crucial role in its performance.

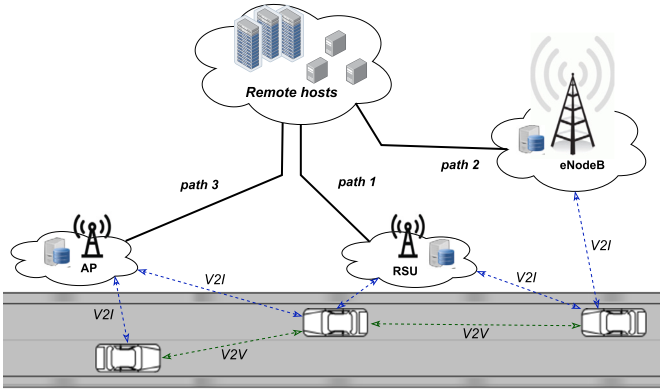

Fig. 1. Heterogeneous vehicular communication system.

3.1. *Attributes to consider*

To ensure service continuity for vehicular users, an advanced PM strategy is needed, that consider various parameters, such as vehicle mobility and real-time network attributes, to make dynamic and adaptive decisions in response to changing environmental conditions. The most appropriate PM scheme for vehicular networks must include advanced context information, and particularly it is relevant to consider the speed, location, and movement direction of the vehicle, which can be readily obtained from the vehicle's OBU [11]. Furthermore, the decision algorithm should take into account the service pricing and the specific QoS requirements of different applications [29]. In this paper, we consider several attributes that are important for network selection framework as described in the next section.

3.1.1. *Latency*

As the latency increases, a TCP-based subflows significantly reduce its data transfer rate, since the delay in receiving acknowledgment packets, affects how quickly the TCP congestion window increases and, subsequently, the achieved throughput. In addition, if the latency is high, it means there is a delay in the transmission of data, which can negatively impact the performance of real-time applications, such as online gaming, video conferencing, or live-streaming.

3.1.2. *Jitter*

Jitter refers to the variation in the delay between packets traveling across a network. In other words, it is the inconsistency in the time it takes for packets to arrive at their destination. This variation can be caused by various factors, such as network congestion, varying distances between nodes, and differences in processing times. Jitter is a negative aspect of the network that can impact the quality of real-time communication and data transfer speeds, particularly for applications sensitive to latency.

3.1.3. Packet Loss Ratio (PLR)

PLR represent the fraction of data packets that are lost during transmission across a network. A high PLR can cause data corruption and reduce network performance. In the event of packet loss, re-transmission becomes necessary to ensure data integrity, leading to further delays and decreased throughput. QoS considerations are closely related to packet loss. The acceptable amount of packet loss depends on the type of data being transmitted. For example, missing one or two packets occasionally may not affect the quality of voice over IP conversations, while losses between 5% and 10% significantly affect their quality. Thus, measuring instantaneous packet loss can provide additional information to achieve a more efficient PM scheme.

3.1.4. Received Signal Strength (RSS)

The access layer provides essential information on various status indicators, such as the busy channel rate, Received Signal Strength (RSS), and frame transmission statistics. Since RSS is an important factor in determining link quality, many handover algorithms rely solely on RSS for decision-making. However, it may not always be sufficient on its own to ensure seamless handover between networks. While a high RSS generally indicates a strong and reliable signal, other factors can also affect the quality of the wireless link. One important factor is the level of interference in the signal. Interference from other devices or sources can weaken or disrupt the signal, even if the RSS is high. Other factors that can affect link quality include the distance between the transmitting and receiving devices, the type of wireless technology being used, and the presence of physical barriers between the devices. Some techniques for evaluating link quality include measuring the bit error rate and signal-to-noise ratio, which provide a more comprehensive assessment of link quality.

3.1.5. Dwell time

Dwell time, or residence time, refers to the duration of time that a mobile device remains connected to a particular network. Typically, when a vehicle connects to an infrastructure node (e.g., eNodeB or RSU), the connection is maintained for as long as the vehicle remains within the coverage area of that node. The average time that a moving vehicle stays attached to the same network can vary depending on the speed of the vehicle and the density of the infrastructure in the area that enables the vehicle's internet connectivity.

3.1.6. Cost

One of the critical factors to consider in PM algorithm, when selecting the optimal connection, is the service pricing. This involves the pricing of various services, as well as different network technologies such as LTE, 5G or Wi-Fi. The pricing of resource usage can vary depending on the service provider, user's demand and context.

3.2. Service profiles

The requirements and preferences for key network attributes, such as latency, bandwidth, delay variation, error rate, and other factors, are likely to differ among various applications. For example, voice and video calls require low packet delivery latency and acceptable jitter, meaning that the packets must be delivered quickly and with minimal delay, in order to provide a smooth and uninterrupted conversation. On the other hand, web browsing is more tolerant of delay but requires a high packet delivery rate, meaning that a lot of data must be transferred quickly to maintain acceptable throughput and allow the user to browse the internet without significant lag. In transportation services, such as remote driving, for instance, data must be transmitted with minimal delay to ensure that the vehicle can be controlled in real-time, and a stable signal quality is necessary to avoid disruptions that could cause safety issues.

One limitation of traditional network selection schemes is that in the event of a handoff, all established connections on the current network must disconnect and reconnect on the next access network. This can be problematic in the context of multipath communication, as it means that all created subflows on a particular interface must switch to another interface, even if the previous network provided better performance for a particular service. Unlike many other proposed works, this paper presents a novel path management scheme that takes into account vehicle mobility, network attributes, and service QoS requirements to optimize network utilization for each application individually.

In order to accomplish this, we classify applications into distinct groups based on their respective requirements, and the PM procedure is fulfilled for each group individually, allowing for tailored handoffs specific to each traffic class. In this paper, we distinguish the three service profiles (SP): (1) **Conversational** (such as VoIP or video chat), (2) **Streaming** (such as video streaming, entertainment) and (3) **Background** (including browsing, file transferring, etc.). By adopting this approach, it becomes easier to optimize network utilization while ensuring a consistent level of performance for data flows across all service types. This not only enables efficient utilization of network resources, but also guarantees a high-quality user experience for different types of network traffic. For example, when a vehicular user is engaged in a phone call while on the move, the PM can choose a network, such as LTE, that offers lower delay and delay variations for uninterrupted communication during the ongoing voice call. At the same time, the PM can select another access technology (e.g., WiFi), for applications that can tolerate longer communication breaks, like internet browsers, while ensuring that packet losses and costs are minimized.

3.3. Userspace path manager

Intelligent Transportation Systems (ITS) typically rely on the exchange of information between different layers of the communication stack to improve traffic management, enhance safety, and reduce congestion. The full ETSI ITS-G5 protocol stack comprises the following layers: *Access*, *Networking & Transportation*, *Facilities*, *Applications*, *Security* and *Management*, as illustrated in Fig. 2. Each layer is responsible for specific functions, and the data exchanged between layers are often encapsulated in different protocols. To manage cross-layer information, ITS systems must ensure that each layer can access the relevant information from the layers below it, and that the information is appropriately translated into the relevant protocol format.

MPTCP is a versatile protocol that has been successfully implemented in the Linux Kernel. It offers the ability for an application to simultaneously send data over multiple IPs and interfaces, without requiring any additional effort from the application itself. This means that MPTCP operates transparently to the application layer, and applications can continue to use the standard socket API as they normally would. The modular architecture of MPTCP supports different path management (PM), congestion control (CC), and packet scheduling (SCH) strategies. When multiple communication paths are available, the packet scheduling method decides which data segments should be transmitted over which subflow. Meanwhile, the PM module controls the use of subflows, with users able to configure specific operational modes for each MPTCP endpoint. For example, the default **full-mesh** mode aims to establish subflows between all pairs of IP addresses on the client and remote host, creating one subflow over each active interface.

Despite this, MPTCP utilizes an unmodified socket interface, and the PM module that regulates the creation and removal of subflows located entirely within the kernel. As a result, MPTCP's standard socket API lacks the ability for dynamic subflow control, i.e., subflows are created immediately following connection creation or when an interface becomes active. In [56], the authors propose to separate MPTCP data plane from the control plane by moving all PM functions into the application layer. The control plane handles functions related to subflow management, without the need for the kernel to manage complex policies, while the data plane is responsible for transmitting and receiving data.

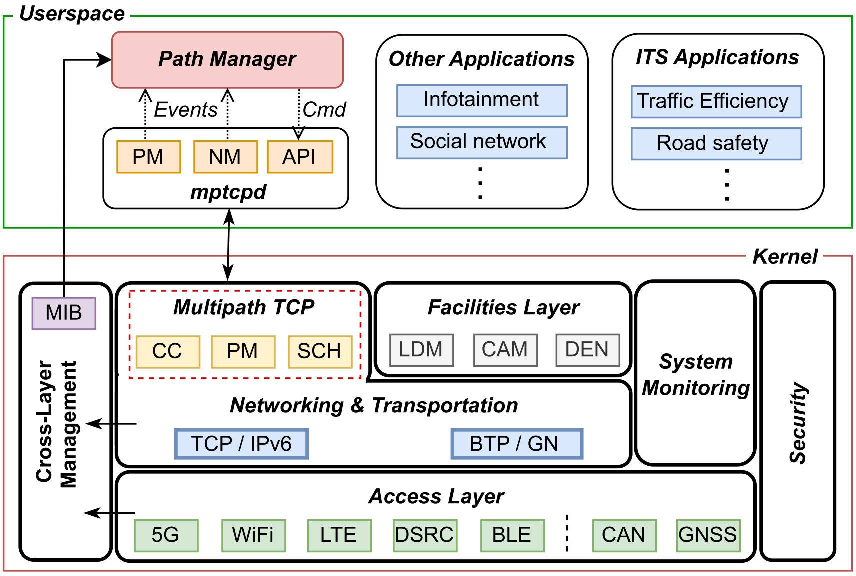

Fig. 2. Multipath TCP make a part of Networking & Transportation layer of the ETSI ITS-G5 stack. The *userspace* PM interacts with kernel through the *netlink* IPC mechanism.

Recently, the MPTCP daemon (*mptcpd*) [57] was introduced, enabling the development of customized PM strategies in userspace. The mptcpd provides an interface that allows userspace applications to send control messages to the in-kernel path manager, offering a high degree of control over MPTCP connections. To interact with the kernel and obtain information about MPTCP events, the netlink inter-process communication mechanism is utilized. By leveraging the netlink interface, mptcpd can efficiently transmit data between the kernel and userspace, enabling real-time monitoring and control of MPTCP connections. Furthermore, the MPTCP upstream implementation [51] offers an interface for PM-related operations, automatic endpoint configuration, and tracking per-connection information.

The mptcpd is responsible for delivering all PM related events, that includes the delivery of notifications regarding the establishment or closure of connections, creation of subflows, addresses advertisements, and other similar events. Additionally, it is also responsible for delivering all network interface events that may occur, such as the availability of a new interface or the removal of an existing one. The necessary cross-layer information can be obtained from the *Management Information Base (MIB)* and delivered to the userspace in real-time. This information is then used to perform path management for each running application, as we will illustrate in the following section. Once the output from the network selection procedure is generated, the userspace PM can alter the state of MPTCP connection using a set of available commands. These commands include requesting to establish a new subflow, modify subflow priority, or remove an existing subflow, as described in our previous work [42].

3.4. The proposed PM algorithm

In contrast to the in-kernel implementation, which controls all connections using global settings, the userspace PM enables individual control of each ongoing subflow. This allows our PM system to dynamically adapt to changes in the vehicular environment and ensure targeted QoS/QoE performance for each application. Our proposed method assumes that the vehicle will store pre-defined requirements for each application profile, along with threshold values to trigger changes in subflow operational mode. Furthermore, in this paper, we only consider one subflow over each active interface towards the remote host. The system is designed to improve MPTCP reactivity by assessing the suitability of paths for specific applications in advance, allowing for optimal resource utilization and minimizing the impact of vehicle mobility. Our main objective is to achieve seamless connectivity and optimize performance, while minimizing latency and data throughput loss related to handovers. The proposed PM scheme is outlined in Algorithm 1.

Algorithm 1: Pseudocode for PM algorithm.

```
Input: $M = [s_{ij}]_{L \times N}$, $T_b$, $T_r$
for each subflow as $SF$ do
    $i \leftarrow$ get service type of SF
    $j \leftarrow$ get network used by SF
    $prio \leftarrow$ get SF priority
    $score = s_{i,j}$                                  // get network score
    $bkp = false$
    if $score \leq T_b$ then
        $bkp = true$
    end
    if $score \leq T_r$ and $SF$ is active then
        set $SF$ as inactive
        remove $SF$ from connection
    end
    else if $score > T_r$ and $SF$ is not active then
        set $SF$ as active with priority $= bkp$
        add $SF$ to connection
    end
    else if $SF$ is active and $prio \neq bkp$ then
        set $SF$ priority $= bkp$
        change $SF$ priority in commection
    end
end
```

Our PM scheme can take into account the path quality and adjust subflow usage based on a score attributed to each available network. The score is calculated using an algorithm based on the MADM method, which will be explained in the next section. The resulting score matrix, M, is of size $L \times N$, where L represents the number of service profiles and N represents the number of available networks, is used as an input for PM algorithm. Additionally, threshold values for changing the subflow backup status (T_b) and removing subflows (T_r) must be provided.

A vehicular user may experience multiple vertical handovers during an MPTCP session, frequently connecting and disconnecting from heterogeneous wireless networks along its path. The proposed PM algorithm enables dynamic **creation**, **removal**, or modification of subflow **priority**, providing control over handover execution in fast mobility scenarios. Unlike the default MPTCP scheme, our PM does not create additional subflows immediately after the connection is established.

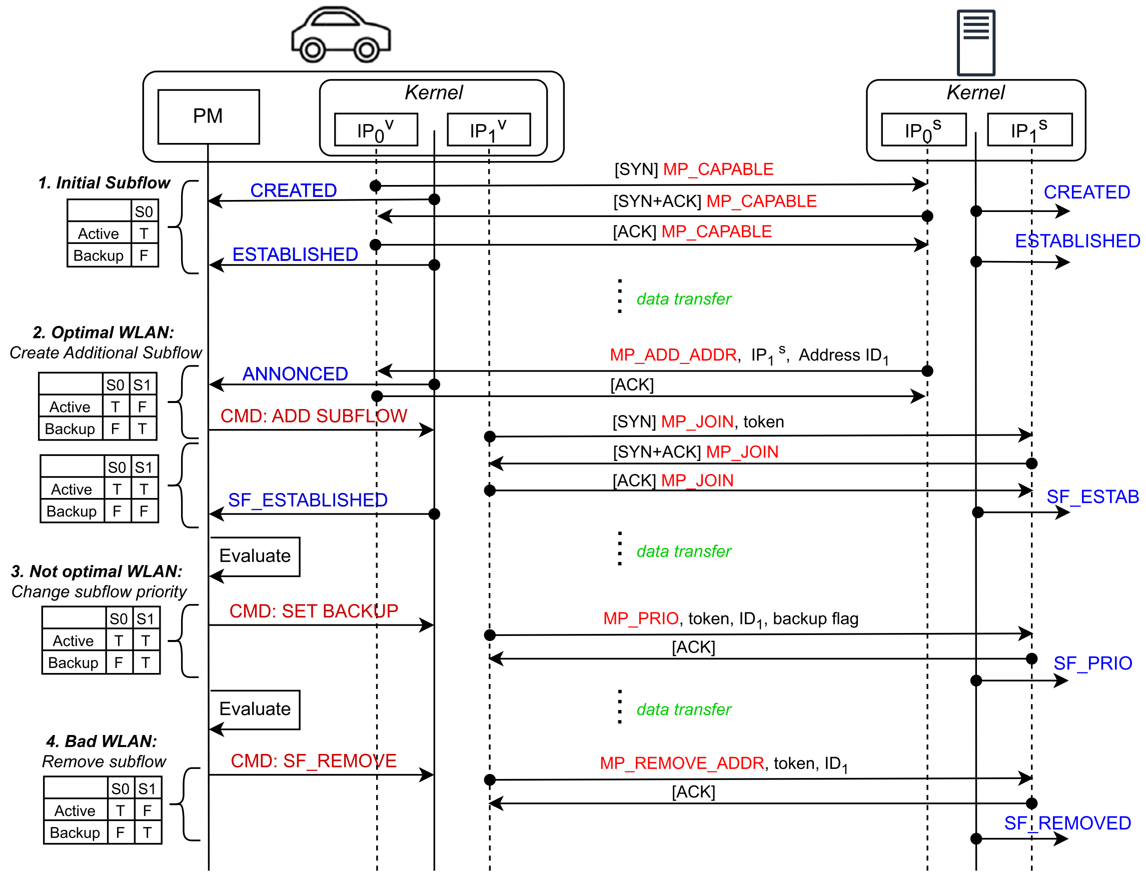

Fig. 3. Signals flow diagram of multipath V2N connection.

Rather than using all available IP addresses to create a *full mesh* by default, a new subflow is only created if the path receives a good score from the network selection algorithm. This approach is more flexible than the existing in-kernel PM, which tries to create additional subflows immediately after the connection is established. Once established, the subflow is marked as *active*. If the network score falls below the T_r, the subflow is removed from the connection and marked as *inactive*. However, the PM retains relevant information about the removed subflow so that it can re-establish the subflow when the score increases above the T_r again. A similar approach is used to determine the priority of the subflow, meaning that a subflow will be used in backup mode when it is active but has a score value less than the backup threshold (T_b). Note that since subflows from the same connection share a unique token, all of them will be removed after the connection terminates.

3.5. *Signaling flow chart*

To provide a more detailed explanation of the path management process, let us consider a straightforward V2N scenario. In this scenario, the vehicle in motion establishes communication with a remote server via MPTCP utilizing both LTE and WLAN interfaces. The signaling flow chart for the connection is depicted in Fig. 3 and explained in the following sections:

3.5.1. *Establish connection*

Firstly, the vehicle initiates the MPTCP connection through LTE. This involves establishing an initial subflow between IP_0^v (the vehicle's IP address) and IP_0^s (the server's IP address) using a three-way handshake procedure. During this handshake, keys are exchanged in the $MP\_CAPABLE$ message to provide authentication material for future subflow setup. As a result, events are triggered on the PM system, and information about the initial subflow (S_0) is added to the subflows table with *active* and *non-backup* flags. Once the subflow is established, the vehicle can start transmitting data on S_0.

3.5.2. *Create additional subflow*

Afterwards, the remote host sends an ADD_ADDR packet to the vehicle, containing its alternative IP address (IP_1^s) and authentication data. The vehicle echoes the packet back to the server to confirm successful receipt. As a result, the *ANNOUNCED* event is triggered on the PM system, providing the IP addresses and ID of the endpoint announced by the remote host. When adding the advertised address to the subflows table, it is initially marked as *non-active* and classified as a *potential* subflow (S_1), without any actual subflow being established. Periodically, the PM system collects cross-layer attributes and runs the network selection algorithm to assess the quality of available paths. If optimal WLAN conditions are detected, the PM instructs the kernel to establish a new subflow. MPTCP then attempts to create another subflow by sending an SYN packet from IP_1^v (the vehicle's WLAN IP address) to IP_1^s (the server's alternative IP address). The new subflow starts as a normal TCP connection, but with the MP_JOIN option and token to identify which MPTCP connection it is joining. Once the new subflow is established, the *ESTABLISHED* event is triggered, and the subflow status is changed to *active* and *non-backup*. At this point, the vehicle can utilize both interfaces simultaneously for data transmission, since it has access to both LTE and WLAN.

3.5.3. *Change subflow priority*

If non-optimal WLAN conditions are detected, the PM system instructs the kernel to use S_1 as a backup subflow. One potential approach could involve designating a path with a medium-level score, as determined by the network selection procedure, for use as the backup subflow. The vehicle can request a change in the subflow priority by sending an MP_PRIO signal to the remote host. The *backup* flag is activated on S_1, indicating that this subflow will be utilized only if the regular (S_0) becomes unavailable. Once the WLAN score surpasses the specified threshold, the backup subflow can be reactivated using the same command.

3.5.4. *Remove subflow*

In the event of the network selection mechanism detecting poor conditions on the WLAN path, such as a decrease in signal strength due to a vehicle moving away from the coverage area of the RSU, the PM system will issue a command to 'deactivate' subflow S_1 from the data transmission process. However, the information about S_1 is still retained in the subflows table. This means that when the WLAN network becomes available again, the PM system is ready to establish the additional subflow without having to wait for the ADD_ADDR packet, which may not even arrive.

This fundamental concept is applied consistently throughout each computational step: following the evaluation of each path by the network selection algorithm, the PM system will initiate the appropriate subflow creation, removal, or backup procedure.

4. Network selection framework

The network selection algorithm should identify the optimal network based on the QoS criteria of ongoing applications and a set of cross-layer attributes. Let $R = \{r_1, ..., r_N\}$ be the set of available networks, and let the set of network attribute values be $C = \{c_1, ..., c_K\}$, where K denotes the number of observed attributes. We also assume that the vehicle can run a set of L types of services $S = \{s_1, ..., s_L\}$. The definition of the network selection problem in multipath environment could be as follows: given a set of available networks R, a group of services profiles S and the set of observed network attributes C, select the optimal set of candidate networks and their corresponding network usage mode (e.g., backup or regular) to ensure the best possible performance for a specific service. Thus, applications are assigned to network interfaces based on their unique requirements and the capabilities of the networks in question. This section describes the three parts of or network selection procedure, namely: attribute selection and utility values calculation, attribute weight calculation and the network ranking. The FAHP-based framework of the network selection procedure is illustrated in Fig. 4. The entire process of the score calculation is shown in Algorithm 2.

Algorithm 2: Network score computation.

```
Input: $A = [a_{ij}]_{N \times K}$ , $S$ , $R$ , $\alpha$
Data: $M = [m_{ij}]_{L \times N}$                                    // score matrix
for each service type as $i$ in $S$ do
    $req \leftarrow$ get requirements of service $i$
    for each network as $j$ in $R$ do
        if $I$ is available then
            $score = \text{FAHP}(req, A_{j,:})$
            $M_{ij} = (1-\alpha) * M_{ij} + \alpha * score$
        end
    end
end
```

Various network and context information from the vehicular environment are stored in the attribute information matrix $A = [a_{ij}]_{(N \times K)}$, that can be expressed as:

$$A = \begin{pmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,j} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i,1} & a_{i,2} & \cdots & a_{i,j} \end{pmatrix} \tag{1}$$

where a_{ij} represents the value of an attribute i observed on the interface j. N indicates the number of available heterogeneous networks, and K represents the number of considered attributes. The algorithm must evaluate each available path, considering the requirements of all defined SPs. Therefore, the FAHP procedure receives the real-time network attributes along with service requirements, to perform score calculation on each computational stage.

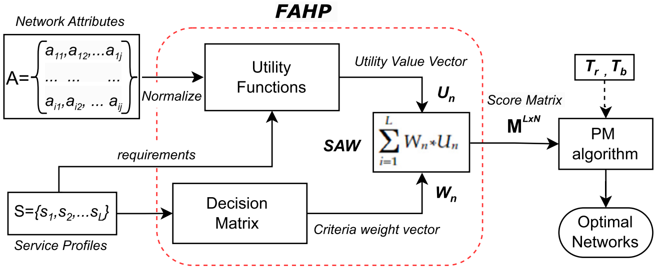

Fig. 4. The framework for network selection based on FAHP method.

Due to the high variance of vehicular networks, the observed parameters undergoes drastic fluctuations, which may lead to frequent changes in subflow operational mode. A simple low-pass filter mechanism is used to reduce the probability of the ping-pong effect when the subflow switches between two modes frequently, resulting in unnecessary handovers. Here, the smooth factor α determines how quickly the filter responds to changes in the input signal. A higher smooth factor means that the PM will respond more slowly to changes in the RSS, resulting in a smoother output. However, too high of a smooth factor can cause the filter to become too sluggish, resulting in a delay in the output response. The choice of the smooth factor depends on the specific vehicular application and the desired balance between unnecessary handovers and maintaining a fast response time.

4.1. *Utility functions*

The utility functions are used to calculate the utility value vector (**U**) of the network attributes to guarantee that the values are normalized according to the objective requirements of each SP. Utility functions are common in multi-criteria decision analysis. They allow decision-makers to translate personal preferences or criteria into a mathematical form that can guide decision-making processes. Utility functions help in comparing different attributes or criteria on the same scale. Having multiple attributes with different units or scales, normalizing them into a common scale allows for meaningful comparisons. This is particularly important in decision-making processes where is required to weigh the importance of various attributes against each other.

Normalization brings values within a standardized range, typically between 0 and 1. This makes it easier to work with data, especially when combining different attributes. For example, in multi-criteria decision analysis, utility functions can transform diverse criteria into a common metric. Furthermore, utility functions can also be used to reduce the dimensionality of a dataset. By normalizing attributes, we are essentially simplifying the dataset and reducing the risk of attributes with large values dominating the analysis.

Attributes can be classified into two categories: **benefit** attributes and **cost** attributes. For benefit attributes, a higher attribute value corresponds to a higher utility value, as is the case with the RSS metric and dwelling time utilized in this paper. Conversely, for cost attributes such as delay, jitter, packet loss rate, and cost attributes, a higher attribute value results in a lower corresponding utility value. When dealing with attributes that have bilateral constraints, we employ the sigmoid utility function for normalization purposes. Specifically, when both upper and lower thresholds exists, we utilize $f(x)$ and $g(x)$ for benefit attributes and cost attributes, respectively. The expressions for these utility functions are given below:

$$f(x) = \frac{1}{1 + e^{-a(x-b)}} \tag{2}$$

Table 1
Utility functions for service profiles.

Attribute	Func.	Conversational	Streaming	Background
RSS	$f(x)$	a = 0.15, b = -80	a = 0.15, b = -80	a = 0.15, b = -80
Delay	$u(x)$	a = 0.1, b = 70	a = 0.07, b = 120	a = 0.03, b = 250
Jitter	$u(x)$	a = 0.15, b = 40	a = 0.12, b = 50	a = 0.07, b = 80
PLR	$h(x)$	g = 1/20	g = 1/15	g = 1/10
Cost	$h(x)$	g = 1/50	g = 1/50	g = 1/50
Dwell T.	$u(x)$	g = 30	g = 20	g = 10

$$g(x) = 1 - f(x) \tag{3}$$

where a and b are constant coefficients determined according to the service requirements for specific attributes. When dealing with attributes that have unilateral constraints, we employ linear and inverse proportional utility attribute functions. Specifically, for attributes which have only one threshold, we utilize $u(x)$ for benefit attributes and $h(x)$ for cost attributes. The definitions for these functions are presented below:

$$u(x) = 1 - \frac{g}{x} \tag{4}$$

$$h(x) = 1 - g \cdot x \tag{5}$$

where g is a constant coefficient that may vary with different attributes and service requirements. Table 1 displays the diverse utility functions and corresponding coefficients utilized for different SPs.

4.2. Applying fuzzy AHP for network selection

This study utilized the Fuzzy AHP (FAHP) method to solve the network selection problem [58,18]. Compared to the traditional AHP approach [59], FAHP is a better method to handle the uncertainty and ambiguity inherent in decision-making processes. It involves breaking down complex problems into hierarchies and constructing a model with the main objective at the top and alternatives at the lower levels. For our network selection problem, a hierarchical structure was established using six input criteria (i.e., RSS, jitter, delay, PLR, usage cost, and dwell time) and a single output, as shown on Fig. 5. Among many FAHP methods in the literature [58], the Buckley's method [60] was preferred for this work.

In some problems, the relationships between criteria and alternatives may not be strictly binary (i.e., yes/no or 0/1). FAHP can model complex and gradual relationships, which is often more representative of real-world situations. FAHP is well-suited for situations where decision-makers have difficulty providing precise numeric values for comparisons. It allows decision-makers to express their preferences using linguistic variables and fuzzy sets, making it a more practical approach when dealing with human judgments. In situations with vague data and complex, interconnected criteria, FAHP may lead to improved decision quality. The consideration of uncertainty and vagueness in decision models can result in more robust and reliable choices.

It's important to note that FAHP is not universally better than traditional AHP. The choice between AHP and FAHP depends on the specific problem, the quality of data available, and the preferences of decision-makers. Traditional AHP may suffice in many cases, especially when data is precise and decision-makers are comfortable providing numerical values for comparisons. However, FAHP is a valuable extension when dealing with more complex and uncertain decision environments. FAHP is based on fuzzy logic, which allows it to handle uncertainty and vagueness in a decision-making process. In real-world scenarios, especially in complex systems or situations with incomplete or imprecise data, FAHP can provide more robust and accurate results compared to traditional AHP.

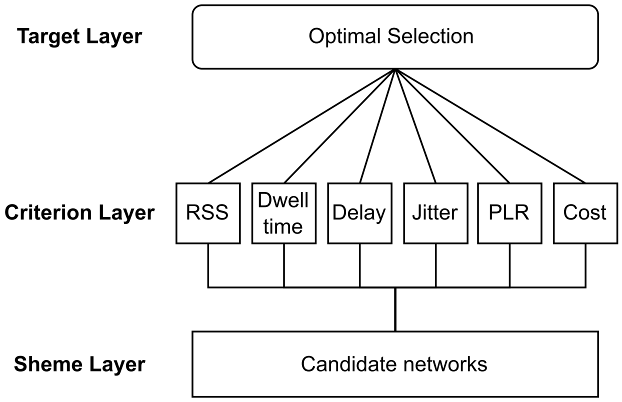

Fig. 5. The hierarchy model of FAHP.

The FAHP method is based on the principles of fuzzy logic and involves rating the decision criteria according to their importance using a set of linguistic terms that convey the degree of significance, such as *very important*, *somewhat important*, and *not important*. However, linguistic values present a challenge in mathematical operations. To overcome this limitation, one effective solution is to convert linguistic comparison ratios into fuzzy numbers. In this approach, each linguistic term is mapped to a fuzzy number, representing the underlying meaning of the term. To represent the fuzziness of preferences, we use triangular fuzzy numbers (TFNs), which are defined as $M = (l, m, u)$ where $l \leq m \leq u$. The decision maker expresses the lower limit value, the most favorable value, and the upper limit value through l, m, and u, respectively. Equation (6) express a membership function of TFN. The calculation rules of TFN are shown in Equation (7), where $\widetilde{N}_1$ and $\widetilde{N}_2$ are two TFN.

$$\mu_{\widetilde{M}(x)} = \begin{cases} \frac{x-l}{m-l} & l \leq x \leq m \\ \frac{u-x}{u-m} & m \leq x \leq u \\ 0 & otherwise \end{cases} \tag{6}$$

$$\begin{aligned} \widetilde{N}_1 + \widetilde{N}_2 &= (l_1 + l_2, m_1 + m_2, u_1 + u_2) \\ \widetilde{N}_1 - \widetilde{N}_2 &= (l_1 - l_2, m_1 - m_2, u_1 - u_2) \\ \widetilde{N}_1 \otimes \widetilde{N}_2 &= (l_1 \otimes l_2, m_1 \otimes m_2, u_1 \otimes u_2) \\ \widetilde{N}_1 \div \widetilde{N}_2 &= (l_1 \div l_2, m_1 \div m_2, u_1 \div u_2) \end{aligned} \tag{7}$$

In order to compare the relative importance of attributes, a linguistic approach must be employed, followed by the transformation of linguistic values into TFNs. Table 2 illustrates the relationship between the importance of attributes and their corresponding TFNs.

4.2.1. Pairwise comparison

To determine the final scores of each available network, the FAHP method involves assigning weights to the various evaluation criteria by conducting pairwise comparisons between the elements of each hierarchy, thereby establishing the priority of each attribute compared to all other attributes.

FAHP is a multi-criteria decision-making methodology that involves comparing the relative importance or preference of different criteria or alternatives. Pairwise comparisons provide a systematic way for decision-makers to express their subjective judgments about these preferences. FAHP calculates weights that represent the relative importance of criteria and alternatives. These weights are crucial for the decision-making process. Pairwise comparisons are the basis for deriving these

Table 2
Importance of TFN value.

	Definition	TFN	Reciprocal TFN
1	Equal Importance	(1,1,3)	(1/3,1,1)
2	Intermediate Values	(1,2,4)	(1/4.1/2,1)
3	Moderate Importance	(1,3,5)	(1/5,1/3,1)
4	Intermediate Values	(2,4,6)	(1/6,1/4,1/2)
5	Strong Importance	(3,5,7)	(1/7,1/5,1/3)
6	Intermediate Values	(4,6,8)	(1/8,1/6,1/4)
7	Very Strong Importance	(5,7,9)	(1/9,1/7,1/5)

weights, and they are used in the subsequent mathematical calculations of FAHP. It provides a structured approach to rank or select alternatives based on the criteria. The pairwise comparison results are used to compute overall scores and rankings, and guide the decision-maker in choosing the most suitable alternative. The relative importance between the attributes is indicated with TFN by considering two criteria at a time. The pairwise comparison matrix $\widetilde{D} = [\widetilde{d}_{ij}]_{(K\times K)}$, can be expressed as:

$$\widetilde{D} = \begin{pmatrix} \widetilde{d}_{1,1} & \cdots & \widetilde{d}_{1,n} \\ \vdots & \ddots & \vdots \\ \widetilde{d}_{n,1} & \cdots & \widetilde{d}_{n,n} \end{pmatrix} \tag{8}$$

where K is a number of network attributes and $\widetilde{d}_{ij}$ indicates the decision maker preference of i^{th} criterion over j^{th} criterion expressed by TFN. It must be constructed one comparison matrix for each SP, considering its requirements.

4.2.2. *Computing the weight vector*

By assigning weights to each attribute, we can effectively prioritize and evaluate the different alternatives based on their respective performance in each category. The geometric mean of fuzzy comparison values of each attribute is calculated as in Equation (9), where $\widetilde{r}$ and $\widetilde{d}_{ij}$ still represent triangular values.

$$\widetilde{r}_i = \left(\prod_{i=1}^{n} \widetilde{d}_{ij}\right)^{\frac{1}{n}} = (\widetilde{d}_{i1} \otimes \widetilde{d}_{i2} \otimes \cdots \otimes \widetilde{d}_{in})^{\frac{1}{n}} \tag{9}$$

Then, to find the fuzzy weight ($\widetilde{w}$) of criterion i, multiply each $\widetilde{r}_i$ with the reverse vector:

$$\widetilde{w}_i = \widetilde{r}_i \otimes (\widetilde{r}_1 \oplus \widetilde{r}_2 \oplus \cdots \oplus \widetilde{r}_n)^{-1} = (lw_i, mw_i, uw_i) \tag{10}$$

Since $\widetilde{w}_i$ are still FTNs, they need to be converted into non-fuzzy values. Equation (11) shows the defuzzification operation according to the center of area method. Then, weights are normalized by applying Equation (12) to find the weight value for each attribute and construct the weight vector $\mathbf{W} = \{w_1, w_2, ..., w_i\}$ for each SP, where $0 \leq w_i \leq 1$.

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \tag{11}$$

$$w_i = \frac{M_i}{\sum_i^n M_i} \tag{12}$$

The pairwise comparison matrix is constructed according to the requirements of a traffic class and the importance of each network attribute. Table 3 demonstrate the three fuzzy matrices and the corresponding weight vectors for tree service profiles, namely conversational (SP_C), streaming (SP_S) and background (SP_B).

4.2.3. *Score computation*

The process of score computation involves collecting raw network attribute values, which are then transformed using utility functions. The coefficients in these functions vary depending on the specific services. The weight vector is initially calculated for each service type from its corresponding fuzzy decision matrix. This vector remains unchanged unless the decision matrix itself is modified, which only occurs when there is a shift in the relative importance of the attributes. Consequently, the equation for score computation is mainly influenced by real-time changes in network attributes.

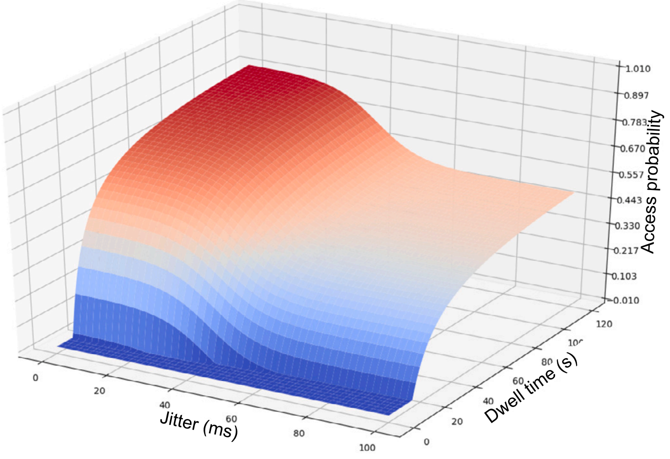

Fig. 6. The probability of *Conversational* service to access the WLAN network with variation of dwell time and jitter.

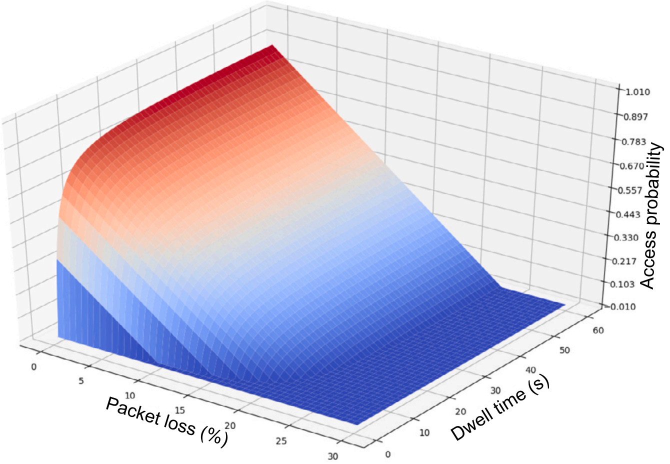

Fig. 7. The probability of *Background* service to access the WLAN network with variation of dwell time and PLR.

The scores for each alternative RAT are determined by multiplying the weight vector of each service criterion by its corresponding attribute utility value, based on the Simple Additive Weighting (SAW) method [23]. We chose the SAW method due to its simplicity and relatively low processing time, which are critical factors for effective decision-making in a highly dynamic environment. SAW method aims to calculate a weighted sum of performance ratings for each RAT across various normalized attributes, as show in Equation (13). The resulting *score* value represents the QoE measure that a vehicle user can achieve for a specific service by using one of the alternative networks. It also indicates the probability of the evaluated network being selected for that particular service.

$$\mathbf{W_n} \cdot \mathbf{U_n} = w_1 u_1 + w_2 u_2 + \cdots + w_i u_i \tag{13}$$

By comparing the network score of the available candidate networks, our PM mechanism is employed to regulate subflow utilization in the active MPTCP connections. It selects alternatives with the highest scores to establish subflows, while excluding RATs with low scores from the connection based on a predefined threshold.

For instance, Fig. 7 illustrates the probability of the *Background* service to access the WLAN network with the variation of PLR and dwell time attributes. It should be noted that while six parameters are utilized

Table 3
Fuzzy comparison matrix and weights for Background, Conversational and Streaming service profiles.

SP_B	RSS	Delay	Jitter	PLR	Cost	Dweel T.	Weight
RSS	1, 1, 3	1, 3, 5	3, 5, 7	1/5, 1/3, 1	1, 1, 3	1, 3 , 5	0.221
Delay	1/5, 1/3, 1	1, 1, 3	3, 5, 7	1/5, 1/3, 1	1/4, 1/2, 1	1/4, 1/2, 1	0.106
Jitter	1/7, 1/5, 1/3	1/7, 1/5, 1/3	1, 1, 3	1/9, 1/7, 1/5	1/7, 1/5, 1/3	1/7, 1/5, 1/3	0.031
PLR	1, 3, 5	1, 3, 5	5, 7, 9	1, 1, 3	1, 2, 4	1, 3, 5	0.328
Cost	1/3, 1, 1	1, 2, 4	3, 5, 7	1/4, 1/2, 1	1, 1, 3	1, 2, 4	0.179
Dweel T.	1/5, 1/3, 1	1, 2, 4	3, 5, 7	1/5, 1/3, 1	1/4, 1/2, 1	1, 1, 3	0.134
SP_C	RSS	Delay	Jitter	PLR	Cost	Dweel T.	Weight
RSS	1, 1, 3	1/4, 1/2, 1	1/3, 1, 1	1, 3, 5	3, 5, 7	1/3, 1, 1	0.160
Delay	1, 2, 4	1, 1, 3	1, 3, 5	1, 3, 5	3, 5, 7	1, 2, 4	0.314
Jitter	1, 1, 3	1/5, 1/3, 1	1, 1, 3	3, 5, 7	1, 3, 5	1, 1, 3	0.210
PLR	1/5, 1/3, 1	1/5, 1/3, 1	1/7, 1/5, 1/3	1, 1, 3	1, 2, 4	1/7, 1/5, 1/3	0.071
Cost	1/7, 1/5, 1/3	1/7, 1/5, 1/3	1/5, 1/3, 1	1/4, 1/2, 1	1, 1, 3	1/7, 1/5, 1/3	0.048
Dweel T.	1, 1, 3	1/4, 1/2, 1	1/3, 1, 1	3, 5, 7	3, 5, 7	1, 1, 3	0.198
SP_S	RSS	Delay	Jitter	PLR	Cost	Dweel T.	Weight
RSS	1, 1, 3	1, 1, 3	1/5, 1/3, 1	1, 1, 3	1, 3, 5	1, 1, 3	0.187
Delay	1/3, 1, 1	1, 1, 3	1/3, 1, 1	1, 1, 3	1, 3, 5	1, 2, 4	0.178
Jitter	1, 3, 5	1, 1, 3	1, 1, 3	1, 3, 5	1, 3, 5	1, 3, 5	0.304
PLR	1/3, 1, 1	1/3, 1, 1	1/5, 1/3, 1	1, 1, 3	1, 2, 4	1, 1, 3	0.133
Cost	1/5, 1/3, 1	1/5, 1/3, 1	1/5, 1/3, 1	1/5, 1/3, 1	1, 1, 3	1/5, 1/3, 1	0.080
Dweel T.	1/3, 1, 1	1/4, 1/2, 1	1/5, 1/3, 1	1/3, 1, 1	1, 3, 5	1, 1, 3	0.117

in the decision-making process, we have chosen to focus on the access probability with respect to the two attributes due to limitations in representing the score variation for all parameters together. A comparable outcome can be observed in Fig. 6, which displays the probability of the *Conversational* service accessing the WLAN network based on the fluctuation of jitter and dwell time. Based on the scores obtained, the PM will determine whether a subflow should be used as a backup, regular, or removed altogether. Indeed, a higher score corresponds to a greater probability of accessing the WLAN network for data transmission. For example, a score below 0.5 may indicate that the path has poor conditions, and the associated subflows should be removed from the session. A score between 0.5 and 0.75 indicates acceptable path conditions; however, it is preferred for use in backup mode. A score above 0.75 identifies optimal path conditions, and the network should be used by the PM to establish regular subflow.

5. Performance evaluation

This section details an emulation-based study conducted on the proposed PM scheme. This study specifically examines a V2N communication scenario where an OBU equipped vehicle maintains network connectivity, accessing a remote host through two wireless technologies, 802.11p and LTE, as shown in Fig. 8. It is assumed that the cellular network is always accessible to the vehicle, while ad hoc connectivity with RSUs deployed at different locations is only available intermittently along the road.

To ensure reliable results, we configured the experimental platform based on the frameworks presented in [61]. We collect network-related information, such as delay, RSS, PLR and jitter, using the ns-3 network simulator [62] and transmit it to the PM for processing. On the other hand, SUMO traffic simulator [63] is used to provide mobility-related information such as vehicle speed, position, and direction. The proposed PM and with other applications were run in an isolated namespace that is connected to the simulated vehicle, according to the framework [64]. All experiments were conducted in real-time using upstream Linux kernel v.15.9 and mptcpd v0.9. To configure a single subflow per interface for each MPTCP connection, we used the latest version of *iptools2*. Furthermore, we employed *iperf3* to generate traffic between the vehicle and remote host. The main focus is to evaluate the impact of proposed PM architecture and FAHP network selection mechanism on the performance of the V2N communication.

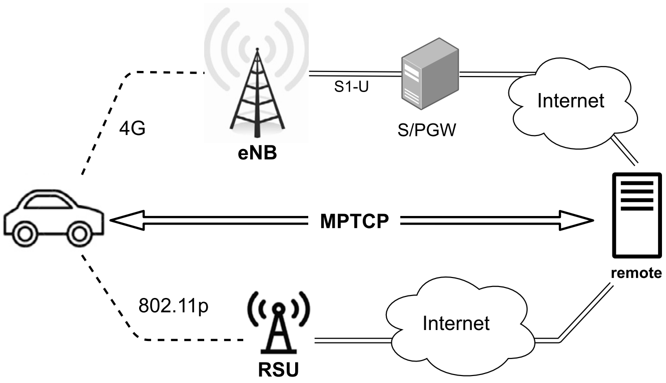

Fig. 8. The V2N multipath scenario under concideration.

5.1. Seamless connectivity

As the vehicle moves on the road within a multi-access environment, frequent handovers are expected. Fig. 9 depicts the average throughput per interface and the total achieved throughput during an MPTCP session, where the vehicle uploads data to the server at a rate of 1 Mbps, using the *Background* service profile. Initially, the PM received high scores to both the 802.11p and LTE interfaces, which allows MPTCP to utilize two parallel connections to transmit a single data stream over them until time $t_1 = 6sec$. After that, the LTE path is demoted to a backup path due to the score drop on cellular network, and only the WLAN interface is used for further data transmission. Around time $t_2 = 20sec$, the vehicle moves out of the RSU coverage area, resulting in a decrease in the WLAN network path's score. As a result, the PM instructs the kernel to remove the subflow on the that interface, and only the cellular network is used for further data transmissions. During an MPTCP session, the connection can migrate from one access technology to another multiple times, but any interruption in service will be perceived at the application layer. This demonstrates the effectiveness of the proposed PM mechanism in providing service continuity and dynamic subflow control for moving vehicles over heterogeneous networks.

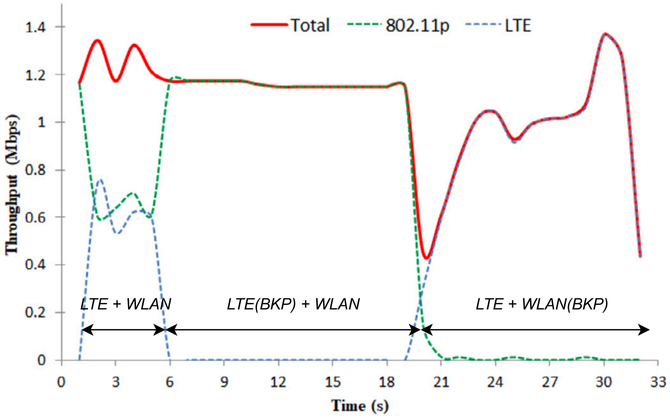

Fig. 9. The throughput of each MPTCP subflow when a vehicle moves in heterogeneous wireless environment.

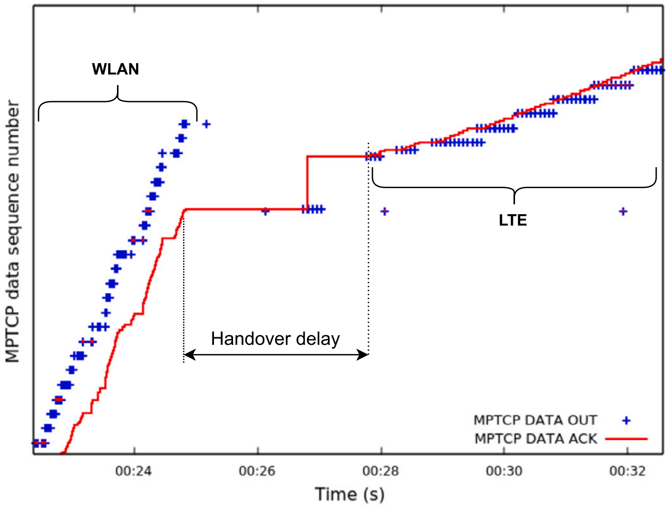

Fig. 10. The behavior of the MPTCP during the handover when our PM is disabled.

5.2. Handover in detail

We will now conduct a detailed examination of the packet traces recorded at the moment when the vehicle moves out of the RSU coverage area and the 802.11p link is lost. Fig. 10 and Fig. 11 presents a comparison between the handover process of the standard MPTCP scheme and our proposed PM mechanism by showing the evolution of Data Sequence Numbers (DSN) over time.

The MPTCP needs to detect the link failure and then adjust the connection accordingly. As a result, there can be a delay before the handover is complete, as shown in Fig. 10. Furthermore, a packet that arrives out of order may be blocked from reaching the destination until the missing packets arrive, leading to a delay in data delivery to the application. This can be particularly problematic for real-time applications such as video conferencing or online gaming, where even small delays can be noticeable and disruptive to the user experience. In addition, the standard MPTCP scheme does not provide any mechanism for the application to utilize the recovered path immediately after its availability [42]. The only option is to wait for successful retransmission, which causes a delay and results in a significant loss of available connection time for the vehicle. Therefore, the standard MPTCP approach may not be suitable for vehicular scenarios, where multiple handovers can occur, leading to significant delays that may negatively impact service continuity.

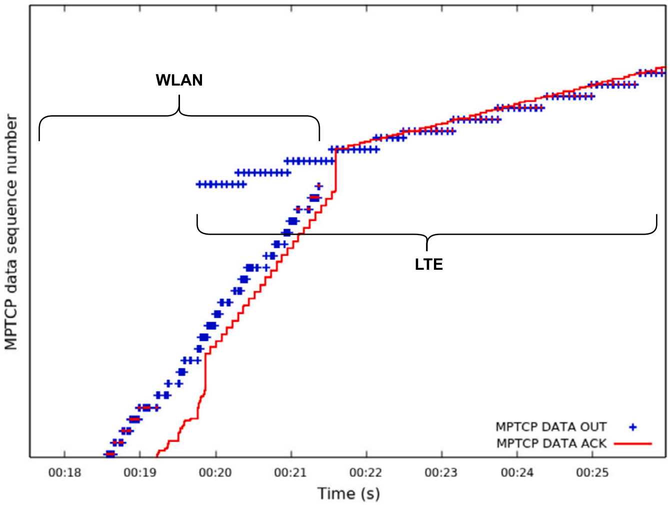

Fig. 11. The behavior of the MPTCP during the handover when our PM is enabled.

The proposed path manager is designed to predict deteriorating network conditions and proactively take appropriate corrective actions to ensure service continuity, before the links eventually break. In the case of the vehicle moving away from the RSU, a drop in network score is observed. Therefore, according to our algorithm, the subflow must be suspended as soon as the score drops below the predefined threshold to ensure seamless handover and uninterrupted service delivery. Initially, the PM removes the backup status of the cellular network, and for a short period, MPTCP uses both interfaces simultaneously, as demonstrated in Fig. 11. Afterward, the PM moves the lossy path to the backup mode in order to prevent it from being used for data transmission. The underperforming subflow could be removed from the MPTCP session if the network score drops below the predefined threshold, as per the proposed PM algorithm. Our path manager can also dynamically reactivate the suspended subflow when the path quality (i.e., score) improves, thereby continuously optimizing the network performance by adapting to changing conditions.

5.3. Application delay

Our path manager was tested in a Manhattan-like urban scenario with bidirectional streets and one lane per direction. During the simulation, the vehicle follows a designated trajectory, moving through various coverage areas while performing data transfer with the remote host. The scenario aimed to assess the algorithm's effectiveness for V2N communication with various infrastructure node deployments. The LTE and IEEE 802.11p interfaces were installed in all vehicles, which ran the CAM service to exchange real-time information. The scenario featured a single LTE base station and a set of RSUs distributed uniformly at random intersections.

To effectively monitor any fluctuations in application delay during the handover, we generate traffic with a timestamp embedded in each data segment. Our approach involves measuring the end-to-end delay, which is determined by calculating the time taken for a packet to leave the source application and reach the destination application. We record the arrival time of each data segment received, and by comparing the timestamps, we can accurately determine the end-to-end application delay. In order to ensure precision in our measurements, our emulation setup employs a same hardware clock across all communication endpoints.

We conducted two identical simulations to compare the effectiveness of our PM with the default MPTCP scheme. In one test, we disabled our PM, while in the other, we enabled it. Each simulation lasted for one hour and involved uploading files of varying sizes from the vehicle to

Table 4
Network parameters variation.

	RSS(dBm)	Delay(ms)	Jitter(ms)	PLR(%)	Cost	Dwell Time(s)
LTE	-100:30	5:80	2:50	1:10	15:45	30:600
WLAN	-100:30	20:250	5:100	2:20	0:20	5:120

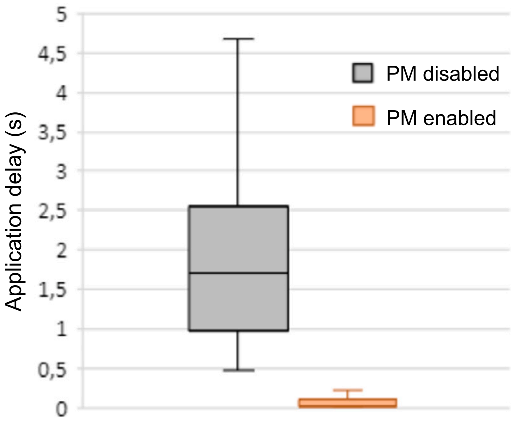

Fig. 12. The end-to-end delay during the handover.

the server. Following the completion of the simulations, we compared the end-to-end delay, and represented the results in Fig. 12. Our findings reveal that the standard MPTCP scheme led to a notable increase in the application layer delay during handover, ultimately resulting in connection glitches. Unlike, our proposed PM scheme demonstrated a considerable reduction in delay during VHO by effectively controlling subflow usage from the userspace, optimizing network performance and ensuring uninterrupted service for vehicular users.

5.4. Network selection probability

This experiment illustrates the response produced by FAHP network selection algorithm under different network conditions for three types of services: background, conversational, streaming. This demonstration provides insight into the algorithm's efficacy and suitability for different network scenarios. We conducted experiments by varying parameters that impact the performance of multipath vehicular communications, including signal strength, delay, jitter, packet loss rate, price and dwelling time. We simulated 10000 network selections activities for each service type by generating random network attributes, as listed in Table 4.

Fig. 13 displays the statistical probability of each network type being selected for different service profiles after completing the experiment. The figure illustrates how the FAHP algorithm adapts to diverse service requirements by creating regular and backup (BKP) subflows through available networks. Our algorithm takes into account the service characteristics and network environment to ensure a balanced probability of selecting each type of network. However, it is more inclined to select the cellular network, which is better aligned with the services under consideration in terms of packet losses, latency, and residence time.

WLAN is more likely to be selected for *background* services due to its low cost and acceptable packet loss rate, while LTE has the highest selection probability for delay-sensitive applications. For *conversational* services, low delay and jitter are important, as well as a long-lived and stable connection with the same infrastructure node to avoid frequent handovers and potential interruptions during service. Therefore, cellular networks are preferred for creating subflows, while WLAN networks are mostly considered as backup paths.

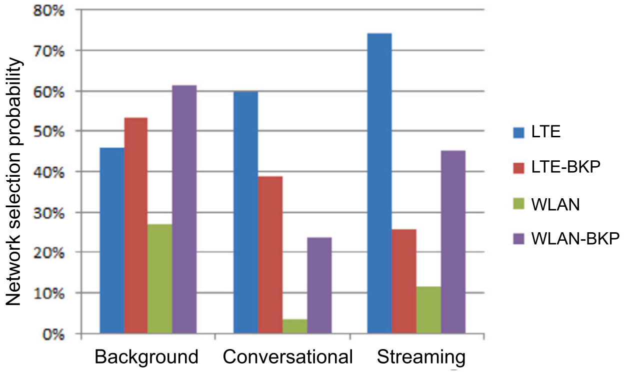

Fig. 13. The statistical probability of each type of network to be selected.

6. Conclusions and future work

This article explores the benefits of multipath communication and discusses the challenges associated with implementing it in highly mobile vehicular networks. It highlights the MPTCP as a potential solution to address service continuity in vehicular communication and introduces a comprehensive PM algorithm that operates at the application layer, which can dynamically adjust subflow usage in response to frequent vertical handovers. The network selection algorithm employed in this study is based on Fuzzy AHP, which considers multiple network attributes, including loss rate, dwelling time, delay, jitter, price, and signal strength. The algorithm involves the calculation of attribute utility values, objective weights, and assigning scores to dynamically evaluate each available access technology. Furthermore, the proposed PM scheme takes into account application requirements by performing the network selection for multiple service types individually, ensuring that the most suitable network is selected for each running application. The result is more effective usage of network resources tailored to the specific needs of each application, which can significantly enhance the overall performance of the system and the user experience. The emulation experiments demonstrate that the proposed algorithm can effectively control multipath connections, ensuring uninterrupted communication in heterogeneous vehicular environments.

While emulation has been instrumental in our testing, it's crucial to highlight the need for real-world evaluations. Real networks introduce unpredictable variables like varying delays, packet losses, and bandwidth fluctuations, impacting multi-RAT vehicle equipment. Although our test bed closely mimics real vehicular environments, comprehensive insights into these dynamic factors and their effects on MPTCP and our path manager will require further real-world testing.

The findings presented in this study primarily center on the utilization of two prominent heterogeneous networks, namely LTE and IEEE 802.11p. These networks were chosen due to their strong potential for delivering effective V2N communication services in the future. However, it's vital to acknowledge that the landscape of wireless technologies is vast and continuously evolving. To provide a more comprehensive understanding of vehicular communication and multipath strategies, the inclusion of additional radio access technologies is essential. This expanded scope would enable us to perform a more detailed and accurate comparison across various networks. These additional RATs could encompass emerging technologies or existing ones, such as 5G, Wi-Fi 6, or other dedicated vehicular communication protocols.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vadym Hapanchak reports financial support was provided by Foundation for Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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