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Research Article

Fast Multiattribute Network Selection Technique for Vertical Handover in Heterogeneous Emergency Communication Systems

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The telecommunication infrastructure in emergency scenarios is necessarily composed of heterogeneous radio/mobile portions. Mobile Nodes (MNs) equipped with multiple network interfaces can assure continuous communications when different Radio Access Networks (RANs) that employ different Radio Access Technologies (RATs) are available. In this context, the paper proposes the definition of a Decision Maker (DM), within the protocol stack of the MN, in charge of performing network selections and handover decisions. The DM has been designed to optimize one or more performance metrics and it is based on *Multiattribute Decision Making* (MADM) methods. Among several MADM techniques considered, taken from the literature, the work is then focused on the TOPSIS approach, which allows introducing some improvements aimed at reducing the computational burden needed to select the RAT to be employed. The enhanced method is called Dynamic-TOPSIS (D-TOPSIS). Finally, the numerical results, obtained through a large simulative campaign and aimed at comparing the performance and the running time of the D-TOPSIS, the TOPSIS, and the algorithms found in the literature, are reported and discussed.

1. Introduction

Natural disaster events such as earthquakes, hurricanes, and floods and man-made ones such as terrorist attacks and toxic waste spills are facts of these last few years. Not only is the number of the disaster occurrences increasing very seriously, but also the number of killed and severely injured people is dramatically high. Environmental impacts on human health and quality of life are very high and there is an increase in disaster risk. Disaster management cycle is very complex and goes from prevention and mitigation to alert, response, and recovery. A quick deployment of a telecommunication infrastructure is essential in this case. For this motivation the role of the Information and Communication Technology (ICT) is topical for the deployment of a telecommunication infrastructure for risk and emergency management, for the technology integration, and for the implementation of specific technological developments possibly offering quick reconfigurability, interoperability, and scalability. The reference telecommunication infrastructure for the aforementioned scenario is necessarily composed of heterogeneous radio/mobile portions. On the other hand, nowadays the increased diffusion of mobile terminals, often called Mobile Nodes (MNs), has multiple network interfaces, such as Wi-Fi, WiMAX, and UMTS, and can assure consistent improvements in the mobile communication field. As a matter of fact, such a type of MN can operate inside the previously mentioned heterogeneous scenario where different Radio Access Networks (RANs) that employ different Radio Access Technologies (RATs) are available. Consequently, users can access a new set of services independently of their positions. It is worth noticing that different RATs have different characteristics and, of course, different strong points and weakness. These can also depend on the emergency conditions in which the MN is operating.

In the introduced context, a useful challenge is to assure an ubiquitous connection to MNs, defining an *anytime* and *anywhere* network, using the most appropriate RAN available that best fits users' requirements. Following the *Always Best Connected* (ABC) criterion (see [1] and references therein) an MN is constantly connected to the core network using a specific RAN that matches some predefined requirements. Moreover, this paradigm enables the MNs to be aware of the heterogeneous and dynamic context where it is, represented by the available RANs status, and to adapt its behaviour consequently during the communication.

In this framework two processes cover a crucial role: *(i)* the *handover* that is the redirection of the active connections from a RAN to another one and *(ii)* the *network selection* that is a decisional process that selects the RAN that the MN has to use, among the available ones. According to the IEEE 802.21 standard, defined in [2] and described in Section 3, whose goal is to facilitate the interoperability of different Radio Access Technologies, these two functions are tightly linked: network selection is a fundamental part of the whole handover process as is detailed in Section 2.1. Both these functions are necessary to enable the MN to use the best RAN in terms of communications performance but they have stringent time requirements in their execution as stated in [3]. So an algorithm for the network selection must reduce the operations number necessary to perform the selection and, as a consequence, the needed time. On the contrary, an increase in the employed algorithm computational complexity may have a negative effect on the considered handover process that must wait for the selection procedure. This waste of time can provoke a performance detriment of the QoS perceived by the user and, in the worst case, can determine a service interruption.

During the network selection process, each RAN can be evaluated considering several characteristics often called attributes. Considering the mobile scenario, it is possible to say that the values of some attributes change dynamically while other attributes keep their values constant independently of the MN position inside the considered coverage area. As a consequence, as presented in [4], the attributes may be divided into 3 groups: *static*, *dynamic*, and *semidynamic*. We propose a novel formulation of the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) algorithm, taken from the Multiattribute Decision Making (MADM) theory [5], called Dynamic-TOPSIS (D-TOPSIS), which has the goal of limiting the operations number necessary to select the network, generating the same selection of the TOPSIS standard formulation.

The main contributions of this paper are listed below:

(i) A description of the mobile communications framework, regarding in particular handover process, network selection, and a possible applicative scenario, is included in Section 2.1.

(ii) A brief overview of the Standard IEEE 802.21, which plays a fundamental role in the management of heterogeneous RANs, is presented in Section 3.

(iii) A classification of the network selection algorithms, found in the literature, is reported in Section 4.

(iv) The formulation of both TOPSIS and D-TOPSIS algorithms, aimed at highlighting the difference among them and the reduction in the computational complexity, constitutes Section 5.

(v) The definition of a *Decision Maker*, within the protocol stack of the MN and in charge of performing network selection and handover decision, is proposed in Section 5.3. In this section the reference scenario used as a common test-bed to compare the considered algorithms is also described.

(vi) The numerical results, obtained through a large simulative campaign and aimed at comparing the different performance and the different execution time of the D-TOPSIS, the TOPSIS, and the algorithm found in the literature, are discussed in Section 6.

2. The Vertical Handover

The handover process can be divided into two categories: (i) *horizontal handover* and (ii) *vertical handover*. While the former occurs when the user switches between the same technologies RAT (for example, passing from a Wi-Fi network to another), the latter happens when the user moves from a technology to another. A possible example of vertical handover is the transparent switch from WiMAX to LTE.

Three main contributions are included in this section: a possible applicative scenario, the description of the handover process, and finally the presentation of the network selection concept.

2.1. A Heterogeneous Communication Network Example. In Figure 1 a possible heterogeneous network composition is represented. Suppose that a member of a rescue team operating during an emergency event is connected to a remote host, for example, an Emergency Operation headquarter, through an MN equipped with several heterogeneous network interfaces. The MN is moving by following the trajectory represented by black, dotted line with the arrow. Until he is in his house, the MN uses the domestic Wi-Fi connection. When he leaves the house, moving outside for the rescue operations, the Wi-Fi coverage area, the MN perceived that the quality of the Wi-Fi channel is degrading. Consequently, the MN decides to execute a handover and redirect the traffic to another RAN to prevent service interruption. In particular a UMTS and a WiMAX networks are available: in this case the network selection algorithm, implemented in the MN, selects the WiMAX network. Obviously, all these functions are executed automatically by the MN that maintains active the connection with the remote host, and the user is unaware of the handover execution. While the user is walking along his path, the MN periodically controls the state of the system, represented by the value of the attributes used to evaluate each RAN, and executes the network selection algorithm. Until the selected network is in use (represented by the black circles in Figure 1), the MN does not perform any handover. On the contrary, when the selected network has not been employed, the MN does the handover, for example, switching from WiMAX to UMTS as reported in Figure 1. Finally, when the user arrives at his office, the MN detects a Wi-Fi network that, according to the network selection algorithm, is

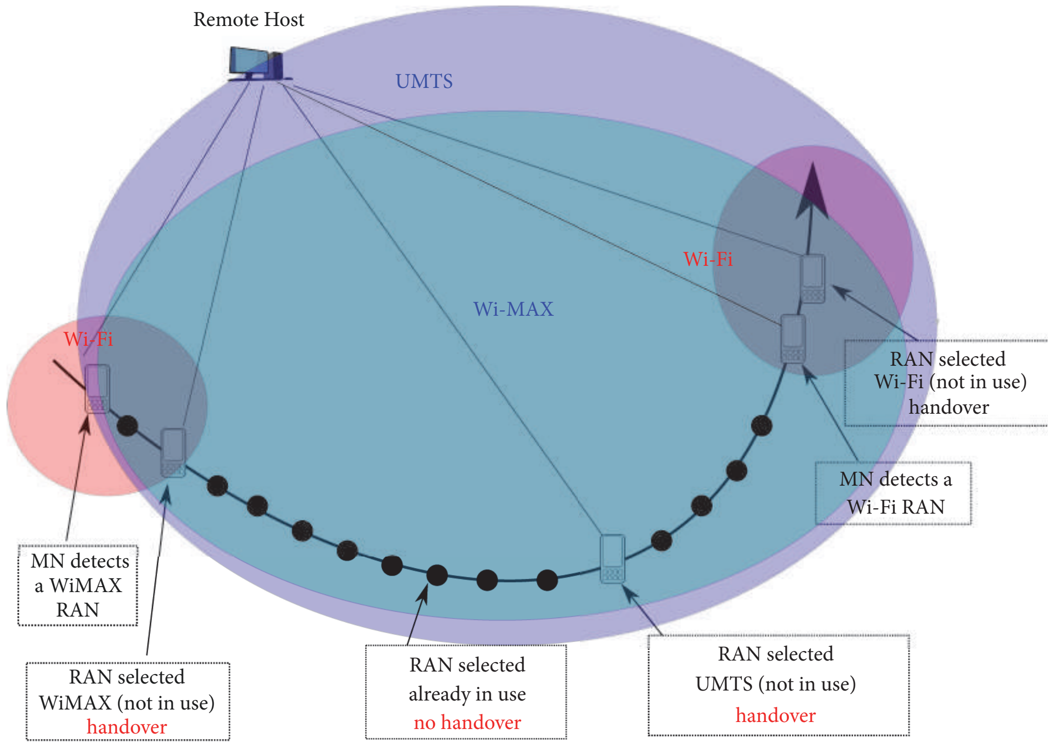

FIGURE 1: A possible applicative scenario of mobile communications.

better than the WiMAX in use, and it executes the handover. Similar behaviour characterizes also different scenarios such as the Intelligent Transportation Systems applications, which constantly monitor a vehicle moving along its path or inside a port area or in a construction site. Obviously, each network selection algorithm can give different decisions and it is characterized by different performance depending on the speed of the MN, as reported in Section 6.

The employment in this reference network of Wi-Fi, WiMAX, and UMTS technologies represents an example. The use of more modern and efficient mobile networks, such as LTE/4G and 5G, is object of ongoing performance investigation but it is worth noting that the network selection techniques presented and evaluated in this paper work independently of the available RATs.

2.2. The Handover Process. The term handover identifies the overall process that enables a Mobile Node (MN) to change the access network that it is using and to switch to another one among the available RANs. As report in [6] and briefly reprised at the beginning of this section, two different types of handover are defined according to the network technologies: *(i) horizontal handover*, when the RAT selected is the same one currently used by the MN, or *(ii) vertical handover*, when the target RAT is different from the one used by the MN. A typical example of horizontal handover happens when an MN moves outside a cell of a RAT such as the UMTS or the Wi-Fi. To maintain the communication active, the MN changes the Point of Access (PoA) and connects itself to the radio base station of the cell in which it enters. On the other hand, a vertical handover occurs, for example, when an MN exits the coverage area of a Wi-Fi network and switches to the UMTS technology in order to maintain the connection active.

Another classification of the handover process is proposed: *(i) soft handover* or *make-before-break* that represents the case in which an MN is connected to both PoAs during the switching phase and *(ii) hard handover* or *break-before-make* in which an MN can have contact with only one PoA at a time. A further type of handover, called *seamless*, meets the following requirements: *(i)* it is a soft handover, which means that the communication is maintained active during the network switching; *(ii)* the whole handover process has a limited duration; *(iii)* the handover must not determine any Quality of Service (QoS) degradation. Such a type of handover execution is also called transparent because the user is unaware of the RAN change performed by the mobile terminal.

2.3. The Network Selection Problem. The network selection is a task that is in charge of selecting the most appropriate RAN that an MN must use among the available ones. This procedure is tightly linked with the handover process. In fact, the decision taken by the network selection algorithm may trigger the handover execution when the selected network is not already used by the MN. In other words, the network selection is in charge of determining when the MN has to switch from a RAN to another: an MN may execute a handover not only when it moves away from the cell in use but also when a different available RAN is better from the network selection algorithm view point. In order to support the cooperation among different RATs the network is in charge of maintaining an efficient signalling architecture, efficiently managing the resource utilization, and assuring the security and the integration of the communications. On the other, hand the network selection decision can be taken by the core network (i.e., *Centralized Network Selection*) or by the MN (i.e., *Distributed Network Selection*).

In a homogeneous environment, where there is only one type of RAT, the network selection is typically based on physical layer parameters, such as the Received Signal Strength Indicator (RSSI) or the Signal to Noise Ratio (SNR). In practice a Decision Maker (DM) entity evaluates only the quality of the channel and selects the PoA that assures the best channel conditions. These algorithms, which belong to the *single-attribute* group, are quite simple but they may provide a suboptimal selection from the user's viewpoint. In fact, different users may have different preferences and requirements not only referring to the quality of the communication but also, for example, to the power consumption minimization or to the Monetary Cost reduction. Moreover the various RATs, which characterize a heterogeneous scenario, may differ from each other not only in the channel quality but also in the aforementioned metrics. Consequently, another family of algorithms applied to solve the network selection problem is called *multiattribute* group; they are able to take advantages from the availability of different RATs and can select the best one evaluating more than one metric (or attribute) simultaneously [7]. More details about these groups of algorithms are reported in Section 4.

3. A Quick Overview of the IEEE 802.21 Standard

The IEEE 802.21 standard for the Media Independent Handover (MIH) defines extensible IEEE 802 media access independent mechanisms that enable the optimization of handover between heterogeneous IEEE 802 networks and facilitates handover between IEEE 802 networks and cellular networks, as reported in [2]. Its purpose is to assure to an MN the service continuity during the handover execution as well as after the handover. Moreover the standard is also aimed at assuring that the change of access network is not noticeable to the end user. As a logical consequence, it is mandatory not to decide the QoS degradation during the handover procedure limiting both packet losses and delay. It is worth noticing that two different aspects of QoS are considered by the standard: *(i)* the QoS experienced by an application during a handover and *(ii)* the QoS considered as part of a handover decision. Therefore, it is clear that this standard supports the handover execution not only for assuring the service continuity but also for selecting the RAN that best fits the MN requirements, in terms of QoS.

In more detail, it represents a common interface between the upper layers and the lower layers inside the protocol stack: even if an MN can have multiple network interfaces inside the lower layers, the MIH Layer is unique (for this reason, it is called technological dependent layer). A further logical element, defined by the standard, is a set of functions, called Media Independent Handover Function (MIHF), whose aim is to support the handover process. Indeed, this set of functions is in charge of activating the communication between the MIH Layer and the upper and the lower layers and providing the necessary information to support the handover procedures.

The standard defines three types of MIHF:

(i) *Media Independent Event Service* (MIES) comprehends the functions that provide the higher layers with some information sent by the technological dependent layer.

(ii) *Media Independent Command Service* (MICS) includes all the functions that send instructions from the higher layer to the technological dependent layers.

(iii) *Media Independent Information Service* (MIIS) defines a set of functions that provides the mechanism for retrieving information and assisting the handover decision.

More details about the aforementioned MIHF can be found in [2, 8].

According to [2] the communication model proposed by the IEEE 802.21 standard is represented in Figure 2, directly taken from [2]. An important virtual entity is introduced: the Point of Service (PoS). The MIHF of each network node becomes a PoS for an MN if it communicates directly with the same layer inside the MN protocol stack. In other words, a PoS is a network element that is in charge of providing an MN with the necessary information to perform the handover. In Figure 2 it is possible to see that there are two network portions, the *client side* where the MN is located and the *network side* that includes the PoS and the non-PoS elements, which are the network nodes that communicate with the MN indirectly. It is possible to view that the PoSs are logically located inside the Points of Access (PoAs) currently in use, inside the target PoAs, and inside other network nodes that are not PoAs but can be, for example, a database that contains some information of the neighbour RANs. All these nodes communicate together directly or indirectly, inside a client-server communication model, where the MN is the client that requires some information to execute the handover, and the core network is the server that provides the necessary information. As previously said, the IEEE 802.21 proposes a new layer, the MIH Layer, inside the protocol stack of each node. The communication with the other layers is based on the concept of Service Access Point (SAP) as reported in Figure 3. Three different types of SAP are defined by the standard:

(i) *MIH-SAP*: This SAP enables the communication between the upper layers, called also MIH Users, and the MIH Layer. Only a single MIH-SAP is implemented in each protocol stack and it is also called Technological Independent SAP

(ii) *MIH-LINK-SAP*: This type of SAPs assures the communication that the MN implements between the MIH Layer and each Link Layer. This communication takes place through media-specific instances of MIH-LINK-SAP for each different Link Layer. As a consequence, this SAP is also called Technological Dependent SAP.

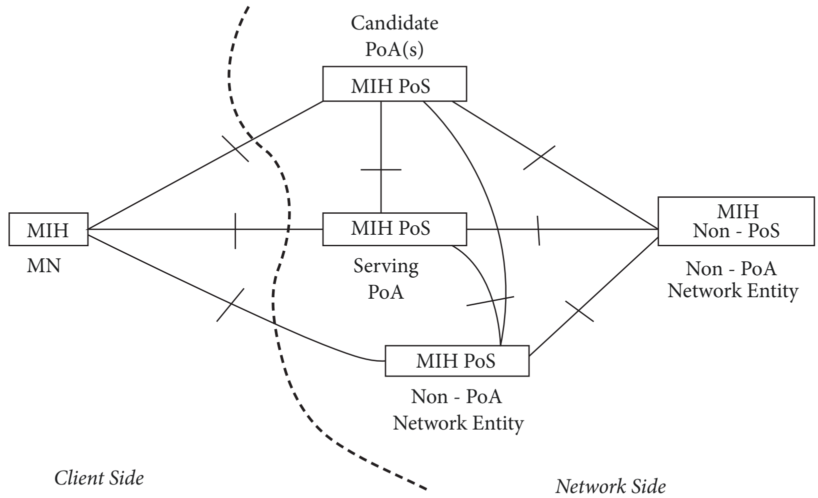

Figure 2: MIHF communication model proposed by [2].

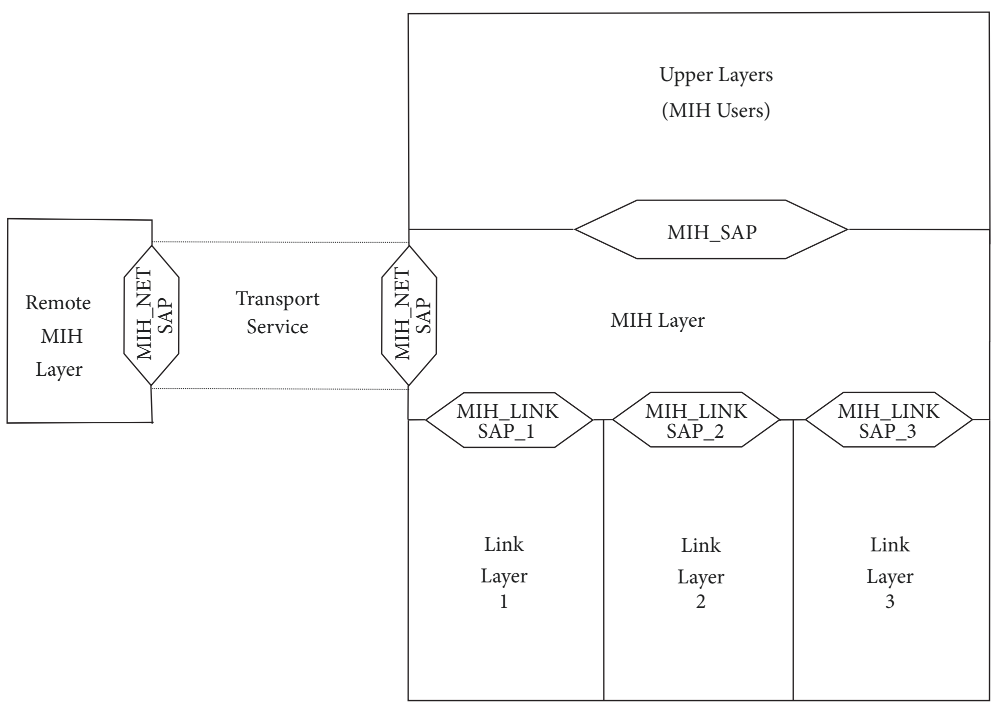

Figure 3: MIH Layer and SAPs reference model proposed by the IEEE 802.21 standard.

(iii) *MIH-NET-SAP*: This is the SAP that provides transport services supporting the exchange of MIH information and messages with the remote MIHF.

IEEE 802.21 also proposes the standardization of the handover procedure. The operations are divided into 3 phases, as reported in Figure 4:

(i) *Handover Initiation*: This is phase one of the handover process. The initiation comprehends message exchange with the Point of Access along with some preliminary measurements on the available RANs.

(ii) *Handover Preparation*: This is phase two. Here the Mobile Node chooses the network that will be employed after the handover and the negotiation for resource reservation that aims to grant that QoS requirements begin.

(iii) *Handover Execution*: In this final phase the traffic flows sent by the MN move to the selected RAN leaving the network access in use.

Some operations are included in the scope of the standard while others are only cited, but their implementation is not specified by the standard and, consequently, many different solutions can be applied. These operations are identified by an asterisk in Figure 4. Among these, a very important function is the handover decision, which refers to decisional process

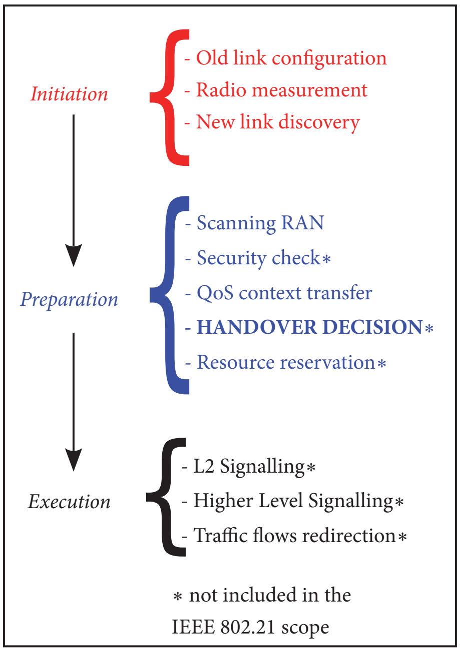

Figure 4: Three procedures that constitute the handover execution according to the IEEE 802.21 standard.

in charge of determining when the MN has to perform the handover and which is the target network: in practice, it identifies the network selection engine. The decision of the appropriate algorithm is something that has not been determined yet. Indeed, the algorithm that can be applied in this context has to assure good performance but at the same time it is characterized by stringent time constraints. It is worth noticing that a technique that selects the network may have a bad effect on the ongoing process, which remains in waiting status until the selection is performed.

4. The Network Selection Algorithms

The state-of-the-art comprehends two main branches of network selection algorithms: Single Performance Metric Optimization (SPMO) and MADM or, in the following, Multi-Performance Metrics Optimization (MPMO). SPMO algorithms choose the RAN by taking into account just one metric. MPMO algorithms take their decisions based on multiple metrics, at the same time, to choose the RAN to use. The object taking decisions about the RAN to be chosen is named Decision Maker (DM).

4.1. SPMO Algorithms. Each available network represents an alternative way that is validated trough one performance metric, named attribute. The DM is used to choose the best possibility, among the available ones, in accord with the maximization (or the minimization) of the metric, used as a utility (Cost) function. Let m be the possible RANs; we call the *alternatives* with an array $\mathbf{A} = (A_1, \ldots, A_j, \ldots, A_m)$. The j-th alternative is defined as $A_j = (x_j)$, where x_j is the considered metric (or attribute). The best option is denoted as A^{opt}_{SPMO} and is achieved by using the following equation.

$$A^{opt}_{SPMO} = \left\{ A_j : \arg\max_j \left(x_j \right) \right\} \quad (1)$$

Equation (1) is true if the employed metric needs to be maximized. If a metric needs to be minimized the $\arg\min_j(\cdot)$ operator is applied in (1).

Within the set of the possible metrics employed by the SPMO algorithms, a commonly taken decision is the RSSI, employed in [9, 10], which represents the received power measured in [dB] and is the parameter taken as a reference during the horizontal handover. Similarly, the same criterion could be employed for vertical handover. The method used for selection is very simple: the MN senses the RSSI from the PoAs among the RANs and determines the one with the highest value. Another weak point of this technique is the "Ping Pong effect" where there is repetitive and not useful handover, which occurs also if the RSSI value of an alternative RAN is slightly higher than the one related to the RAN currently employed [9]. This represents a drawback that affects negatively the QoS of MNs. The SPMO family techniques require a low computational burden, a low running time, and a limited power consumption. Differently, they can yield scarce performance if the goal would be the optimization of multiple metrics.

Target collision probability is another possible metric that has been used in network selection algorithms. Reference [11] uses it to maximize secondary users' throughput by employing a Markov queuing model. The authors evaluate their proposal by comparing it with other state-of-the-art strategies (Random and Greedy algorithms) showing its superior performance.

4.2. MPMO Algorithms. More than one metric is considered at the same time [7, 12]. They can be divided into

(1) QoS-based metrics, for example, packet loss, RSSI, bandwidth throughput, and transmission rate;

(2) power saving-based metrics, for example, MN battery lifetime and power consumption;

(3) other parameters-based metrics, for example, user preferences, Monetary Cost, and RAN security level.

DM task is to choose the best option in accord with a certain criterion. Most of the time MPMO techniques are characterized by higher computational burden than the SPMO ones. This is due to the fact that they can optimize simultaneously more metrics. MPMO approaches may select a suboptimal RAN by taking into account just one parameter and by finding the optimal solution considering all the different metrics at the same time.

Recalling the concept that the alternatives array m is defined with $\mathbf{A} = (A_1, \ldots, A_j, \ldots, A_m)$, for the MPMO algorithms the j-th alternative is denoted as $A_j = (x_{1j}, \ldots, x_{ij}, \ldots, x_{n,j})$, where x_{ij} represents the i-th attribute of the j-th alternative. The quantity n stands for the attributes number employed to compute each alternative.

4.2.1. Simple Additive Weight (SAW). The solutions that belong to this category (see [13] and references therein) leverage on a quantity, called *cost*. In particular they assign to each *alternative* a *cost* value calculated trough the summation of the normalized value of each considered attribute. To further strengthen the importance of each attribute, weights may also be employed. Finally, the chosen network is the one that presents the smallest *cost* value. The mathematical detail is provided in (2).

$$V_{SAW}\left(A_j\right) = \sum_{i=1}^{n} w_i \cdot V_{SAW}^{A_j}\left(x_{ij}\right)$$
$$A_{MPMO-SAW}^{opt} = \left\{A_j : \arg\min_j \left(V\left(A_j\right)\right)\right\} \quad j = 1, \ldots, m \tag{2}$$

(i) $A_{MPMO-SAW}^{opt}$ is the provided alternative that the algorithm SAW has chosen;

(ii) $V_{SAW}(A_j)$ is the quantity linked to the alternative j, denoted by A_j (i.e., the cost);

(iii) $V_{SAW}^{A_j}(x_{ij})$ is the normalized cost of the j-th alternative computed by considering the i-th attribute x_{ij};

(iv) w_i is the weight associated with the i-th attribute.

This idea is already present in several papers within the same field, for example, in [13–17]. Within such a plethora of works, valuable realization of this approach can be found in [14]. It minimizes the generic cost of the employment of j-th network, based on the power consumption, Monetary Cost, and the bandwidth made available. The paper in [13] publishes a network selection strategy which defines the cost of the j-th network by using the weighted sum of the available bandwidth (normalized) and the Received Signal Strength Indicator (RSSI).

4.2.2. Weighted Product Method (WPM). It provides each alternative with a cost computed through the product of the attribute values [18]. It permits avoiding the normalization required by the SAW method. The detailed mathematical expression is written in (3).

$$V_{WPM}\left(A_j\right) = \prod_{i=1}^{n} V_{WPM}^{A_j}\left(x_{ij}\right)^{w_i}$$
$$A_{MPMO-WPM}^{opt} = \left\{A_j : \arg\min_j \left(V_{WPM}\left(A_j\right)\right)\right\} \quad j = 1, \ldots, m \tag{3}$$

(i) $A_{MPMO-WPM}^{opt}$ is the choice made by the WPM technique;

(ii) $V_{WPM}(A_j)$ is the quantity linked to the j-th alternative A_j;

(iii) $V_{WPM}^{A_j}(x_{ij})$ is the value of the i-th attribute of the j-th alternative x_{ij};

(iv) w_i is the weight associated with the i-th attribute.

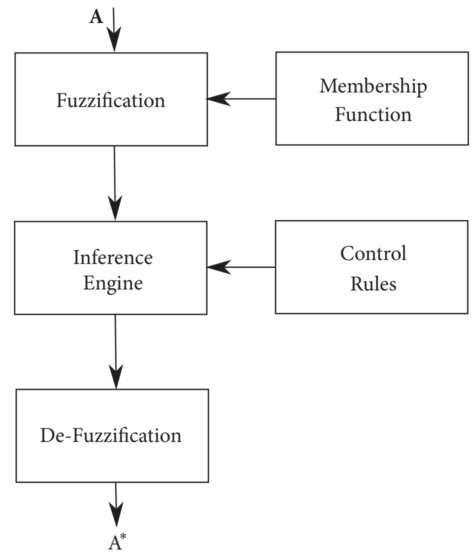

Figure 5: Block diagram of Fuzzy Logic Algorithm.

Apart from [18], WPM is not employed in many practical scenarios. For example, it is also used in [19] as a reference to show an analysis based on multiattribute error so as to obtain more robust differentiation between alternatives in a specific scenario.

Under certain constraints (see [20]), the minimization/maximization of the sum of logarithms is the same mathematical operation. Simplifying, $\max \prod_{j\in J} f_j(x)$ corresponds to $\max \sum_{j\in J} \ln f_j(x)$, where $f_j(x)$ are the utility functions. Reference [20] also stresses a similar concept.

To sum up, taking into account all the aforementioned reasons, the WPM has been taken as a reference in this paper.

4.2.3. Fuzzy Logic. A widely employed method for *network selection* consists in exploiting the Fuzzy Logic [21, 22]. It comes directly from the Fuzzy Set Theory. Specifically, the considered variables can have a "truth value" that can assume any value between 0 and 1. The scheme of a generic Fuzzy Logic technique is sketched in Figure 5. It takes as input all the alternatives **A**, evaluated according to the employed metrics. The algorithm begins with the *fuzzification* step that links RAN attributes to fuzzy sets by relying on each set *membership function*. Figure 6 provides an example of membership functions for three fuzzy sets. They are LOW, MEDIUM, and HIGH for the i-th attribute referred to as the j-th alternative, x_{ij}.

The next operation required by the Fuzzy Logic Algorithm is the use of the *inference engine*. Namely, in accord with the control rules, it decides a strategy to evaluate each RAN set of the attributes.

Finally, the ultimate step requires the *defuzzification*. The output provided by the *inference engine* will be employed to decide which is the best alternative.

4.2.4. Mixed Approach. The Mixed Approach merges together the Fuzzy Logic and a cost function for the *network selection*. This idea is reported in [23] in which 4 quantities

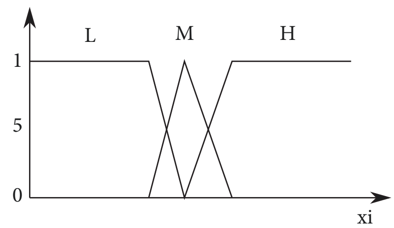

Figure 6: Membership function of the Fuzzy Logic Sets.

have been taken into account as input for the DM: Monetary Cost, available bandwidth, Received Signal Strength (*RSS*), and user preferences. Mixed Approach is then employed in order to decide the WWANs and the WLANs by making these steps:

(1) for each RAN, input quantities are normalization;

(2) for each parameter, the normalized values are to one fuzzy set: LOW, MEDIUM, HIGH. This is called *fuzzification*.

(3) Performance Evaluation Value (PEV) is finally computed and the best RAN is selected based on the highest PEV.

In the performance evaluation section, we refer to the Mixed Approach as Fuzzy-Simple Additive Weight (F-SAW). *Network Selection* methods that provide a similar approach can be found in [21, 24, 25].

5. The Proposed Network Selection Algorithm

The technique discussed in this paper, called D-TOPSIS, is a variation of the TOPSIS algorithm, already employed in the network selection algorithm [26–28]. This new formulation provides similar results in the decision processes and, at the same time, it lowers the operation number fundamental to obtain the solution.

5.1. The TOPSIS Algorithm. TOPSIS takes into account the *alternatives* defined by the quantities assumed by the considered *attributes*. The *i-th alternative* is denoted by an array $A_i = (x^*_{i1}, \dots, x^*_{ij} \cdots, x^*_{in})$ for $i \in [1, m]$ in which n and m are the number of *attributes* and the number of *alternatives*, respectively. As you can find in [5], the TOPSIS technique may be modeled by exploiting the geometry with m points in a n-dimensional space. Thus, we can use the Euclidean Norm to calculate the distance between each alternative and one or more reference points.

TOPSIS requires several steps that are summarized as follows:

(i) Calculation of the weighted normalized attribute values:

$$v_{ij} = w_j \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (4)$$

every $i = 1, \dots, m$ *alternative*, for each $j = 1, \dots, n$ *attribute*. w_j represents the weigh linked to the $j - th$ *attribute*, and the condition $\sum_{j=1}^{n} w_j = 1$ must hold.

(ii) Identification of the Positive Ideal Solution A^* (PIS) and the Negative Ideal Solution A^- (NIA), as detailed by

$$\begin{aligned} A^* &= \left(v_1^*, \dots, v_j^*, \dots, v_n^*\right) \\ &= \left(\left(\max_i v_{ij} \mid j \in J_1\right), \left(\min_i v_{ij} \mid j \in J_2\right) \mid i \right. \\ &= \left. 1, \dots, m\right) \\ A^- &= \left(v_1^-, \dots, v_j^-, \dots, v_n^-\right) \\ &= \left(\left(\min_i v_{ij} \mid j \in J_1\right), \left(\max_i v_{ij} \mid j \in J_2\right) \mid i \right. \\ &= \left. 1, \dots, m\right) \end{aligned} \quad (5)$$

in which J_1 is a quantity that stands for the set of positive attributes (which have to be maximized) and J_2 is a quantity the represents the set of negative attributes (which have to be minimized).

(iii) Calculation of the Separation Measures (SMs): to compute the distance between *alternatives* and the optimal, utopia point the Euclidean Norm is applied (see (6)).

$$\begin{aligned} SM_i^* &= \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^*\right)^2}; \quad \textit{for } i = 1, \dots, m \\ SM_i^- &= \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}; \quad \textit{for } i = 1, \dots, m \end{aligned} \quad (6)$$

(iv) Calculation of the Similarity Index (SI): for the $i - th$ *alternative*, A_i, the SI is calculated as $SI_i = SM_i^- / (SM_i^- + SM_i^*)$. The values range is within $[0 - 1]$. Specifically, the quantity $SI_i = 0$ occurs if the *alternative* coincides with the NIS (i.e., $A_i = A^-$). On the other hand, the case $SI_i = 1$ refers to the situation where the *alternative* coincides with the PIS (i.e., $A_i = A^*$). It is hence possible to state that the best *alternative* is represented by the one which presents the higher associated similarity index.

5.2. New Formulation of the TOPSIS Algorithm. The novel variant of the TOPSIS technique is named Dynamic-TOPSIS (D-TOPSIS). This name has the purpose to stress the concept that the decision at the generic step t also considers the decision previously taken. In more detail, at the step t employed to compute the $i - th$ *alternative*, the *attributes* are split into two groups: the *static attributes* $\mathbf{s}_i(t)$ and the *dynamic attributes* $\mathbf{d}_i(t)$. For each *alternative* the attributes keep their numbers constant at each step t when the network selection is performed, when the *alternative* is available. Consequently, for the $i - th$ *alternative* the quantity associated with each static *attribute* at the step t is equal to the value

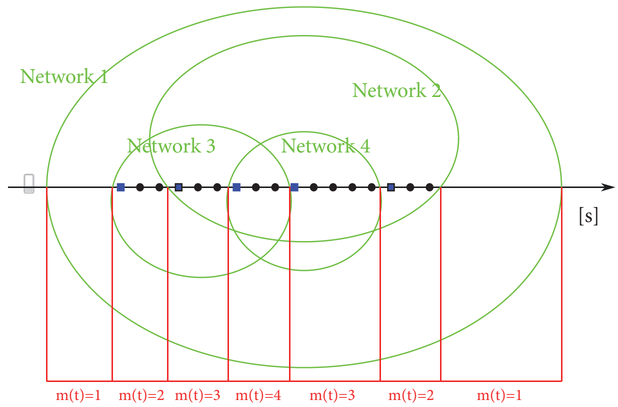

FIGURE 7: Variation of the number of alternatives over time in the network selection problem.

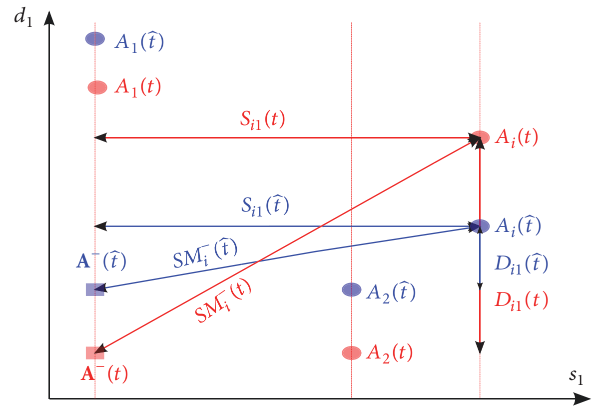

FIGURE 8: Distance of the $i-th$ alternative from the Negative Ideal Solution (NIS).

of the same attribute at the time of the previous TOPSIS execution $\hat{t}$. In practice $s_i(t) = s_i(\hat{t})$.

The next steps, which must be done to compute the selection, depend on the alternatives that are available at the instant t: if the set of available RANs is the same in t and in $\hat{t}$ the nonstatic (i.e., the dynamic) form of the technique is used, while, if this condition does not occur, the static version of the technique is then used. Figure 7 highlights how this condition impacts on the network selection formulation: the position of the MN moving along its path is represented. It enters and exits the coverage area of different RANs and periodically executes the network selection. The number of available *alternatives* (i.e., the number of available networks), $m(t)$, in each instant in which the selection is performed, is also reported. In particular, the blue squares represent the execution of the standard TOPSIS algorithm, while the black circles identify the execution of the D-TOPSIS.

As a consequence of the distinction among static and dynamic *attributes* the *i − th alternative* can be defined as in

$$\mathbf{A}_i(t) = (\mathbf{s}_i(\hat{t}), \mathbf{d}_i(t)) = \left(s_{i,1}(\hat{t}), \ldots, s_{i,j}(\hat{t}), \ldots, s_{i,n_s}(\hat{t}), d_{i,j}(t), \ldots, d_{i,j}(t), \ldots, d_{i,n_d}(t)\right) \quad (7)$$

where n_s and n_d are the number of static and dynamic *attributes*, respectively. The matrix $\mathbf{A}(t)$, reported in (8), describes all the available *alternatives* at the step t.

$$\mathbf{A}(t) = \begin{pmatrix} \mathbf{A}_1(t) \\ \vdots \\ \mathbf{A}_i(t) \\ \vdots \\ \mathbf{A}_{m(t)}(t) \end{pmatrix} = \begin{pmatrix} \mathbf{s}_1(\hat{t}), \mathbf{d}_1(t) \\ \vdots \\ \mathbf{s}_i(\hat{t}), \mathbf{d}_i(t) \\ \vdots \\ \mathbf{s}_{m(t)}(\hat{t}), \mathbf{d}_{m(t)}(t) \end{pmatrix} \quad (8)$$

As previously said the TOPSIS algorithm is based on the concept of distance between alternatives represented by points inside a multidimensional space. Applying the Euclidean Norm it is possible to measure the distance between each alternative and two reference points (the PIS and the NIS previously defined). In order to better explain the D-TOPSIS approach, the distance reported above is highlighted in Figure 8. Both the *attributes* are positive which means that they must be maximized. One of them is static (s_1) and the other is dynamic (d_1). In Figure 8 only the distance from the NIS is represented. Even though not plotted, analogous deductions can be obtained for the PIS case.

Considering Figure 8 the NIS $A^-(t)$ at the instant t and the NIS $A^-(\hat{t})$ at the instant $\hat{t}$ are denoted by a red and blue squares, respectively. The distance between the PIS and the *i − th alternative* at the instant t is determined by the two components $S_{i1}(t)$ and $D_{i1}(t)$. In this paper, we name it *Partial Distance*. It have to be computed for each *alternative* for each run of the TOPSIS technique. From Figure 8 we can see that $S_{i1}(t) = S_{i1}(\hat{t})$. Thus, there is no need to compute the value of this parameter since it reduces the operations number necessary to effectuate the RAN selection. In an intuitive way, such reduction is even more notable if the number of static parameters or the number of *alternatives* increases.

As a consequence, the algorithm proposed is based on the following steps:

(i) Calculation of the weighted normalized values of the static and dynamic *attributes*.

$$N(s_{ij}(t)) = \begin{cases} N(s_{ij}(\hat{t})); & \text{if RANs do not change} \\ w_j \dfrac{s_{ij}(t)}{\sqrt{\sum_{i=1}^{m(t)} s_{ij}(t)^2}}; & \text{otherwise} \end{cases}$$
$$i = 1, \ldots, m; \quad j = 1, \ldots, n_s; \quad (9)$$
$$N(d_{ij}(t)) = w_j \frac{d_{ij}(t)}{\sqrt{\sum_{i=1}^{m(t)} d_{ij}(t)^2}}$$
$$i = 1, \ldots, m; \quad j = 1, \ldots, n_d;$$

(ii) Identification of the Positive $A^*(t)$ and the Negative $A^-(t)$ Ideal Solution

$$A^*(t) = \begin{cases} (\mathbf{N}(\mathbf{s}^*(\hat{t})), \mathbf{N}(\mathbf{d}^*(t))); & \text{if RANs do not change} \\ (\mathbf{N}(\mathbf{s}^*(t)), \mathbf{N}(\mathbf{d}^*(t))); & \text{otherwise;} \end{cases} \quad (10)$$

where

$$\begin{aligned} \mathbf{s}^*(t) &= \left(N(s_1^*(t)), \ldots, N(s_{n_s}^*(t))\right) \\ &= \left(\left(\max_i N(s_{ij}(t)) \mid j \in J_{s_1}\right), \left(\min_i N(s_{ij}(t)) \mid j \in J_{s_2}\right)\right) \\ \mathbf{d}^*(t) &= \left(N(d_1^*(t)), \ldots, N(d_{n_d}^*(t))\right) \\ &= \left(\left(\max_i N(d_{ij}(t)) \mid j \in J_{d_1}\right), \left(\min_i N(d_{ij}(t)) \mid j \in J_{d_2}\right)\right). \end{aligned} \quad (11)$$

$$A^-(t) = \begin{cases} (\mathbf{N}(\mathbf{s}^-(\hat{t})), \mathbf{N}(\mathbf{d}^-(t))); & \text{if RANs do not change} \\ (\mathbf{N}(\mathbf{s}^-(t)), \mathbf{N}(\mathbf{d}^-(t))); & \text{otherwise} \end{cases} \quad (12)$$

where

$$\begin{aligned} \mathbf{N}(\mathbf{s}^-(t)) &= \left(N(s_1^-(t)), \ldots, N(s_{n_s}^-(t))\right) \\ &= \left(\left(\min_i N(s_{ij}(t)) \mid j \in J_{s_1}\right), \left(\max_i N(s_{ij}(t)) \mid j \in J_{s_2}\right)\right) \\ \mathbf{N}(\mathbf{d}^-(t)) &= \left(N(d_1^-(t)), \ldots, N(d_{n_d}^-(t))\right) \\ &= \left(\left(\min_i N(d_{ij}(t)) \mid j \in J_{d_1}\right), \left(\max_i N(d_{ij}(t)) \mid j \in J_{d_2}\right)\right). \end{aligned} \quad (13)$$

In (11) and (13) J_{s_1} and J_{d_1} represent the sets of positive static and dynamic *attributes*, respectively, that have to be maximized. Similarly, J_{s_2} and J_{d_2} represent the sets of negative static and dynamic *attributes* that need to be minimized, respectively.

(iii) Calculation of the *Partial Distances* for all the attributes between each *alternative* and the Ideal Solutions as in (14) and (15).

$$\begin{aligned} N(S_{ij}^*(t)) &= \begin{cases} S_{ij}^-(\hat{t}); & \text{if RANs do not change} \\ \left|N(s_{ij}(t)) - N(s_j^*(t))\right|; & \text{otherwise} \end{cases} \\ & i = 1, \ldots, m; \; j = 1, \ldots, n_s; \\ D_{ij}^*(t) &= \left|N(d_{ij}(t)) - N(d_j^*(t))\right| \\ & i = 1, \ldots, m; \; j = 1, \ldots, n_d; \end{aligned} \quad (14)$$

$$\begin{aligned} S_{ij}^-(t) &= \begin{cases} S_{ij}^-(\hat{t}); & \text{if RANs do not change} \\ \left|N(s_{ij}(t)) - N(s_j^-(t))\right|; & \text{otherwise} \end{cases} \\ & i = 1, \ldots, m; \; j = 1, \ldots, n_s; \\ D_{ij}^-(t) &= \left|N(d_{ij}(t)) - N(d_j^-(t))\right| \\ & i = 1, \ldots, m; \; j = 1, \ldots, n_d; \end{aligned} \quad (15)$$

(iv) Calculation of the Separation Measures (SMs) as reported in (16).

$$\begin{aligned} SM_i^*(t) &= \sqrt{\sum_{j=1}^{n_s} \left(S_{ij}^*(t)\right)^2 + \sum_{j=1}^{n_d} \left(D_{ij}^*(t)\right)^2} \\ SM_i^-(t) &= \sqrt{\sum_{j=1}^{n_s} \left(S_{ij}^-(t)\right)^2 + \sum_{j=1}^{n_d} \left(D_{ij}^-(t)\right)^2} \\ & i = 1, \cdots, m; \end{aligned} \quad (16)$$

(v) Calculation of the Similarity Index (SI) as $SI_i(t) = SM_i^-(t)/(SM_i^-(t) + SM_i^*(t))$. The highest Similarity Index identifies the best alternative for the D-TOPSIS algorithm too.

Employing the D-TOPSIS algorithm for each *alternative*, it is not mandatory to compute both values of the *Partial Distances* for the static *attributes*. Indeed, these values are memorized during the last run of the standard TOPSIS and therefore loaded during the execution of the D-TOPSIS. As a consequence, the sole *Partial Distances* referred to as the dynamic attributes have to be determined so as to compute the Separation Measures and the Similarity Index, during the execution of each network selection process independently of the set of available alternatives.

5.3. The Network Selection as IEEE 802.21 Component. In order to compare the performance of the D-TOPSIS with the other network selection algorithms described in Section 4, the authors propose a definition of a new component, called *Decision Maker* (DM), modeled as a virtual entity, which is in charge of performing the selection of the RAN implementing the considered algorithms. The structure of the DM is represented in Figure 9, where it is possible to see that it is integrated into the MIHF Layer of the MN. As a matter of fact this virtual entity is deputy to take the handover decision functions, which is included in but not defined by the IEEE 802.21 standard, as reported in Section 3. In other words, the DM senses the heterogeneous environment in which the MN is moving; it acquires the characteristics of each RAN and,

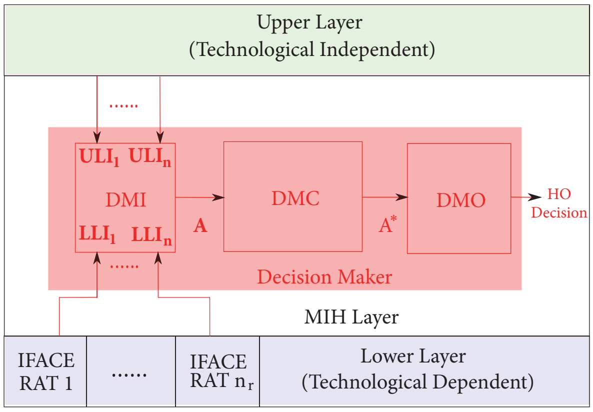

Figure 9: Structure of the proposed Decision Maker set inside the MIH Layer.

according to the implemented algorithm, selects the one that the MN has to use.

Observing Figure 9, it is possible to see that the DM is composed of three parts. The first block, called *Decision Maker Input* (DMI), collects the values of each metric that defines each available RAN through the MIH Layer primitives. This information belongs to two different groups: *(i)* Information from the technological dependent lower layers, which comprises the Lower Layers Information (**LLI**) vector, one for each available RAN. This information is taken directly from the heterogeneous RAT interfaces and includes, for example, the RSSI and the power consumption. It is worth noticing that n_r is the number of different RAT interfaces of the MN, in Figure 9. *(ii)* Information from the technological independent upper layers that comprises the Upper Layer Information (**ULI**) vector, again one for each available RAN. This information is collected inside the matrix **A** created by the DMI.

The algorithm used to evaluate the RANs available is implemented inside the *Decision Maker Core* (DMC) block. It receives as an input the matrix **A** used to describe each RAN (i.e., each alternative) and produces as an output the alternative selected according to the used algorithm, $\mathbf{A}^*$.

Finally the *Decision Maker Output* (DMO) block receives as input the selected RAN from the DMC block and it decides to perform the handover, if the selected network is not already in use; otherwise, it decides to do nothing. If it decides to change RAN, it initiates the handover procedure using the MIH Layer primitives.

6. Performance Analysis

6.1. Simulation Scenario. As already done in other works (see [29]), the simulated scenario adopted to test the network selection algorithms and to compare their performance has been realized by using Network Simulator 2 (*ns-2*). To support the IEEE 802.21 standard, the package provided by the National Institute of Standards and Technology (NIST) is used inside *ns-2* [30]. Moreover the authors implement in the simulated MN the aforementioned DM and the considered network selection algorithms.

Table 1: Range value of the attribute considered.

Parameters	Range Value
Power Consumption	[0, 16 - 0, 22] w
Monetary Cost	[1-10]
Wi-Fi Capacity	[1 - 20] Mbps
Wi-Max Capacity	2 Mbps
UMTS Capacity	0.384 Mbps

The communication is established by a User Datagram Protocol (UDP) traffic flow generated by a remote host to the MN. The DM inside the MN collects the values of each attribute of each RAN, executes the network selection algorithm, and decides to perform or not the handover each 5 [s] (i.e., the decision period) when two or more RANs are available.

As in the reference example described in Section 2.1, three different RATs are considered: UMTS, WiMAX (IEEE 802.16), and Wi-Fi (IEEE 802.11). There is a single UMTS cell that contains the entire environment equal to 2000x2000 [m], a single WiMAX cell, and 8 Wi-Fi cells. Two separate cases are taken into account according to the MN speed: *pedestrian*, 3 [m/s], and *vehicular*, 10 [m/s]. The overall duration of the simulation is set equal to 500 [s]. While the aforementioned parameters are kept constant in each simulation, other parameters are casually determined in each simulation. Such parameters are the position and the dimension of the WiMAX and Wi-Fi networks, the start point and the end point of the MN.

The metrics used as attributes of the RANs are four (n = 4); three of them are static (n_s = 3) and only one is dynamic (n_d = 1).

(i) The *Received Signal Strength Indicator* measure which is related to the distance between the MN and the PoA of each RAN. It represents a positive, thus having to be maximized by the network selection algorithm, and dynamic attribute.

(ii) The *Capacity* that each RAN reserves for the MN. It is a positive and static attribute. Its value, for each RAN, is set in each simulation according to Table 1.

(iii) The *Monetary Cost* that the MN has to pay to use a RAN. It is a negative, thus having to be minimized by the network selection algorithm, and static attribute. Its value, for each RAN, is set in each simulation, according to Table 1.

(iv) The *Power Consumption* of the MN to maintain the communication active with the remote host. It is a negative and static attribute. Again, its value, for each RAN, is set in each simulation, according to Table 1.

It is worth noticing that, in Table 1, the Monetary Cost is a rough indication that allows sorting the network from the cheaper, in which *MN* is set equal to 1, to the more expensive one, with *MC* = 10.

6.2. Performance Comparison. In the performance comparison, 9 network selection algorithms are considered.

Specifically, we have employed 5 MADM techniques that comprise also the TOPSIS and the D-TOPSIS. The rest are single-attribute Decision Maker algorithms. Namely, each of the remaining selection algorithms is devoted to the optimization of one of the attributes only: *(i)* Received Signal Strength Indicator based, *(ii)* Available Capacity, *(iii)* Monetary Cost, and *(iv)* Power Consumption.

To evaluate the network selection algorithms six metrics are adopted:

(i) Capacity (C) (expressed in [bps]) that the RAN in use assigns to the traffic flow transmitted by the remote host to the MN;

(ii) *RSSI* (expressed in [dBW]);

(iii) Monetary Cost (MC) payed for employing the RANs;

(iv) power consumption (P) (expressed in [W]) of the MN to maintain the communication active;

(v) packets delay (D) calculated as the difference between the packet transmission time and the time in which the packet is received by the MN in [s];

(vi) number of handover processes executed by the MN (H).

All the aforementioned metrics are negative except for the first two. The optimal choice of the network selection technique is to select the network that guarantees the best compromise between the considered metrics, maximizing the positive one and minimizing the negative one.

In Figures 10, 11, 12, 13, 14, and 15 the evaluated techniques are labeled as follows: the single-attribute methods that optimize *RSSI*, C, MC, and P are reported as #1, #2, #3, and #4, respectively; the multiattribute optimization approaches SAW, *Fuzzy Logic*, WPM, TOPSIS, and D-TOPSIS are indicated with #5, #6, #7, #8, and #9, respectively.

Concerning the *RSSI* metric, among the single-attribute methods, the best performance (i.e., the highest *RSSI*) is obtained, obviously, if the metric optimized is exactly *RSSI* (in this case #1). The MADM techniques perform satisfactorily in all cases: from #5 to #9 the obtained *RSSI* is almost equal to #1. In general the obtained *RSSI* is approximately similar for all the evaluated network selection approaches. Analogous considerations are valid if the other performance metrics are used to evaluate the techniques.

Indeed, when MADM tools are applied, it is not simple to define a best performance: the outcome of a MADM solution is a compromise by definition. The key point is to obtain comparable performance with respect to the cases in which the metrics are considered singularly. This is true for almost all the considered MADM techniques employed in this paper to implement the network selection. The crucial difference is the time needed to find the aforementioned compromise solution: this motivates the analysis reported in the next subsection.

6.3. Computational Complexity Study. A computational complexity analysis of TOPSIS and D-TOPSIS is discussed in this subsection. As previously said, one of the most important requirements for an MN is to limit the complexity of the implemented algorithm in order to reduce the execution time. As a consequence, limiting the number of necessary operations to select a network is a crucial task in order to define a new algorithm.

Table 2: Number of operations performed by TOPSIS and D-TOPSIS.

Operation	Standard TOPSIS	Dynamic TOPSIS	Percentage
ArgMin	$n_s + n_d$	n_d	$\frac{n_s}{n_s + n_d}$
ArgMax	$n_s + n_d$	n_d	$\frac{n_s}{n_s + n_d}$
Multiplication	$m \cdot (n_s + n_d)$	$m \cdot n_d$	$\frac{n_s}{n_s + n_d}$
Power 2	$m \cdot (n_s + n_d) \cdot (m + 2)$	$m \cdot n_d \cdot (m + 2)$	$\frac{n_s}{n_s + n_d}$
Subtraction	$2 \cdot m \cdot (n_s + n_d)$	$2 \cdot m \cdot n_d$	$\frac{n_s}{n_s + n_d}$
Division	$m \cdot (n_s + n_d + 1)$	$m \cdot (n_d + 1)$	$\frac{n_s}{n_s + n_d + 1}$
Square root	$m \cdot (n_s + n_d + 2)$	$m \cdot (n_d + 2)$	$\frac{n_s}{n_s + n_d + 2}$

The first two columns of Table 2 show the number of operations that are necessary to select the *alternative* with the two TOPSIS algorithm variants. The third column indicates the reduction (as a percentage) in the number of operations obtained using the D-TOPSIS algorithm with respect to the TOPSIS. This percentage is computed as the difference between the number of operations for the D-TOPSIS and that for the standard TOPSIS, divided by the number of operations of the TOPSIS.

Each row identifies one operation used in the formulation of both the algorithm versions; as previously defined n_s is the number of static *attributes*, n_d is the number of dynamic *attributes*, and m is the number of available *alternatives* (i.e., the number of available RANs). It is important to notice that the percentage of reduction in the number of operations does not depend on the number of *alternatives* m that are available. This consideration is confirmed by the numerical results discussed in Section 6. Moreover the reduction in the number of operation is explicitly calculated considering different number of dynamic and static attributes (i.e., $n_d = [1, \ldots, 10]$ and $n_s = [1, \ldots, 10]$). In Figure 16 the reduction of a first group of operations is plotted, including the *Argmin*, the *Argmax*, *Multiplication*, *Power 2*, and *Subtraction*, which is equal to $n_s/(n_s+n_d)$ as reported in Table 2. Two further groups of operations are considered, referred to as the *Division* and the *Square root*. Their reductions, which are, respectively, equal to $n_s/(n_s+n_d+1)$ and $n_s/(n_s+n_d+2)$, are calculated over the same variation of the number of attributes considered for the first group and are plotted, respectively, in Figures 17 and 18. As previously said a network selection method has stringent execution time constraints in order to avoid unnecessary time waste for the handover process as a whole. As a consequence it is necessary to limit the computational complexity of the used technique. The proposed D-TOPSIS algorithm can assure great benefits in this direction with

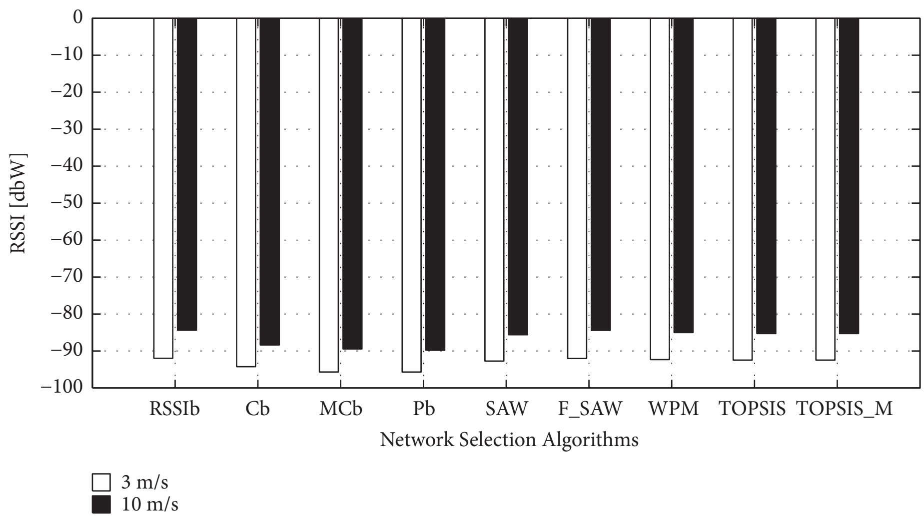

Figure 10: The considered *RSSI* metric for various network selection techniques.

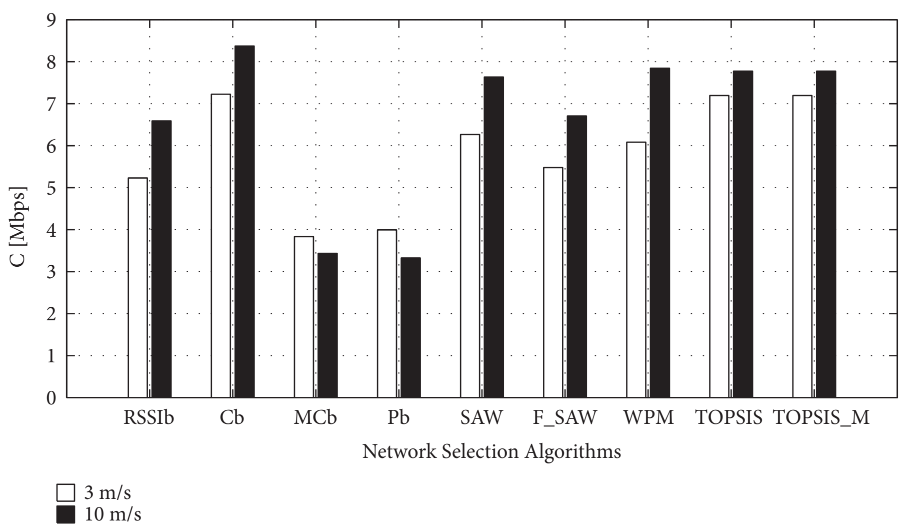

Figure 11: The considered *C* metric for various network selection techniques.

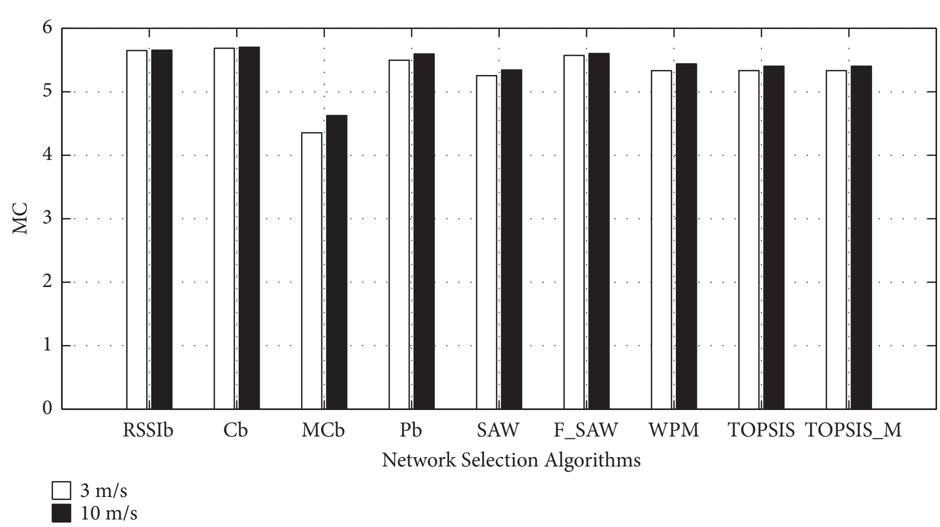

Figure 12: The considered *MC* metric for various network selection techniques.

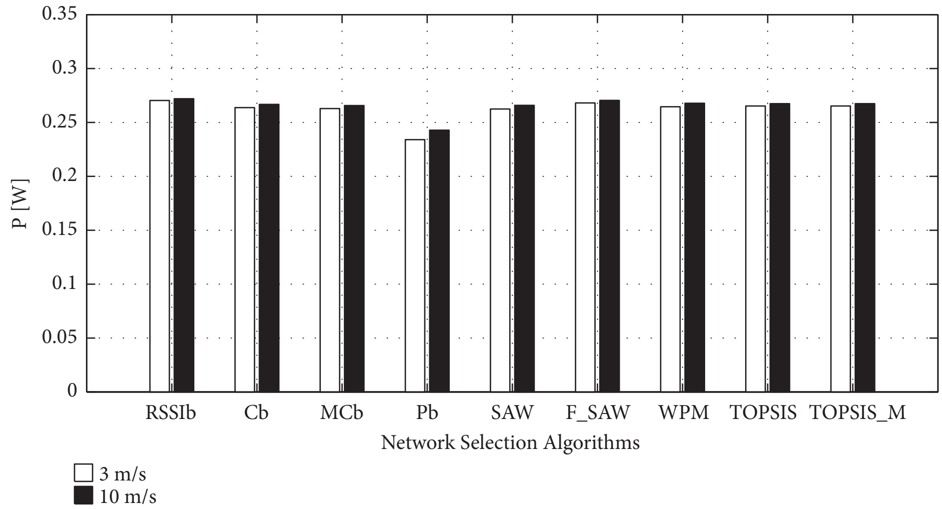

Figure 13: The considered P metric for various network selection techniques.

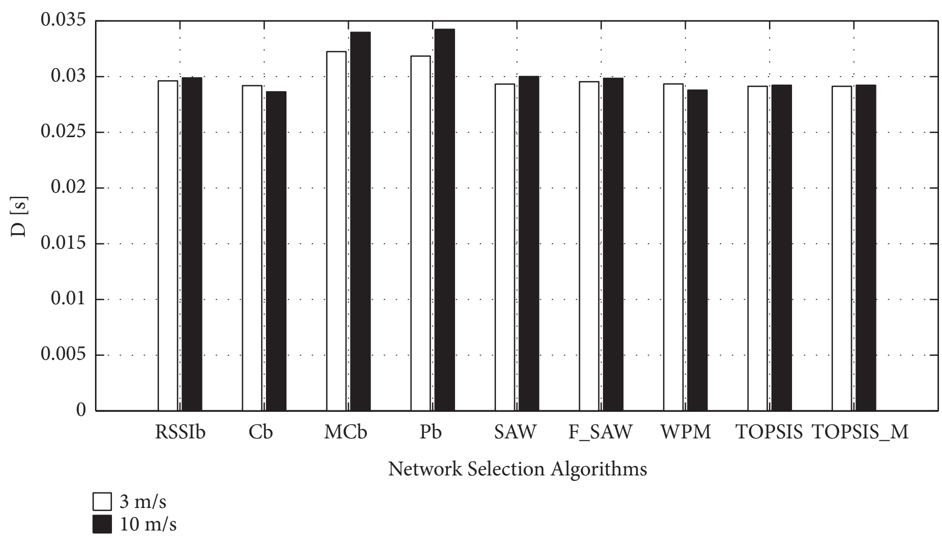

Figure 14: The D metric for various network selection techniques.

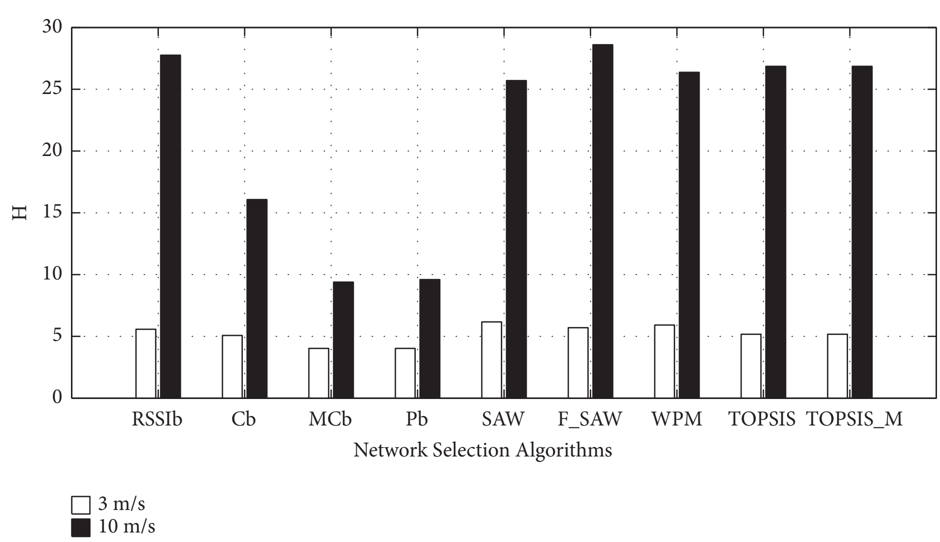

Figure 15: The H metric for various network selection techniques.

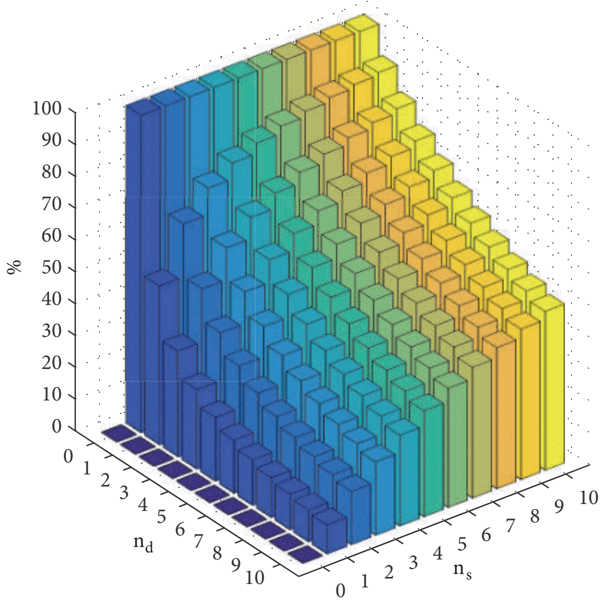

Figure 16: Percentage of reduction in the number of operations of first group using D-TOPSIS respect to TOPSIS.

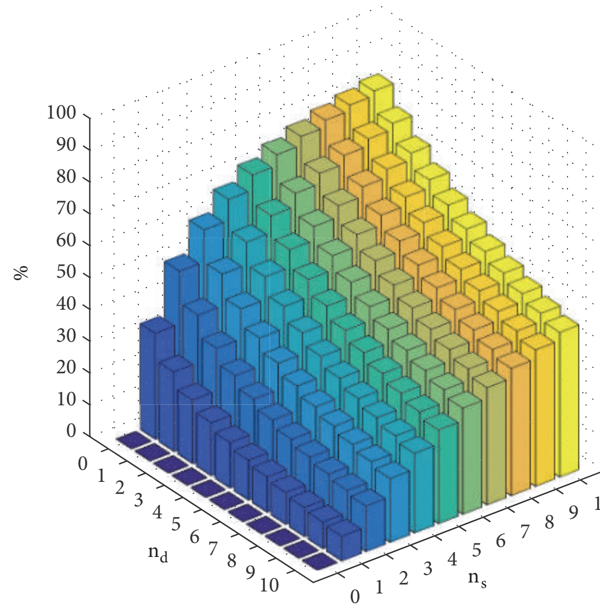

Figure 18: Percentage of reduction in the number of operations of third group using D-TOPSIS compared to TOPSIS.

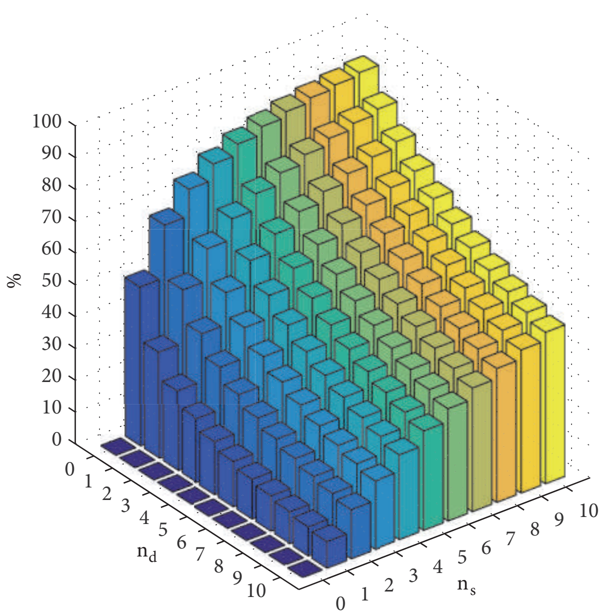

Figure 17: Percentage of reduction in the number of operations of second group using D-TOPSIS compared to TOPSIS.

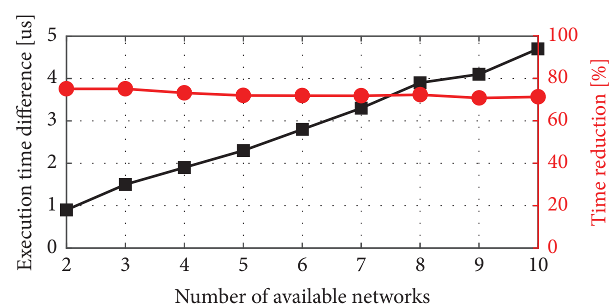

Figure 19: Execution times of TOPSIS and D-TOPSIS and percentage of execution time reduction of D-TOPSIS over different number of *alternatives*.

respect to the standard TOPSIS implementation as highlighted in Section 5. Now the question is, how much does this complexity reduction impact the execution time? So in this subsection a comparison of the execution time of both the TOPSIS implementation versions is proposed. Moreover also the execution time of the algorithms cited in Section 4 is evaluated and compared.

Figure 19 highlights 2 different quantities: the difference in the execution time between the two different implementation versions of the TOPSIS algorithm (see left ordinate axis) and the percentage of the execution time reduction of the D-TOPSIS with respect to the TOPSIS (see right ordinate axis). This quantity is calculated as the difference between the two execution times, divided by the TOPSIS execution time. The total number of attributes is four ($n = 4$) while the number of static and dynamic attributes is, respectively, three and one. In practice, $n_s = 3$ and $n_d = 1$.

From the figure we can extrapolate the idea that the difference between the execution times of the two versions of the TOPSIS algorithm gets bigger if the number of *alternatives* increases. On the other hand, this is not true for the reduction of execution time [31]. Indeed, such quantity is constantly between 70% and 75% independently of the number of *alternatives*. In practice, these results confirm that the execution time reduction is independent of the number of available *alternatives*, as anticipated in Section 5. Figure 20 shows the execution time for all the considered network selection algorithms for a different number of RANs with $n_s = 3$ and $n_d = 1$. One more time, D-TOPSIS is the

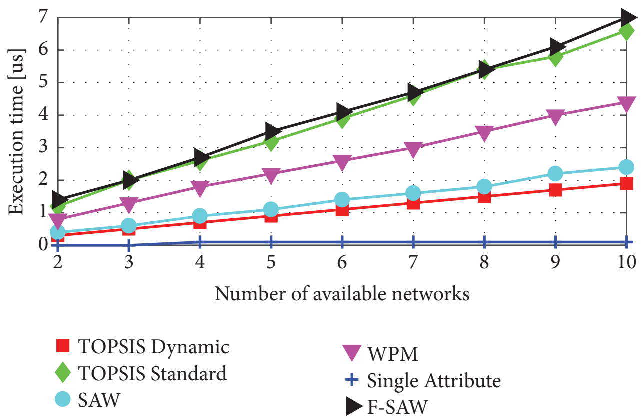

FIGURE 20: Execution time of the considered network selection algorithms over different number of *alternatives*.

second fastest algorithm among the considered algorithms. As a matter of fact the algorithms that belong to this group are computationally lighter with respect to the multiattribute approaches and select the network considering a single parameter applying only an *argmax* or *argmin* operator. On the other hand, these algorithms give poor results and a suboptimal selection [31].

Further considerations can be made observing the multiattribute algorithms: the D-TOPSIS can assure good results, in terms of fast execution with respect to all the considered network selection algorithms. As is shown in Figure 20, the D-TOPSIS is the fastest algorithm among the multiattribute ones, while the standard TOPSIS is set in a middle range and the fuzzy solution requires the maximum execution time. This is due to the fact that it needs many operations during the *fuzzification* and *defuzzification* steps.

Finally, we can observe how the difference between the running times gets bigger when the number of *alternatives* increases. If $m = 10$, the D-TOPSIS running time is equal to 1.9 [μs]. For the TOPSIS standard such quantity is 6.6 [μs], while, for the *Fuzzy Logic*, it has the value of 7 [μs].

7. Conclusions

The paper considers the problem of the network selection when different Radio Access Networks (RANs) that employ different Radio Access Technologies (RATs) are available and can be used to guarantee communications in case of emergency event during which more than one network has to be used to allow a continuous exchange of information between a Mobile Node (MN) and a remote host.

In more detail, in the general framework of the IEEE 802.21 standard, a Decision Maker (DM), within the protocol stack of the MN, in charge of performing network selections and handover decisions, has been proposed. From the mathematical viewpoint, the Multiattribute Decision Making (MADM) techniques are considered and in particular the TOPSIS approach, which has been made lighter (and called D-TOPSIS) with respect to the computational burden, needed to select the RAT. The concept applied is that the *attributes* (i.e., the performance metrics) used to evaluate an *alternative* (i.e., a RAT) can be divided into two groups: the *static attributes* and the *dynamic attributes*. The static attributes for each *alternative* maintain their values constant when the *alternative* is available. The *dynamic attributes* change over time. The basic idea is to run TOPSIS each time the set of available RANs changes (i.e., the MN enters or leaves a new RAN), to find a partial solution (based on the *static attributes*) and reuse it in each successive decision selection. This is D-TOPSIS.

A large simulative campaign, aimed at comparing the performance and the running time of the D-TOPSIS, the TOPSIS, and the technique found in the literature, has been finally reported. MADM approaches guarantee a satisfactorily compromise performance for all the considered metrics, *RSSI*, Capacity (C), Monetary Cost (MC), power consumption (P), packets delay (D), and the number of handover processes executed by the MN (H)). On the other hand, in terms of computation burden, for a single network selection decision, D-TOPSIS allows saving from 10% to 70% of the time needed by the other MADM decision techniques to provide the selected RAT.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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