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A Multi-Layer Parametric Approach to Maximize the Access Probability of Mobile Networks

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ABSTRACT Next-generation mobile networks (5G) are defined to provide access in the framework of heterogeneous systems where it is crucial to have ''always on'' and ''everywhere connectivity'' capabilities. This is of fundamental importance even in 4G mobile systems, down to 3G and also Wi-Fi and WiMAX. In order to guarantee access to users with handheld devices equipped with multiple radio interfaces, an automated and reconfigurable tool for selecting the best network to be connected with is needed. This should be achieved by avoiding service outages. Current vertical handovers, i.e., switching from a network to another, are essentially based on power received levels and often do not avoid temporary service outages. We propose in this paper a procedure to access mobile networks by sensing multiple performance parameters related to networks available in the considered area. We target at maximizing the probability of accessing the wireless medium despite the technology used. We develop an algorithm, based on dynamic programming, able to select the most suitable network. We present the performance of the proposed algorithm both on the basis of computer simulations and on tests performed in an Arduino-based hardware platform.

INDEX TERMS Opportunistic access, link measurements, outage, heterogeneous networks, vertical handover.

I. INTRODUCTION

Nowadays wireless network connectivity is on one side a mandatory condition and on another side a possibility thanks to the large amount of wireless access points present in the same area. We are surrounded by several networks as Wireless Local Area Networks (WLAN) or cellular ones (Universal Mobile Telecommunication System-UMTS, Wi-MAX, Long Term Evolution-LTE). In the near future also access from small cells, femtocells, vehicular cells and others will provide us a plethora of choices for our network connectivity. In this framework, concepts of network switching and vertical handover are becoming very popular. However they are very challenging due to the heterogeneity of the available networks and services. Challenging issues are related to the possibility to switch from one network to another by considering multiple performance figures, not only related to the classical physical layer parameters (like the Signal to Noise Ratio - SNR) but also to other layers spanning from the physical to the transport/application one. Indeed, the number of applications that we are running on our wireless devices are changing and, as a consequence, also the importance that is given to the network performance strictly depends on the application itself. While for voice services the handover has been defined with strict requirements on the time delay, for mobile data applications (like data transfer, Voice over IP, video streaming, etc.) performance metrics may be very different. To this aim, we define a framework to have an opportunistic access to different wireless networks based on multi-layer parametric measurements (MOVE - Multilayer Opportunistic VErtical handover). The proposed solution is designed to be configured according to the specific application needs (delay, Bit Error Rate (BER), jitter, etc.) as well to be implemented in simple wireless devices (smartphones as well as Internet of Things or Machine to Machine devices). The only assumption is that these devices have multiple radio interfaces. A considered constraint is instead that they may have reduced computational capabilities. To this aim we show the performance behavior of our MOVE algorithm in an Arduino-based implementation.

A. RELATED WORK

In the recent literature, an extensive analysis has been dedicated to network selection procedures in the class of the Vertical Handovers (VHO). However, only a few number of papers include multiple-layers and heterogeneous networks together.

The taxonomy on handover strategies (hard, semi-soft, soft, softer vertical handovers) is recalled in [1] where the authors propose a softer vertical handover and evaluate its performance under different assumptions. Their results demonstrate the feasibility of softer vertical handover, with an achievable throughput as high as the sum of that provided by the single radio access technology, but they comment on the not negligible modifications required at some layers of the protocol stack. The paper in [2] proposes a comprehensive handover strategy based on a two-way handover for both macro-femto and femto-macro sides in LTE systems. Different steps are formulated to derive the decision process, these steps consider multiple system parameters and layers, but are only relevant to the LTE. An exhaustive survey of the vertical handover in all-IP next generation networks with an effective classification based on the VHO decision schemes is in the paper by Ahmed *et al.* [3]. Other approaches that are in the class of VHO are presented in [4]. There, a set of procedures for the vertical handover in heterogeneous networks is surveyed and an algorithm empowered by the IEEE 802.21 standard [5] is proposed. The algorithm is specifically designed for vehicular networks, and takes into account the surrounding context, the application requirements, the user preferences, and the different available wireless networks (i.e., Wi-Fi, WiMAX and UMTS) in order to improve users' quality of experience. Mandatory components for this algorithm are the GPS-based geolocation and geonavigation, multiple wireless network interfaces, continuous power supply and powerful computing resource. It may result quite simple to be implemented on network elements with powerful computation capabilities (like vehicular On Board Units) while it may be complex for simpler devices.

A paper that deals with vertical soft handover is PAVSH in [6] where the power is the parameter driving the network selection. They show the performance of PAVSH in heterogeneous networks and demonstrate that it works quite well in heavily loaded networks compared to other existing algorithms with which it is compared. The approach is only based on the power required by the transmitters and is not tailored to other parameters of interest of an application (e.g. packet delay, jitter and others).

A network switching scheme is presented in [7] based on a Markov Chain (MC) model. This approach, although interesting, is limited to the VoIP service and apparently cannot be adapted directly to other services.

A cross-layer switching mechanism between UMTS and WiMAX is proposed in [8] where the specific signaling scheme and system architecture are taken into account to implement the switching protocol. The extension to different kind of networks results not straightforward.

Another approach, related to vehicular connectivity, is proposed in [9] where vehicle to infrastructure links are established if a WLAN is available in order to offload the best effort traffic. This approach, although effective, is strongly heuristic since whenever a WLAN is available (based on WLAN coverage range), a connection is established.

Interestingly, the work in [10] proposes an integration between GPRS cellular and WLAN hot-spots by showing the effect of proactive actions (soft and hard) at IP and TCP levels.

Moreover, two other contributions consider MCs for performing network selection [11], [12]. In [11] a hybrid mechanism based on soft and hard decisions has been proposed while a Markov Decision Process (MDP) has been considered in [12] for measuring merits of accessing a network with respect to another. Although rigorous, that approach considers transition probabilities, related to network states, taken from models or, in some cases, as the output of ns-2 simulator statistics.

In [13], a mechanism based on trellis (so, somewhat similar to the above two approaches) has been used by considering closed-form performance evaluation. These are even though, based on statistical modeling and not tied to real measurements. More, [13] takes into account the signal strength at the receiver only on the basis of the user speed and distance. Last, the work in [14] incorporates the use of parameterized utility functions in order to model several Quality of Service (QoS) elasticities of different applications. The authors adopt a fuzzy logic based approach for the representation of weights in the multiple criteria decision-making problem related to the network selection. The adopted selection criteria are bandwidth, delay and energy consumption and the goal of that paper is to show how the proposed method achieves a balance between QoS performance and energy consumption. The above works seem to consider only few aspects related to a whole communication system since they try to face the problem of network selection by considering some abstract modeling and no tests on real environments appear to be carried out.

B. OUR GOALS

Starting from our early work in [15], where the network selection was performed according to some performance parameters and with a scoring method for different networks, we here propose MOVE, a procedure that continuously measures all available networks quality on the basis of some predefined parameters. It allows a mobile device to autonomously and opportunistically access the network that is able to provide connectivity with a given level of network quality. MOVE allows the mobile device to be connected to a network till it finds a suitable new available connection so maximizing the access probability. This means that, thanks to MOVE, a mobile device has the highest probability to be always connected with a good quality of service parameters.

MOVE is defined in order to be flexible, being able to work with different networks and taking care contemporaneously of several parameters, also heterogeneous in their nature. Its design is specifically tailored fro future 5G architectures where on the one hand the existence of many wireless mobile technologies is expected [16] and where a user centric approach will be on paramount importance. We expect that an approach like MOVE would have benefit in the use of different cell types (femto, small, macro cells) as well different communication paradigms (MIMO, mm-waves etc.) where a multi-parametric approach gives the flexibility to better select the radio access tecnology and the serving base station. Finally, MOVE is shown to be enough simple to be implemented on boards, even on devices with few memory and processing capabilities (like the Arduino platform used in our demo).

The contributions of this paper can be summarized as follows:

- we propose MOVE, an opportunistic network selection algorithm that maximizes the access probability;
- we introduce a cost function to perform opportunistic access;
- MOVE is designed to avoid (or reduce) the ping-pong effect between two or more networks;
- we propose a set of metrics for measuring the access quality;
- we implement, on an Arduino processor, the MOVE algorithm and test its performance in a real scenario.

The remainder of the paper is as follows. In Sec. II we introduce the adopted reference model, while in Sec. III we state the problem of opportunistic access. The performance evaluation of our approach is detailed in Sec. IV. Last, Sec.V draws the main conclusions.

II. SYSTEM MODEL AND ASSUMPTIONS

We consider a reference Mobile Device (MD) able to transmit and receive according to L possible radio technologies ranging from UMTS to Wi-Fi. Moreover, we consider that the device can connect to N different networks. We indicate a network as *connectable* when its signal strength exceeds the MD receiver sensitivity and where the MD has credentials for accessing it and is already authenticated, if needed.

In order to guarantee connectivity without incurring in service outages, the MD should be proactive in selecting a network able to provide access. For this aim, we detail a procedure able to proactively execute the switching from a network to another one without waiting for the outage to manifest, thus minimizing undesired out of service events. In fact, it is a common experience when Internet access is performed via multi-interface devices (i.e., smartphones) that the network preferences follow the rule *Wi-Fi before* so when the received power by an access points is too low, the device switches on the cellular interface (usually 3G/4G). Unfortunately, basing the procedure only on received power level leads to temporary disconnections that result in contents/applications discontinuities. The procedure here proposed is instead proactive and it aims at suitably monitoring and sensing selected parameters from the connectable networks (and including them in a proper mathematical framework) so as to detect the most favorable network to switch to, in order to minimize the outage probability.

To elaborate, let us define, for the n-th network, with $n = 1, \ldots, N$, a set of performance parameters, not necessarily exhibiting mutual independence, and let us suppose to have an arbitrarily ordered set:

$$\mathcal{E}_n \triangleq \{\eta_1^{(n)},\ \eta_2^{(n)}, \ldots, \eta_M^{(n)}\} \tag{1}$$

where the generic $\eta_m^{(n)}$ parameter is one out of M possible performance metrics. We assume that the MD is able to know, through measurements, the values of the M parameters for the n-th network.

For each of the $\eta_m^{(n)} \in \mathcal{E}_n$, a specific minimum value $\eta_{m_{\min}}^{(n)}$ is identified (as a threshold), so that for the generic $\eta_m^{(n)}$ the access opportunity is represented by the event $\eta_m^{(n)} > \eta_{m_{\min}}^{(n)}$. Once inserted all the thresholds in the $(1 \times M)$ vector $\boldsymbol{\eta}_{\min}^{(n)}$ and all the M measured parameters in the $(1 \times M)$ vector $\boldsymbol{\eta}_n$, we can formally define that a connectable network is *Available* (A) if and only if:

$$\boldsymbol{\eta}_n > \boldsymbol{\eta}_{\min}^{(n)} \tag{2}$$

where the symbol '>' means element-by-element inequality. This implies that a network is identified as available when all the M parameters exceed the minimum level. On the contrary, if at least one parameter is below its minimum target value, the network is identified as *Unavailable* (U). As an example, Figure 1 shows the case of 4 connectable networks using the same technology (e.g. Wi-Fi) and two performance parameters. It is possible to note that while networks A-B-C have at least one parameter below the minimum, the network D has both parameters above the relevant thresholds. Based on our previous definition, networks A-B-C are unavailable while D is available. The same concept can be extended in a multidimensional context.

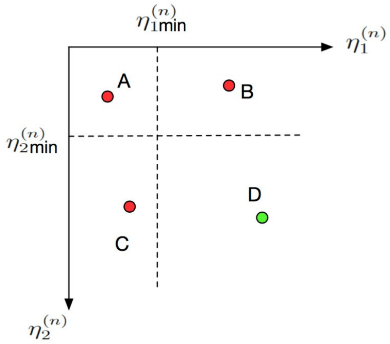

FIGURE 1. Graphical representation of 4 Wi-Fi networks (A, B, C, D) and their condition with respect to the two selected parameters: red points correspond to the Unavailable networks while the green one is the Available network.

III. PROBLEM FORMULATION AND OPPORTUNISTIC ACCESS DECISION

In order to minimize the outage events we should define a mechanism able to allow the MD to select and access a network if it is available without causing the same network to go in the U state in the short or long term. We target at an approach where the MD selects autonomously the network to be connected to.

Notice that in general the network parameters in the set $\mathcal{E}_n$ are influenced by the presence of one or more MDs in the network itself, so a network that is in the A state, after the access of one or more MDs, may fall to the U one. For instance, if the access of multiple users implies link throughput reduction we can experience a worsening of the parameter measuring the throughput rate [17]. Hence, it implicitly indicates that a *suitable* decision mechanism, that is, a network selection algorithm, should present the probability of accessing a network equal to the probability of having at least a network available. This can be formally described by considering that the probability of having access to an available network is strictly tied to the outage probability; we have then:

$$Pr\{availability\} \geq Pr\{access\} = 1 - Pr\{outage\}. \quad (3)$$

We can highlight that typical values of the performance parameters offered by the various (heterogeneous) networks can be considerably different. For instance, the power transmitted/received by an UMTS base station and by a Wi-Fi access point are different in the order of magnitude, hence a preliminary normalization is performed so as to have values ranging in the interval [0,1]. On the basis of this observation, by considering the possible wireless technologies for the MD, we can identify the maximum value for each parameter. Let us then gather these maximum values in the $(1 \times M)$ vector $\boldsymbol{\eta}_{\max}$, formally defined as:

$$\boldsymbol{\eta}_{\max} = [\max_n \eta_1^{(n)},\ \max_n \eta_2^{(n)}, \ldots, \max_n \eta_M^{(n)}]. \quad (4)$$

where the generic m-th element indicates the best m-th parameter evaluated among the N networks as defined by the standards. For example, if the parameter is the data rate, the best parameter among different networks will be defined by the network able, in principle, to provide the highest rate. Once the maximum values are computed, for the n-th network the performance parameters in (1) are normalized and these normalized values are inserted in the $(1 \times M)$ vector $\boldsymbol{\rho}_n$:

$$\boldsymbol{\rho}_n = \left[\frac{\eta_1^{(n)}}{\max_n \eta_1^{(n)}}, \frac{\eta_2^{(n)}}{\max_n \eta_2^{(n)}}, \ldots, \frac{\eta_M^{(n)}}{\max_n \eta_M^{(n)}} \right] \quad (5)$$

The vector $\boldsymbol{\rho}_n$ can be equivalently defined as:

$$\boldsymbol{\rho}_n = \boldsymbol{\eta}_n / \boldsymbol{\eta}_{max} \quad (6)$$

where ' / ' indicates the element-by-element division.
The same normalization is done for the minimum values identifying the outage events so defining the $(1 \times M)$ vector $\boldsymbol{\rho}_{n_{\min}}$:

$$\boldsymbol{\rho}_{n_{\min}} = \left[\frac{\eta_{1_{\min}}^{(n)}}{\max_n \eta_1^{(n)}}, \frac{\eta_{2_{\min}}^{(n)}}{\max_n \eta_2^{(n)}}, \ldots, \frac{\eta_{M_{\min}}^{(n)}}{\max_n \eta_1^{(M)}} \right] \quad (7)$$

that accounts for the normalized minimum requirements.

Stemming on the definitions given in (5) and (7), we can reformulate the outage probability for the whole system at hand, i.e. that characterized by the presence of N heterogeneous networks, as follows:

$$Pr\{outage\} = \prod_{n=1}^{N} \left[1 - Pr\{\boldsymbol{\rho}_n > \boldsymbol{\rho}_{n_{\min}}\} \right]. \quad (8)$$

Since it is not possible to analytically evaluate $Pr\{outage\}$, as it depends on several system configurations/characteristics like the relative node positions (access point vs. MD), channel attenuation, propagation effects, network congestion, etc., it is worth to consider the problem of outage probability minimization as the minimization of the number of occurrences of outage events s_{out} during the observation time s. In this way, $Pr\{access\}$ will be evaluated as:

$$Pr\{access\} = 1 - Pr\{outage\} \simeq \lim_{s \to \infty} \frac{s_{acc}}{s}. \quad (9)$$

where the variable s_{acc} counts the number of times the condition $\boldsymbol{\rho}_n > \boldsymbol{\rho}_{n_{\min}}$ is verified. The above formulation reflects the Venn interpretation of probability according to the frequentist approach.

We can then formulate the network selection problem as the following discrete problem:

$$\max_n s_{acc} \quad (10a)$$

$$\text{s.t.} \quad \boldsymbol{\rho}_n < 1,\ n = 1, \ldots, N. \quad (10b)$$

Before proceeding we argue that, maximizing the probability in (9) means maximizing the number of access opportunities so, a real-time procedure able to find an available network and to access it, leads to maximize the whole access probability.

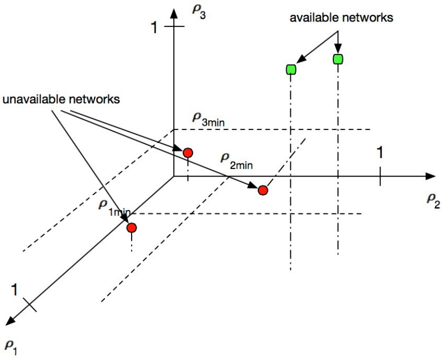

FIGURE 2. Graphical interpretation of available network and unavailable ones.

A geometric interpretation of the outage can be inferred by observing Fig. 2. For sake of simplicity in the representation we consider only three normalized parameters. All the points having at least one projection on the three planes falling within the area limited by 0 and the minimum threshold, are unavailable and then give rise to an outage. On the other hand, if all the projections of a point on the planes are outside the area limited by zero and the threshold, that network is available for the access. The network selection mechanism should maximize the number of times a MD selects a network that is characterized by a green point, if at least one exists, and contemporary it should grant not to overload a network in order to have more than one green point, if possible.

Hence, due to discrete nature of the formulation, we can resort to some discrete optimization methods to obtain the above maximization. This optimization well fits a class of problems, namely Markov Decision Problems (MDPs), since we can model each *state* of the Markov Chain (MC) by characterizing the possible connectivity to each available network, and model the impossibility of accessing the system, namely outage, as the state where there are not available networks. In fact MDPs provides a tool for modeling decision processes where the results come from random behavior and a decision maker has the control of decisions. In other words, the decision maker decides for an action by considering the status where the whole system is.

According to the MC, we model the space state

$$X = \{1, 2, \ldots, 2^N\} \tag{11}$$

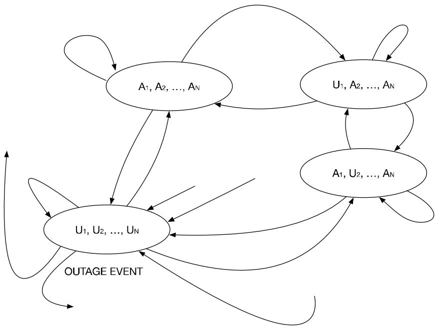

FIGURE 3. Representation of the Markov Chain for the considered problem.

as the 2^N-ple constituted by all the possible combinations (availability-unavailablity) of each of the N networks of the system. In other words, the c-th element X refers to the c-ple system state. In Fig. 3 the MC for the opportunistic access is reported. The label of each state is characterized by A_i and/or U_i. So the outage event is represented by the state with all labels set to $U_i, \forall i$. This latter is not a terminating state but it represents the outage event and it is possible to leave it by performing a different network selection which gives rise to one or more state with at least an A to access.

In order to solve our problem by resorting to MC, we need to know of the transitions probabilities. These latters depend on several and unpredictable factors that range from the signal propagation in the environment, traffic levels to specific position of the MD. As a consequence, we base our approach on evaluating the worthiness of changing network on actual, measured, performance parameters.

To do so we resort to the dynamic programming that is one of the recognized method used to solve MDP.

To this aim we introduce the cost function $G(n, v, k)$, that is the cost to access the v-th network starting from the n-th at time index k. More, we account for the memory weight to be given to the past (through index l starting from K time periods before with the respect to the current, k) with the $d[l]$ term.[1]

We have then at time period k the overall cost is described by the following Bellman equation [18, Ch. 5]:

$$J_v[k] = \left[G(n, v, k) + \sum_{l=k-K}^{k-1} d[l] J_v[l] \right]. \tag{12}$$

We then look for the minimum cost as:

$$J_v^*[k] = \min_{v=1,\ldots,N} \left[G(n, v, k) + \sum_{l=k-K}^{k-1} d[l] J_v[l] \right]. \tag{13}$$

Before detailing the above equation, we must consider the initial state that is for $k = 0$. Hence we detail the cost to move from the outage (since the MD is not connected to any network, so $n = 0$) to a connectable network, if it exists. This is identified as:

$$J_v[0] = G(n = 0, v, k = 0) \tag{14}$$

where we define $G(n = 0, v, k = 0)$ as:

$$G(n = 0, v, k = 0) = -\sum_{m=1}^{M} \rho_m^{(v)}[0] e^{\alpha \cdot \mathrm{sign}[\rho_m^{(v)}[0] - \rho_{m_{\min}}]}. \tag{15}$$

Since we have in Eq. (15) the negative sum of parameters, the minimum is achieved by the network exhibiting the highest (in absolute value) parameter sum. Furthermore, the exponential weight and the sign function in (15) are adopted to avoid that networks unable to preset parameters below $\rho_{m_{\min}}$ can exhibit the minimum value.

As for the general $k - th$ time period, we define $G(n, v, k)$ as:

$$G(n, v, k) = \sum_{m=1}^{M} \left(\rho_m^{(n)}[k-1] - \rho_m^{(v)}[k] \right) e^{-\alpha \cdot \mathrm{sign}[\rho_m^{(v)}[k] - \rho_{m_{\min}}]} \tag{16}$$

and this latter measures how much convenient is moving from the n-th network to the v-th. So, when $\rho_m^{(v)}[k] >> \rho_m^{(n)}[k-1]$ changing network is convenient since the difference

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[1] In principle it is possible to use different values of $d[l]$ by considering it as dependent on n and v but no reasons to apply different weights to memory related to different networks have been considered.

$\rho_m^{(n)}[k-1]-\rho_m^{(v)}[k]$ is high in the absolute value. Obviously the memory K plays an important role so the above considerations is mainly true when the memory is low. It is important to notice that the term $\text{sign}(\rho_m^{(v)}[k]-\rho_{m_{\min}})$ has been introduced in order to avoid the situation where a network presents really good parameters (closer to unity than zero) even though one is below the minimum requested (so leading to outage). Also in this case α can penalize the unavailable network. In fact, in this last case the exponential parameter leverages the cost of $G(n, v, k)$ so penalizing, or better, excluding that network from the set of the available ones. This implicitly indicates that if there is a possibility of excluding the outage, this algorithm will do, so maximizing s_{acc}. Before concluding this formulation we explain how to sample the measurements, that is, the sample time to acquire new measurements so to move from step k to step $k+1$. Starting from the possibilities that a MD has to access networks in terms of network cards/interfaces (e.g., 3G, Wi-Fi, etc.) the sample time is equal to the time related to the shortest frame time among all the above standards.

A. OPPORTUNISTIC ACCESS

An outage event occurs when the set of the available networks able to satisfy the MD requirements is empty. The occurrence of an out-of-service event is in turn due to both the users requirements in terms of specific service specifications (user rate, Bit Error Rate, Round Trip Time, etc.) and the network state.

During time, the generic MD shall take autonomously its decision on the network to switch to a quite intuitive scheme may be based on the following rule for the network to be chosen at time k, that is $v^*[k]$, given by:

$$v^*[k] = \arg \min_{v=1,\ldots,N} J_v[k] \qquad (17)$$

It is worth notice that, by representing the MC of Fig. 3 as a trellis, the time variable k is equivalent to the space variable related to the trellis representing it and spanning it from left to right.

One drawback of accessing a network on the basis of a minimum cost function or maximum of an utility function is the possible rise of ping-pong effect (see [19]) that induces the MD to continuously switch between two or more networks. In this context, we take into account the above mentioned effect by properly using the *memory* coefficient $d[l]$ in (12) so as to weight the past and reduce unnecessary network switches.[2] In fact, when we choose the network of the basis of $J_v[k]$, the effect of memory is already considered. Numerical results confirm this point as it will be clearer in the following.

About complexity of the proposed procedure, it involves only summations and multiplications, so the computational cost is limited and depends on the network availability (the number of networks available in a certain area). More, about how much frequently this procedure is performed, that is the time passing from k-th to $(k+1)$-th, it is regulated by the shortest frame with present technologies since when a parameter m of a network n changes then the $J_v[k]$ term must be updated.

We remark that this approach is always valid, no matter what are the selected parameters η_m. Here we propose to consider six main figures of merit that are:

1) received power;
2) Bit Error Rate (BER);
3) queueing access delay;
4) user rate;
5) Round Trip Time (RTT);
6) jitter.

As for the received power parameter, namely $\rho_1^{(n)}$, it is defined as:

$$\rho_1^{(n)} = \frac{P^{(n)}}{P_{\max}} \qquad (18)$$

being $P^{(n)}$ the power received by the MD as for the n-th base station/access point.

For what the BER is concerned, it is not independent from $P^{(n)}$ even if it depends on modulation formats adopted in the network (and/or link). On the basis of the maximum possible BER ($BER_{\max}$), the BER parameter, namely $\rho_2^{(n)}$, is defined as:

$$\rho_2^{(n)} = 1 - \frac{BER^{(n)}}{BER_{\max}} H(BER_{\max} - BER^{(n)}) \qquad (19)$$

being $H(.)$ the Heaviside function, also know as unit-step function, so when BER is very low $\rho_2^{(n)}$ approaches 1 while when BER is close to $BER_{\max}$ or higher, $\rho_2^{(n)} = 0$.

Dealing with congestion, we relate the third parameter to the delay due to queuing at MAC layer:

$$\rho_3^{(n)} = \frac{Q_{\max} - Q^{(n)}}{Q_{\max}} \qquad (20)$$

where $Q_{\max}$ takes care of the dimension of the MAC buffer, tied to the maximum queueing delay, while $Q^{(n)}$ is the effective position in the scheduler of the n-th network. This latter depends on the level of traffic.

Moreover, the user rate can be defined according to the network. In fact in Wi-Fi and WiMAX (also classified as Wi-Fi family) the rate scales with the number of user as:

$$\rho_4^{(n)} = \frac{1}{Z^{(n)}} \qquad (21)$$

where Z is the number of connected users. On the other hand, in the case of UMTS, LTE (cellular family), the user has an assigned rate and when the number of users exceeds a maximum value, the resulting blocking probability is grater than zero. So, for the rate we have in the case of cellular family:

$$\rho_4^{(n)} = H(Z_{max} - Z^{(n)}). \qquad (22)$$

being $H(.)$ the Heaviside function as before.

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[2] We neglect the overhead to perform the handover in the cost function since it has a low impact on traffic and throughput. Furthermore, the memory in the Eq. (13) aims at reducing also the number of unnecessary handovers.

Furthermore, the parameter related to the RTT can be defined as:

$$\rho_5^{(n)} = \frac{T_r^{(n)} - T_e^{(n)}}{RTT_{max}} \tag{23}$$

where $T_e^{(n)}$ is the emission time of the reference packet while $T_r^{(n)}$ is the time when packet has been received and RTT_{max} is the maximum allowed round trip time. The packet to be sent can be a simple *ping* packet.

Last, related to jitter, we have a parameter that is similar the one introduced for queuing delay and it is given by:

$$\rho_6^{(n)} = \frac{W_{\max} - W^{(n)}}{W_{\max}} \tag{24}$$

where $W_{\max}$ indicates the maximum jitter tolerated and W is the measured one.

Before discussing practical implementation issues and complexity, it is important to highlight that we normalize the above parameters with respect to the maximum of their respective values. It is to be noticed that different normalization functions are possible and that by changing the definition of a $\rho_m^{(n)}$ also different values of $G(n, v, k)$ arise. However, this does not impact on the switching mechanism, even if, the normalization can be also used to give more significance to some parameters with respect to others.

B. REMARKS ON MULTIPLE ACCESSES

We focused on the access performed by a single MD, by considering the other devices apparently as static. However, it is worth noting that in case of network switching some parameters change while others remain unaltered. For example, the received power does not depend on the presence of other nodes and the same stands for BER (under the hypothesis of no multi-user interference present). On the other hand, the other three parameters are influenced by the presence of other nodes with a sole exception. In cellular networks the presence of new users can lead to a performance degradation just close to the rate saturation. However, it is important to highlight that even multiple accesses are possible, this will reflect on a change in the cost function with respect to the value at the previous step for the access networks and nodes exhibiting quality close to the minimum threshold are expected to switch network, thus meaning that it happens if they are far from the access point/base station and/or at rate saturation, hence it is valid very dense networks.

C. REMARKS ON COMPLEXITY

The complexity of MOVE depends on two main factors, that are, N and M since at each time step the algorithm must compute the comparison between N different values, on a summation operated over M parameters. From this point of view the cost C of the computation is:

$$C = \mathcal{O}(NM) \tag{25}$$

Apparently the parameter K is not counted in the cost. This is true since even though the memory depends on K time steps before, the summation in (12) means that at each step a stored value is added and then it is updated at the next step be removing the oldest value and considering the newest one. So we can conclude that if we consider multiple parameters (in the order of 6 or 7), and number of networks, depending on the area, is in the order of (even though, since it is expected that the access is not granted to all the networks due to possible subscriptions to a subset of them), the cost is really limited and affordable with the hardware available in the market.

IV. NUMERICAL RESULTS

The numerical analysis is organized in two different subsections. The first one gathers results obtained via Matlab simulations of MOVE while the second group is related to implementation of the proposed procedure on an Arduino based test-bed. For what concerns simulations we consider the following values as reference for the *best performance* and *minimum performance*. Regarding $\rho_1^{(n)}$ we set the $P_{\max}$ value to $10\,W$, equivalent to a 3G Base Station while the minimum threshold $\rho_{1_{\min}} = 10^{-7}$. Dealing with $\rho_2^{(n)}$, we consider $BER_{\max} = 10^{-3}$ and $\rho_{2_{\min}} = 0.9$, while for $\rho_3^{(n)}$, we assume $Q_{\max} = 150000$ bytes that is the maximum allowed value in LTE and $\rho_{3_{\min}} = 0.05$. For what concerns $\rho_4^{(n)}$, $Z_{\max} = 256$ as for UMTS and $\rho_{4_{\min}} = 0.05$, while by considering $\rho_5^{(n)}$, $RTT_{\max}$ is set to 150 ms, as recommended by ITU-T G.114, for Voice over IP application and $\rho_{5_{\min}} = 0.8$, and basing on this latter, $W_{\max} = 50$ ms ($\rho_{6_{\min}} = 0.7$). If not differently specified we considered a memory $K = 6$ and $\alpha = 8$.

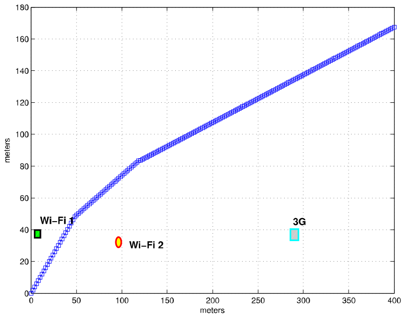

FIGURE 4. Network topology and user path with Wi-Fi 1, Wi-Fi 2 and 3G.

We start by considering a scenario where three available networks are present, namely Wi-Fi 1, Wi-Fi 2 and 3G (UMTS-based) at the reciprocal distances and in the area of $180\ m \times 400\ m$ depicted in Fig. 4. The MD is supposed to move at $4 km/h$ (pedestrian speed) in the area from left to right according to the path depicted in Figure 4. This scenario may represent a pedestrian moving in a city area or in an indoor space (office, mall, etc.).

TABLE 1. Effects of number of parameters and memory values on the number of network switches.

Parameters	Memory	1st NS	2nd NS	3rd NS	4th NS	5th NS
6 parameters	$K = 4$	(30,Wi-Fi 2)	(88, 3G)	×	×	×
	$K = 2$	(25,Wi-Fi 2)	(80, 3G)	×	×	×
	$K = 1$	(23,Wi-Fi 2)	(76, 3G)	×	×	×
3 parameters (Received power, BER, jitter)	$K = 4$	(23,Wi-Fi 2)	(76, 3G)	×	×	×
	$K = 2$	(22,Wi-Fi 2)	(75, 3G)	×	×	×
	$K = 1$	(21,Wi-Fi 2)	(25, Wi-Fi 1)	(29, Wi-Fi 2)	(74, 3G)	×
1 parameter (Received power)	$K = 4$	(18,Wi-Fi 2)	(22, Wi-Fi 1)	(27, Wi-Fi 2)	(67, 3G)	×
	$K = 2$	(17,Wi-Fi 2)	(20, Wi-Fi 1)	(26, Wi-Fi 2)	(65, 3G)	×
	$K = 1$	(16, Wi-Fi 2)	(19, Wi-Fi 1)	(25, Wi-Fi 2)	(62, Wi-Fi 1)	(64, 3G)

Each marker is the point where measurements are performed as for the parameters indicated in Section III-A. A number of six parameters are considered and these are, received power, error rate, queueing delay, transmission rate (e.g. modulation formats), round trip time and jitter.

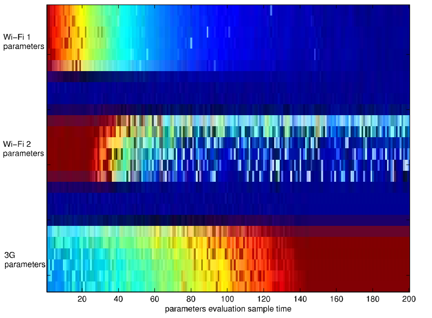

FIGURE 5. Network parameters (pictorial view) for Wi-Fi 1, Wi-Fi 2 and 3G.

In Figure 5 the parameters quality is reported. In detail, the horizontal axis reports time steps related to measurements operated by the MD on the three different networks. Each of the three different patterns represents with a color the quality of the single parameter (6 parameters per network can be recognized reported as a row, red is good value for the considered parameter, blue is bad). When a red to blue transition is present, it means that the quality of the considered parameter is decreasing, a blue to red transition indicates that the quality of the parameter is increasing. Qualitatively speaking, it is possible to appreciate how both the Wi-Fi networks are able, in the first samples, to present high quality parameters while 3G is unable. By considering higher values for the sample index, 3G presents better parameters with respect to Wi-Fi networks. An interesting information that can be inferred from Fig. 5 is that a color change affects all the parameters very quickly, usually starting from received power (the first one) so as to propagate to the others so giving evidence of the correlation among them.

The real impact of parameters can be better explained by observing the curves in Figure 6. This latter reports the costs related to accessing the networks without considering

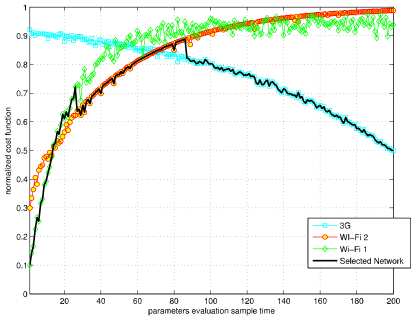

FIGURE 6. Normalized cost function as in (12) for Wi-Fi 1, Wi-Fi 2 and 3G.

the second term in the sum in (12). In this sense, it is the instantaneous cost, while the decision about network access is based on the basis of previous states (if $d_{n,t}(v) \neq 0$). The MD trying to access the network is initially connected to the Wi-Fi 1 and it follows its performance reported in terms of cost function according to (12). So, even though starting from sample number 12, Wi-Fi 2 presents lower cost with respect to Wi-Fi 1, the network access toward Wi-Fi 2 happens only at sample 30 due to the *memory* introduced in (12) via the use of the parameter $d_{n,t}(v)$ set to 0.7 in order to give a quite high weight to the past incurred costs. In the following we also show the effect of the memory K on the number of network switches.

It is possible to appreciate that when a network switching happens, the parameters evaluation in Fig. 5 are considerable better for Wi-Fi 2 with respect to Wi-Fi 1. Moving on the horizontal axis till to sample number 74, the 3G network presents lower cost locally with respect to Wi-Fi 2. However the network access to 3G happens around sample 85. Also, in this case a comparison of Fig. 6 plots with the pictorial view in Fig. 5, helps to understand the behavior of MOVE.

In order to evaluate the effects of the number of parameters used in MOVE and of the memory, we report in Table 1 the network switches (NS) with the notation (time instant, network) for the same scenario of Fig. 4 and for different values of the memory K. It is possible to appreciate how the number of network switches increases when less memory is used and when the number of parameters taken into account decreases. Moreover, it is possible to notice that when the only one parameter is considered (the received power in this case) the ping-pong effect takes place if the memory is set to 1, since if the power received by a network is higher for few time periods, this latter is chosen for the access and a network switch occurs. This leads to conclude that both the use of memory and of multiple parameters gives robustness to MOVE. This is also true even if we introduce possible errors in the measurements. If we have no memory and only one parameter is used, a wrong or imprecise measurement of this parameter can lead to wrong decisions about the network selection, while considering a higher number of parameters (and an higher memory value) reduces the effect of errors.

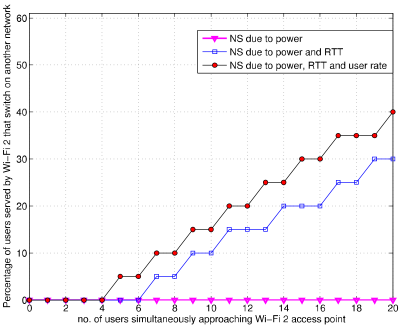

FIGURE 7. Percentage of users attached to Wi-Fi 2 that migrates on other networks when some other nodes approach the Wi-Fi2 access point.

Before moving to the section when real data are taken into account, it can be of interest evaluating in the previous defined scenarios the behavior of 20 users attached to Wi-Fi 2 when other nodes approach the Wi-Fi 2 access points. More into detail, we want to highlight the different behaviors of the users already connected if they use only power level as mechanism for switching from a network to another one or if they account for other parameters. In Fig. 7 we have in the horizontal axis the number of *simultaneous* users approaching the Wi-Fi 2 access point while in the vertical axis it is possible to measure how many nodes (expressed as percentage) switch to another network (that is 3G or Wi-Fi 1, also depending on their positions). It is interesting to note that when only power is considered, since the presence of other users does not influence the channel between access point and MD, then no user migrates while the link quality degrades since the medium is shared with more users. On the other hand, when also the RTT is taken into account the percentage achieves 30% when 20 nodes simultaneously approach Wi-Fi 2 access point. This value increases when also the user rate is considered as a MOVE parameter. We can conclude that, even though with several parameters the number of network switches can increase, this happens because we are able to grant, when and where possible, higher service quality to the MDs.

As for the performance analysis derived from real measurements, an interesting case study that can be shown is case of a urban trajectory of a vehicle moving at an average speed of $10km/h$ and showing which network is selected. The measurements have been performed by using Rohde&Schwarz CMW500 that is able to test both cellular-like and Wi-Fi families. The considered area is in the city of Rome close to the Colosseum and to our university (''Sapienza''). We present in this scenario five different networks. We have one base station providing LTE access and a 3G one. We also consider the presence of two Wi-Fi hotspots. The first one (Wi-Fi 1) is located at Engineering Faculty of Sapienza University of Rome, while the second one (Wi-Fi 2) is managed by the Province of Rome. Last, a WiMAX base station is also present. The measurements of the Wi-Fi 1 and Wi-Fi 2, 3G and LTE are gathered during measurements campaigns, while the data related to WiMAX are fully simulated by considering appropriate propagation modeling. In Fig. 8 we show which network is chosen with MOVE and, at the same time, the outage events happening when a scheme simply based on the received power level is adopted. Interestingly,

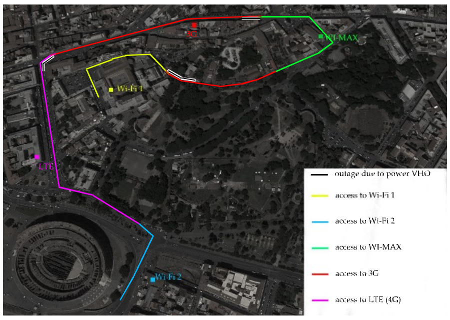

FIGURE 8. MOVE network selection based on some measurements (Wi-Fi 1, Wi-Fi 2, 3G, LTE) and emulated parameters (WiMAX) with comparison with power-based network selection.

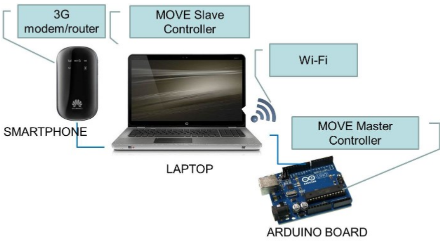

FIGURE 9. Architecture of the Arduino-based implementation.

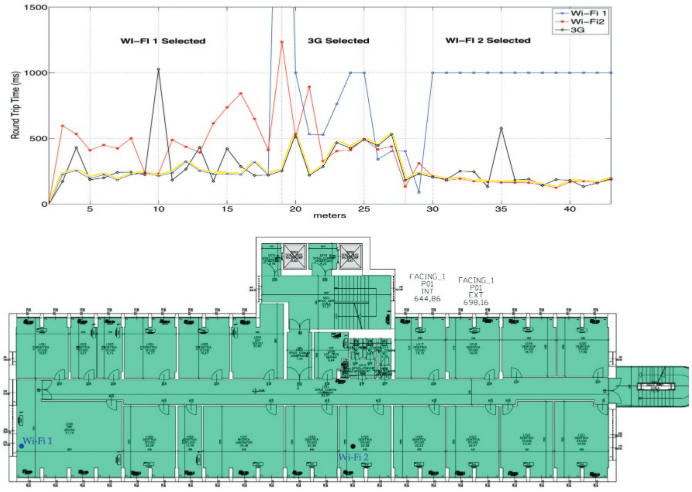

FIGURE 10. Experimental results obtained via Arduino implementation of MOVE when RTT is taken into account as measured parameter.

starting from the Engineering Faculty, MOVE is connected to Wi-Fi 1 (yellow line) and switches to 3G when the receiver device is on the opposite side of the Faculty. In that case, MOVE switches to 3G (red line), while an access procedure based only on power does the same choice with an outage event represented by the black line on white background. Later, the device switches to WiMAX (green line) and once more on 3G and a new outage occurs in the power-based VHO procedure. When MOVE selects LTE (magenta line) another outage for power-based VHO occurs while no more outages are experienced in the subsequent switch to Wi-Fi 2 (blue line).

A. ARDUINO-BASED IMPLEMENTATION AND TESTS RESULTS

We describe in this section a full implementation of MOVE on a simple hardware composed by: i) one Arduino UNO board, equipped with an Atmel ATmega328P microcontroller running at 16MHz; ii) a PC-laptop (running MS Windows 7 OS) with integrated Wi-Fi interface card; iii) one Huawei 3G modem/router to provide a 3G based network interface, with network access granted by a Subscriber Identity Module (SIM) of an Italian mobile telecom operator. We highlight that the tests are performed on Internet services allowing data download when the IP address changes while it is not applicable, as well as other concurrent network selection algorithms, when a service forbids data download continuity when the IP address changes. Services requiring the same IP are for example email and ftp, while streaming via you tube does not require the same IP for the whole duration of the download.

In this architecture, depicted in Fig. 9, the Arduino board hosts the implementation of the MOVE algorithm and acts as a master controller to a Java/Processing slave application on the PC-laptop side. The aim of having Arduino as testbed for MOVE is to implement it in a very limited system where both computational and memory resources are constrained; thus demonstrating the feasibility of such an approach in the presence of this kind of constraints, e.g., small and portable hardware with limited resources. The PC-laptop and related application are intended to provide services to the Arduino master. The PC-laptop slave app communicates with the Arduino master providing services, like metrics readouts through TCP/IP protocol stack and system applications like ping (for the RTT); the PC-laptop offers also hardware resources like the USB bus for interconnection with the 3G modem/router and the integrated Wi-Fi interface and antennas. The advantage of using Arduino, PC-laptop and an external 3G modem/router is related to the wide availability of this board: one of the key constraints in the implementation was the ability to perform tests with no special hardware or costly, giving preferences to a simple, fast and cheap solution. The presence of PC-laptop OS gave us the ability to focus on MOVE logic instead of requiring special implementation of on-board solution just for network and hardware related details (e.g. TCP/IP stack, ICMP, 3G device interconnections, etc) that are not feasible without specialized solutions, although possible in a real application scenario, e.g,. commercial devices required to maximize the connection up time to the Internet, minimizing the probability of outages and provided with hardware required on board. The ability of collecting logs and visualizing data was mandatory so the slave app was designed to provide these functionalities and collect data during test sessions. The test reported in Fig. 10 refers to the above laptop in the hands of a tester/user walking at an average speed of $4km/h$ from left to right side of the first floor of the Dept. of Information, Electronics and Telecommunication engineering (DIET) of Sapienza University of Rome whose map is reported in the bottom side of Fig. 10. In the map it is possible to recognize the presence of two Wi-Fi access points. The 3G base station location cannot be represented in the same figure due to its high distance. In the upper part of Fig. 10, we report the RTT of the three networks by showing the measured values in correspondence of the space walked (as for example the authors of [20] did, in another context). Considering the speed of $4km/h$ it is possible also to translate the space in time. The yellow highlighting shows the behavior of the selected networks. In detail, at the beginning the network selected is Wi-Fi 1 since its access point is very close to the laptop.

When the laptop results to be a bit far from the Wi-Fi 1 access point $(18m)$, the RTT starts to increase and achieves a value considerably higher with respect to that offered by 3G. So, MOVE selects 3G as preferable network and accesses it. Furthermore, when the position of the laptop approaches that of the second access point (Wi-Fi 2), the RTT of this latter becomes the smallest so MOVE selects Wi-Fi 2. We show the effect of only one parameter since is it easier to show and comment. It is important to notice that we were downloading a file with FTP during this experiment and no interruptions happened during the downloading. From this experiment we can assess three main features of the proposed approach:

1) MOVE is able to effectively switch from an available network to another by avoiding outage events when at least one network is available;
2) the positive effect of the memory reduces network switching to the minimum necessary;
3) MOVE can be implemented easily and with low complexity in mobile devices.

V. CONCLUSIONS

We proposed a multi-parametric and multi-layer vertical handover procedure, named MOVE, able to maximize the access probability of users having different and heterogeneous wireless connectivity (e.g., Wi-Fi, WiMax, UMTS and LTE). We defined the MOVE problem and solved it by resorting to dynamic programming considering the possibility of selecting the best wireless network by considering also the effect of memory, so avoiding ping-pong effect. The results confirm at different levels the effectiveness of such a proposal. In fact, both simulations performed on the basis of modeling and those using measurements show that no outages occur. More, we showed the performance behavior in an Arduino-based implementation confirming both the simulated and expected results as well as the simplicity and feasibility of the proposed approach.

REFERENCES

[1] A. Bazzi, B. M. Masini, A. Zanella, and D. Dardari, "Performance evaluation of softer vertical handovers in multiuser heterogeneous wireless networks," *Wireless Netw.*, pp. 1–18, Dec. 2015. [Online]. Available: http://dx.doi.org/10.1007/s11276-015-1140-8
[2] M. Behjati, J. P. Cosmas, R. Nilavalan, G. Araniti, and M. Condoluci, "Self-organising comprehensive handover strategy for multi-tier LTE-advanced heterogeneous networks," *IET Sci., Meas. Technol.*, vol. 8, no. 6, pp. 441–451, 2014.
[3] A. Ahmed, L. Boulahia, and D. Gaiti, "Enabling vertical handover decisions in heterogeneous wireless networks: A state-of-the-art and a classification," *IEEE Commun. Surveys Tut.*, vol. 16, no. 2, pp. 776–811, 2nd Quart., 2014.
[4] J. M. Marquez-Barja *et al.*, "Breaking the vehicular wireless communications barriers: Vertical handover techniques for heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5878–5890, Dec. 2015.
[5] *IEEE Standard for Local and Metropolitan area Networks—Part 21: Media Independent Handover Services*, IEEE Standards 802.21, Jan. 2009, pp. 1–289.
[6] R. Singh, S. Mukherjee, and S. C. Ghosh, "Improving user coverage through resource aware handoff management in heterogeneous networks," in *Proc. 13th Int. Conf. Adv. Mobile Comput. Multimedia (MoMM)*, 2015, pp. 179–188.
[7] H.-H. Choi, O. Song, Y.-K. Park, and J.-R. Lee, "Performance evaluation of opportunistic vertical handover considering on–off characteristics of VoIP traffic," *IEEE Trans. Veh. Technol.*, vol. 59, no. 6, pp. 3115–3121, Jul. 2010.
[8] J. Jo and J. Cho, "A cross-layer vertical handover between mobile wimax and 3G networks," in *Proc. Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Aug. 2008, pp. 644–649.
[9] M. Gramaglia, C. J. Bernardos, and M. Calderon, "Seamless Internet 3G and opportunistic wlan vehicular connectivity," *EURASIP J. Wireless Commun. Netw.*, vol. 2011, pp. 183–202, Nov. 2011.
[10] R. Chakravorty, P. Vidales, K. Subramanian, I. Pratt, and J. Crowcroft, "Performance issues with vertical handovers—Experiences from gprs cellular and wlan hot-spots integration," in *Proc. IEEE 2nd Annu. Conf. Pervasive Comput. Commun. (PerCom)*, Mar. 2004, pp. 155–164.
[11] A. Vegni and E. Natalizio, "A hybrid (N/M)CHO soft/hard vertical handover technique for heterogeneous wireless networks," *Ad Hoc Netw.*, vol. 14, pp. 51–70, Mar. 2014.
[12] E. Stevens-Navarro, Y. Lin, and V. W. S. Wong, "An MDP-based vertical handoff decision algorithm for heterogeneous wireless networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 1243–1254, Mar. 2008.
[13] C. Fischione, G. Athanasiou, and F. Santucci, "Dynamic optimization of generalized least squares handover algorithms," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1235–1249, Mar. 2014.
[14] I. Chamodrakas and D. Martakos, "A utility-based fuzzy TOPSIS method for energy efficient network selection in heterogeneous wireless networks," *Appl. Soft Comput.*, vol. 12, no. 7, pp. 1929–1938, 2012.
[15] M. Biagi, S. Rinauro, S. Colonnese, G. Scarano, and R. Cusani, "Short paper: Dynamic network selection in V2I systems," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2013, pp. 190–193.
[16] A. Gupta and R. K. Jha, "A survey of 5G network: Architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, Jul. 2015.
[17] G. Bianchi, "IEEE 802.11-saturation throughput analysis," *IEEE Commun. Lett.*, vol. 2, no. 12, pp. 318–320, Dec. 1998.
[18] D. Bertsekas, *Dynamic Programming and Optimal Control* (Athena Scientific Optimization and Computation Series), vol 1. Belmont, MA, USA: Athena Scientific, 2005.
[19] G. Tamea, M. Biagi, and R. Cusani, "Soft multi-criteria decision algorithm for vertical handover in heterogeneous networks," *IEEE Commun. Lett.*, vol. 15, no. 11, pp. 1215–1217, Nov. 2011.
[20] O. B. Akan and I. F. Akyildiz, "ATL: An adaptive transport layer suite for next-generation wireless Internet," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 5, pp. 802–817, Jun. 2004.

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