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Vertical Handover between WiFi and UMTS Networks: Experimental Performance Analysis

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Abstract

In this paper, we analyze the performance of vertical handover (VHO) algorithms for seamless mobility between WiFi and UMTS networks. We focus on a no-coupling scenario, characterized by the lack of any form of cooperation between the involved players (users and network operators). In this "hostile" scenario, the VHO operations are completely operated by the mobile terminal (MT), and the network authentication procedures are unoptimized, leading to typically long handover times. In this context, we first propose a low-complexity Received Signal Strength Indicator (RSSI)-based algorithm and, then, an improved hybrid RSSI/goodput version.

We present experimental results based on the implementation of a real testbed with commercial WiFi (Guglielmo) and UMTS (Telecom Italia) Italian deployed networks. Despite the relatively long handover times experienced in our testbed, the proposed RSSI-based VHO algorithm guarantees an effective goodput increase at the MTs. Moreover, this algorithm mitigates the ping-pong phenomenon. Our results show that, by using simple MT-driven VHO mechanisms, the users can benefit from redundant and heterogeneous wireless network infrastructures. This can be done by leveraging on pre-existing commercially deployed networks, without the need for any modification of them.

1 Introduction

The concept of *always connected*—the possibility of being connected everywhere at any time—was born with the advent of cellular networks, which can be considered as the first example of really pervasive wireless communications, at least in terms of voice connections. Since its origin, the meaning of *always connected* has been continuously changing. Nowadays, it coincides with the capability of surfing the web, taking advantage of its plethora of services through a high-speed Internet access. This condition, at least in technologically advanced countries, has been achieved. In fact, the frontier of today is represented by the concept of being *Always Best Connected* (ABC), as introduced several years ago [8]. According to this concept, the user should be able of taking advantage of the best available access network at any point in time, choosing among the large array of solutions offered by the market, including the various generations of cellular networks (e.g., GSM/GPRS, UMTS, and LTE) [2], metropolitan area networks (e.g., IEEE 802.16 [11] and HiperLAN [6]), wireless local area networks (e.g., IEEE 802.11a/b/g/n [9]), and also personal area networks (e.g., Bluetooth [23]).

The idea of connecting to the best access point[1] of the network is not novel, since it is used by the so-called *Horizontal HandOver* (HHO) mechanism [17], which is crucial, in cellular networks, to offer continuous connectivity to the customers. Unfortunately, the HHO procedure works only with access points belonging to the same access network. Therefore, in order to achieve a real ABC connectivity, it is necessary to extend the functionalities of the HHO, in order to make the transition of a mobile terminal (MT) between access points belonging to *heterogeneous* networks possible. A mechanism able to perform this task, possibly in a transparent way from upper-layer applications and "painlessly" from the user perspective, is commonly known as *Vertical HandOver* (VHO).

A VHO procedure is composed by three main phases: initiation, decision, and execution [14]. During the initiation phase, the MT or the network controller triggers the handover procedure, according to the specific conditions of the network. In the second phase, the VHO algorithm chooses the new access point according to a pre-determined set of metrics, such as the Received Signal Strength Indicator (RSSI), the network connection time, the available bandwidth, the power consumption, the monetary cost, the security level, and, obviously, the user preferences [26]. During the final execution phase, all signaling operations for communication re-establishment and data transfer are carried out. The most relevant international standardization effort regarding VHO and continuous communications, the IEEE 802.21 standard [10], only refers to the first two phases (initiation and decision) that are relatively technology-independent, but it deliberately ignores the execution phase. The latter is considered by other standardization bodies, like the 3GPP consortium [2] or the Internet Engineering Task Force (IETF) [12]. However, there is no universal and definitive solution, since the mobility management problem is affected by too many factors (technological, commercial, and even social). Most of the VHO approaches, for example that considered in [22], are based on Mobile IP [19], a level-3 solution that is based on the idea of maintaining the same IP address in every network visited by the MT. In the last years, several works have been based on the application-level Session Initiation Protocol (SIP) [20], mostly because it can better support Voice over IP (VoIP) applications [21].

According to [17], there are several possible classifications of VHO algorithms. In this work, we only focus on a *no-coupling* scenario, i.e., a scenario without any form of cooperation between the involved players (users and network operators) [14]. This situation offers the maximum degree of freedom to the user, at the price of an increased complexity of the whole handover procedure and of a worse performance. Clearly, with a higher level of coupling (e.g., *loose* or *tight* coupling) better performance can be achieved. In our no-coupling scenario, handover times are typically large. Therefore, in order to avoid any lack of connectivity during the handover *execution* phase, it is necessary to adopt a *make-before-brake* approach. In other words, the old connection is torn down only after the new connection has been established, thus yielding to a coexistence phase of the two connections, during which the MT becomes a temporary multi-homed host [5]. The management of a multi-homed host during the execution phase is an open problem, without a universal solution,

[1]The access points are also referred as "points of attachment" by some authors (i.e., [3, 26]).

and, currently, every operating system (OS) has its own solution for this problem [25].

In the considered no-coupling scenario, the handover procedure is initiated by the MT (mobile-initiated handover), without any assistance from the network (unassisted handover) and with full control from the MT (mobile-controlled handover) [17]. Therefore, we adopt a Mobile terminal-Controlled HandOver (MCHO) approach, characterized by the fact that the MT is the only active player in the VHO process [3]. Conversely, in the case of a Network-Controlled HandOver (NCHO), a certain network agent is the initiator and the controller of the handover process [3]. The HHO in cellular networks is a typical example of a NCHO handover.

The algorithms presented here are low-complexity extensions of the hybrid RSSI/goodput VHO algorithm, between UMTS and WiFi networks, originally presented in [13] and recalled, in more detail, in Subsection 2.2. In particular, the original algorithm presented in [13] is based on the estimation of both the received power and the instantaneous goodput available at each network interface, but, as discussed in Subsection 2.1, obtaining a good estimation of the goodput is, from a practical viewpoint, very challenging. Therefore, we modify the original VHO algorithm of [13], to derive a couple of simpler, yet with good performance, VHO algorithms suitable to a real-world scenario. The two low-complexity algorithms are described, respectively, in Section 3 and Section 4, while their performance, evaluated experimentally, are described in Section 5. The experimental results are presented and discussed in Section 6. Finally, concluding remarks are given in Section 7.

Please note that, in the following, the subscripts U and W indicate, respectively, the UMTS and the WiFi network. For the purpose of notational simplicity, the symbol x will be used to indicate a generic interface (U or W). Moreover, the pair of terms WiFi and IEEE 802.11 and the pair of terms UMTS and 3G will be used interchangeably.

2 Preliminaries on VHO Algorithms

2.1 Bandwidth Estimation Techniques

A bandwidth estimation technique aims at estimating, as accurately as possible, the bandwidth offered by a certain network.[2] In our case, the network could be split in two portions: the *local*, between the MT and the access point; and the *remote*, that coincides with the backbone feeding the access point. The end-to-end bandwidth is obviously determined by the minimum of the bandwidths offered by the individual networks. In the case of the UMTS network, the local system portion (i.e., the cell) is certainly the bottleneck, as it is reasonable to expect that the backbone bandwidth will be larger than that offered to the customers. On the other hand, in WiFi networks the quality of the backbone connection is unpredictable by the MT, which, therefore, cannot predict if the bottleneck is the local or the remote portion.

There are two main categories of bandwidth estimation techniques: direct and indirect. The techniques of the first group actively estimate the available bandwidth by sending a train of probe packets across the network, towards a known (either remote or local) destination. Conversely, the indirect methods try to passively estimate the available bandwidth without introducing network overhead and, therefore, they are more appealing.

[2] In this work, the terms goodput are bandwidth are used interchangeably.

In a UMTS network, it is possible, in principle, to indirectly estimate the available bandwidth, by knowing the modulation format and the channel coding technique currently adopted by the Adaptive Coding Modulation (ACM) mechanism. Disappointingly, this information rarely coincides with the truly available bandwidth, since the network operator dynamically assigns (on-demand) the resources to the customers. However, due to the MCHO assumption, the MT has no means to know what the available bandwidth will be in the future.

On the other hand, several studies have shown that the local bandwidth could be indirectly estimated also in IEEE 802.11 networks, by observing the physical and medium access control (MAC) parameters, such as the modulation format, the RSSI, or the Network Allocation Vector (NAV) [9]. The indirect estimation techniques have shown to be sufficiently accurate [15] and they have also the advantage of being non-intrusive. Unfortunately, when the bottleneck is given by the remote network, local information is useless.

It can then be concluded that, in both IEEE 802.11 and UMTS networks, passive estimation of the available bandwidth, through indirect estimation techniques, is not feasible. Conversely, direct techniques can be certainly employed in these networks, since they are independent of the type of network and of the characteristics of the MT. Moreover, these techniques, such as Wbest [16], have shown to be able to obtain an accurate estimate of the end-to-end bandwidth. Despite its attractive features, direct bandwidth estimation techniques have still two critical drawbacks: (i) they are always characterized by a certain degree of intrusiveness; (ii) in order to offer valuable information, they require that the MT is already authenticated to the network of interest. The latter is the major drawback for VHO, since it implies that, for the purpose of proactive estimation of the end-to-end bandwidth (as required by the VHO algorithm described in Subsection 2.2), the MT has to keep alive both previous and new connections, leading to energetic and economical inefficiencies.

2.2 A Starting Hybrid RSSI/Goodput VHO Algorithm

The VHO algorithm proposed in [13] is based on two performance metrics: the received Power (denoted with P) and the GoodPut[3] (denoted with GP), which coincides with the effective bandwidth independently available in each link. This VHO algorithm, illustrated in Figure 1, requires a fresh and reliable estimation of the instantaneous goodput and of the instantaneous received power. These are periodically estimated, considering a constant sampling interval T_{s} (dimension: [s]). While an estimation of the received power can be easily obtained in most cases, the estimation of the bandwidth can be challenging, as preliminary discussed in Subsection 2.1.

We observe that the algorithm illustrated in Figure 1 uses the *instantaneous* received power and an *average* goodput, obtained with proper filtering techniques. More specifically, in [13] the average goodput is computed using two different filtering techniques: (i) weighed Moving Average (MA) and (ii) Exponential Smoothing Average (ESA). In the case of MA filtering, the length of the moving window (in terms of samples), denoted as $K \in \mathbb{N}$, is the only design parameter. In particular, given the sequence of $K+1$ instantaneous goodput samples $\{g_i\}_{i=n-K}^{n}$ till the (discrete-scale) estimation epoch $n \in \mathbb{N}$, the average goodput

[3] In this paper, we consider the goodput as the transmit rate (dimension: [b/s]) at which *data* information is transmitted. Alternatively, the goodput could be defined as the long-term fraction of time during which transmitted *data* packets are successfully received. The throughput should instead be defined as the long-term fraction of time during which (*data* and *control*) packets are successfully received.

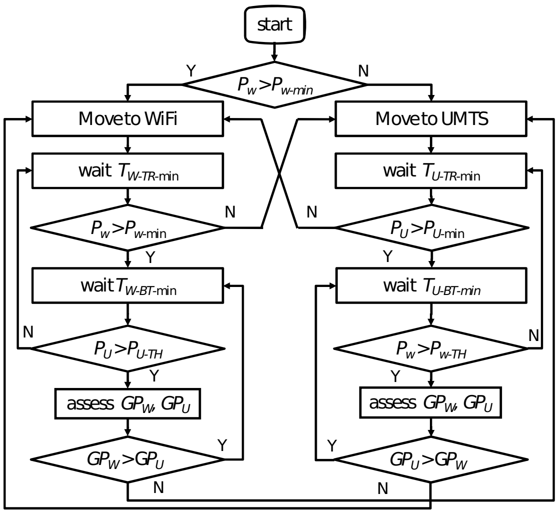

Figure 1. Flowchart of the original VHO algorithm proposed in [13, Fig. 1] (courtesy of T. Inzerilli and A. M. Vegni).

$\mathrm{GP}(n)$ can be expressed as

$$\mathrm{GP}(n) = \sum_{i=n-K}^{n} \frac{g_i}{K}.$$

Assuming that $g_i = 0$, $i < 0$, it follows that $\mathrm{GP}(n) = 0$, $n < 0$. If ESA filtering is considered, then the average goodput can be computed as follows:

$$\begin{cases} \mathrm{GP}(n) = w_1 g_n + w_2 \mathrm{GP}(n-1) + w_3 \mathrm{GP}(n-2) \\ w_1, w_2, w_3 \in [0,1] \\ \sum_{i=1}^{3} w_i = 1 \end{cases} \tag{1}$$

where $\{w_1, w_2, w_3\}$ are real weighing coefficients that can be tuned to obtain the desired filter behavior. Under the assumption that $g_i = 0$, $i < 0$, also with the ESA filter it follows that $\mathrm{GP}(n) = 0$, $n < 0$.

The received power P_x ($x \in \{\mathrm{U}, \mathrm{W}\}$) is used twice. First, it is compared with a threshold $P_\mathrm{x}^{\mathrm{MIN}}$ to decide whether the corresponding network is available. Then, it is compared with the threshold $P_\mathrm{x}^{\mathrm{TH}}$ to decide if this network can be a potential handover candidate. If both networks have a sufficient level of received power (i.e., $P_\mathrm{x} > P_\mathrm{x}^{\mathrm{TH}}$ for both $\mathrm{x} = \mathrm{U}$ and $\mathrm{x} = \mathrm{W}$), the decision algorithm elects the WiFi network if its filtered goodput (namely, $\mathrm{GP_W}$) is higher than that of the 3G network (namely, $\mathrm{GP_U}$). On the other hand, the algorithm selects the UMTS network when $\mathrm{GP_U} > \mathrm{GP_W}$. The waiting times inserted between the various decision blocks are expedient to reduce the ping-pong effect between the two networks. One should observe that, with the exception of the first decision block ($P_\mathrm{x} > P_\mathrm{x}^{\mathrm{MIN}}$), the algorithm outlined in Figure 1 is perfectly symmetric.

The performance of the VHO algorithm proposed in [13] is analyzed using a custom-made Matlab simulator [18]. In particular, we consider a single WiFi cell (with "optimistic" radius equal to 125 m) and a single UMTS cell (with radius equal 500 m—this limited radius is considered only for the purpose of simulation). The simulator considers only the variations of the received power and of the bandwidth, ignoring any physical and MAC

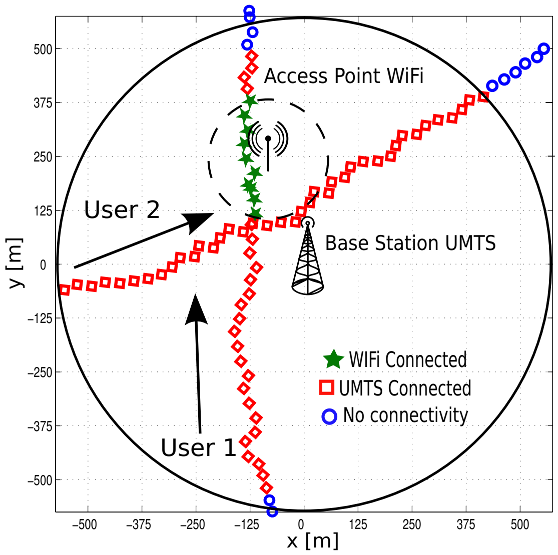

Figure 2. Two sample realization of the VHO algorithm obtained with Matlab simulation results.

layer details. In particular, the received power is a function of the distance between the MT and the access points (according to the Friis formula), while the available bandwidth is a function of both distance and network congestion. In order to simulate different levels of traffic loads at UMTS and WiFi cells, a random number of users (on average, 20), generating traffic according to three different classes of services (asynchronous data, voice, and video streaming), is considered. The users are moving following a pre-determined random direction with a limited speed (between 0.5 m/s and 1.5 m/s).

In Figure 2, simulation results, relative to two significant realizations (paths), are shown. In particular, they refer, respectively, to a first user crossing vertically the simulation area, passing close to the WiFi access point, and to a second user, who follows a path almost tangent to the WiFi cell. The first user, after entering the WiFi cell, can successfully complete the handover from the UMTS network to the WiFi network, since the received power P_{W} is much higher than the considered threshold. On the other hand, the WiFi signal power received by the second user, in passing by the WiFi cell, is close to the threshold: this could lead to a ping-pong phenomenon, but the considered VHO algorithm, owing to the considering filtering approach, prevents it.

3 A Low-complexity RSSI-based VHO Algorithm

The first simplified novel VHO algorithm is derived from the algorithm presented in Subsection 2.2 by applying the following modifications.

- The goodput is no longer considered to make a handover decision. In fact, as explained in Subsection 2.1, indirect estimation does not provide sufficient information, and direct estimation cannot be a feasible solution, because of its economical and efficiency drawbacks.
- The VHO algorithm is asymmetric, as it assigns an intrinsic preference to IEEE 802.11 networks. This is motivated by two reasons. First, WiFi connectivity is currently less

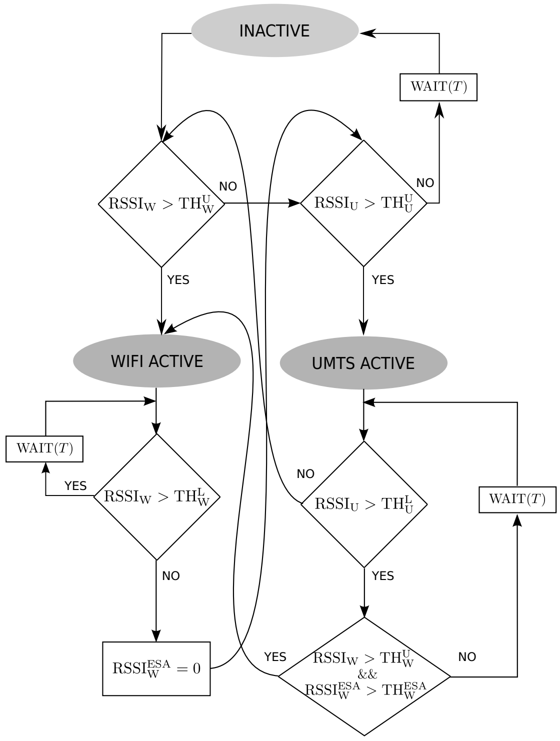

Figure 3. Dataflow of the low-complexity RSSI-based VHO algorithm.

expensive (at least in Italy) than 3G connectivity. Moreover, our experimental results have shown that the bandwidth offered by IEEE 802.11 networks is typically larger than that offered by 3G networks.

- The received power is replaced with the RSSI, as the latter can be measured more easily from the received packets.
- The waiting times between consecutive operations are removed, due to their inefficiency.

We now describe the operations of the novel VHO algorithm, with reference to the dataflow shown in Figure 3. As in the Subsection 2.2, the symbol x is used to represent both types of interface. The algorithm is entirely based on the RSSI measurements. Note that in both WiFi and UMTS cases the instantaneous RSSI values (denoted as $\mathrm{RSSI_x}$) are considered. In the WiFi case, the filtered values of the RSSI (denoted as $\mathrm{RSSI_W^{ESA}}$) are also considered.

The instantaneous RSSI value $\mathrm{RSSI_x}$ (at each interface) is compared with two thresholds, denoted as $\mathrm{TH_x^U}$ and $\mathrm{TH_x^L}$. The *lower* threshold $\mathrm{TH_x^L}$ is used to determine when the RSSI is not sufficient to guarantee a stable connectivity: therefore, it is slightly higher than the corresponding interface sensitivity. Clearly, when $\mathrm{RSSI_x} < \mathrm{TH_x^L}$ the connection on the interface x is torn down. On the other hand, the *upper* threshold $\mathrm{TH_x^U}$ is used to determine if the measured RSSI is sufficient to establish a stable connection. To this end, we assume that $\mathrm{TH_x^U} > \mathrm{TH_x^L}$. The use of two thresholds (per network interface) is the first countermeasure against the ping-pong effect and was historically introduced in the context of cellular networks for managing horizontal handovers [24].

The WiFi RSSI values obtained with ESA filtering can be expressed using (1) and simply replacing the goodput with the RSSI:

$$\begin{cases} \mathrm{RSSI}_{\mathrm{W}}^{\mathrm{ESA}}(n) = v_1 \mathrm{RSSI}_{\mathrm{W}}(n) + v_2 \mathrm{RSSI}_{\mathrm{W}}^{\mathrm{ESA}}(n-1) + v_3 \mathrm{RSSI}_{\mathrm{W}}^{\mathrm{ESA}}(n-2) \\ v_1, v_2, v_3 \in [0,1] \\ \sum_{i=1}^{3} v_i = 1 \end{cases} \tag{2}$$

where $\{v_1, v_2, v_3\}$ are proper weighing coefficients and n is the time epoch. We have chosen the ESA filter because it offers performance similar to the MA filter, but with a more compact structure. The filtering operation is only performed on the WiFi interface, in order to avoid instantaneous peaks on the RSSI of the WiFi network. The $\mathrm{RSSI}_{\mathrm{W}}^{\mathrm{ESA}}$ values are compared to another threshold, denoted as $\mathrm{TH}_{\mathrm{W}}^{\mathrm{ESA}}$. Unlike the instantaneous RSSI, that is used to take forced and quick decisions, the filtered measures of the RSSI are used to make "effective" ABC decisions. Moreover, the use of average measurements is expedient to further mitigate the ping-pong phenomena.

According to Figure 3, the MT can be in three different self-explanatory states: INACTIVE, WiFi ACTIVE, and UMTS ACTIVE. When in the INACTIVE state, the MT measures, with period T_{s} (dimension: [s]), the RSSI level at each network interface. As soon as the first (of the two) RSSI level overcomes its upper threshold, the corresponding interface notifies the event to the VHO manager, triggering the execution of the Authentication, Authorization, and Accounting (AAA) procedure to join the selected network. We observe that if both networks are available, the priority is always given to the WiFi network. If the AAA procedure in the selected network x succeeds, the state of the MT switches from INACTIVE to "x ACTIVE."

Due to the asymmetric nature of the algorithm, the WiFi ACTIVE and the UMTS ACTIVE states have to be treated separately.

When in the UMTS ACTIVE state, the MT periodically (with period T_{s}) compares $\mathrm{RSSI}_{\mathrm{U}}$ with the lower threshold $\mathrm{TH}_{\mathrm{U}}^{\mathrm{L}}$. If $\mathrm{RSSI}_{\mathrm{U}} < \mathrm{TH}_{\mathrm{U}}^{\mathrm{L}}$, the handover manager immediately starts the authentication of the WiFi network, after verifying that $\mathrm{RSSI}_{\mathrm{W}} > \mathrm{TH}_{\mathrm{U}}^{\mathrm{U}}$. If the latter condition is not satisfied, the VHO manager is forced to torn down the UMTS connection and the MT switches to the INACTIVE state. On the other hand, if $\mathrm{RSSI}_{\mathrm{U}}$ remains higher than the threshold $\mathrm{TH}_{\mathrm{U}}^{\mathrm{L}}$, the manager has the opportunity of "quietly" evaluating the condition of the WiFi network, in order to assess the possibility of performing a handover. In particular, the algorithm performs a double check, verifying that $\mathrm{RSSI}_{\mathrm{W}} > \mathrm{TH}_{\mathrm{W}}^{\mathrm{U}}$ and that $\mathrm{RSSI}_{\mathrm{W}}^{\mathrm{ESA}} > \mathrm{TH}_{\mathrm{W}}^{\mathrm{ESA}}$. In case of success, the VHO manager starts to re-route the user traffic on the IEEE 802.11 interface and begins the log-off procedure on the UMTS network.[4] Obviously, in the case of a failure of the double check, the MT is forced to maintain the current UMTS connection returning to the UMTS ACTIVE state.

When the MT is in the WiFi ACTIVE state, the behavior of the VHO algorithm is different from that observed when the MT is the UMTS ACTIVE state. In fact, in this case, until $\mathrm{RSSI}_{\mathrm{W}}$ remains higher than the threshold $\mathrm{TH}_{\mathrm{W}}^{\mathrm{L}}$, the MT is forced to remain in the WiFi ACTIVE state, ignoring the conditions on the UMTS interface. Only when the WiFi connectivity is lost ($\mathrm{RSSI}_{\mathrm{W}} < \mathrm{TH}_{\mathrm{W}}^{\mathrm{L}}$), the VHO manager compares $\mathrm{RSSI}_{\mathrm{U}}$ with the threshold $\mathrm{TH}_{\mathrm{U}}^{\mathrm{U}}$, in order to initiate the AAA procedure in the UMTS network—as

[4] The re-routing of existent connections needed to have seamless connectivity after a handover is a problem not addressed in this work. Therefore, after a handover the pre-existent user connections will be likely interrupted.

already explained, the intrinsic preference for the WiFi network is only motivated by real-life experience. Before the AAA operation is started, the filtered value of the RSSI is set to zero in order to prevent rapid re-connections to the WiFi network.[5] Finally, due to the long duration of the WiFi AAA procedure, during the UMTS ACTIVE → WiFi ACTIVE transition, there are some hidden transitional states, not shown in Figure 3 for the sake of simplicity. However, one should take into account the possibility of a failure of the AAA procedure: this will produce a back transition towards the UMTS ACTIVE state or towards the INACTIVE state.

4 A Simplified Hybrid RSSI/Goodput VHO Algorithm

While the VHO algorithm presented in Section 3 is based on the implicit assumption that, when available, an IEEE 802.11 network always offers a better service than a 3G network, we now propose another VHO algorithm that builds on the previous one, but makes also use of goodput information. This extension is motivated to avoid switching from the UMTS network to the WiFi network when the latter offers a smaller effective bandwidth. Although this extension goes back to the approach proposed in [13], the complexity will be kept lower.

The dataflow of the new hybrid algorithm is shown in Figure 4. By comparing this dataflow with the dataflow of the RSSI-based algorithm (Figure 3) there is an additional state, the WiFi CONNECTED/UMTS ACTIVE state (highlighted at the bottom), where the MT is authorized in both networks. The presence of this state is expedient to estimate the bandwidths of both networks. The bandwidth is estimated by measuring the time necessary for downloading a 400 Kbyte size file from a remote host (for the ease of simplicity, the file is hosted by a Google server). The bandwidth estimation method is explained in more detail in Section 5.

Due to the asymmetric nature of the algorithm, the MT can move towards this new state only from the UMTS ACTIVE state. In particular, during this transition the MT performs the AAA procedure towards the IEEE 802.11 network. Then, the MT remains in the WiFi CONNECTED/UMTS ACTIVE state for all the time needed to estimate the goodput of both networks. As soon as the new measurements, denoted, respectively, as $\mathrm{GP_W}$ and $\mathrm{GP_U}$, are available, the VHO algorithm decides to switch to the WiFi ACTIVE or to come back to the UMTS connected state. In the latter, the MT disconnects from the IEEE 802.11 network and resets its filtered RSSI, in order to reduce the waste of resources, as previously explained in Section 3. From a practical point of view, when $\mathrm{RSSI_W^{ESA}} > \mathrm{TH_W^{ESA}}$ the goodput is periodically estimated with a variable (but short) period, given by the sum of the time necessary to complete the AAA procedure and the time necessary to fill again $\mathrm{RSSI_W^{ESA}}$.

Finally, due to the typically long times needed by the WiFi AAA procedure, during the UMTS ACTIVE → WiFi CONNECTED/UMTS ACTIVE transition there are some hidden transitional states, not shown in Figure 4 for the ease of simplicity. In particular, when the AAA procedure fails, the transition to the WiFi CONNECTED/UMTS ACTIVE state cannot happen and it is necessary to come back to the UMTS ACTIVE state.

[5]Note that the same result can be obtained by inserting a delay with fixed duration $T \gg T_s$. However, our solution allows to continuously check the $\mathrm{RSSI_U}$ which cannot be done with the fixed delay.

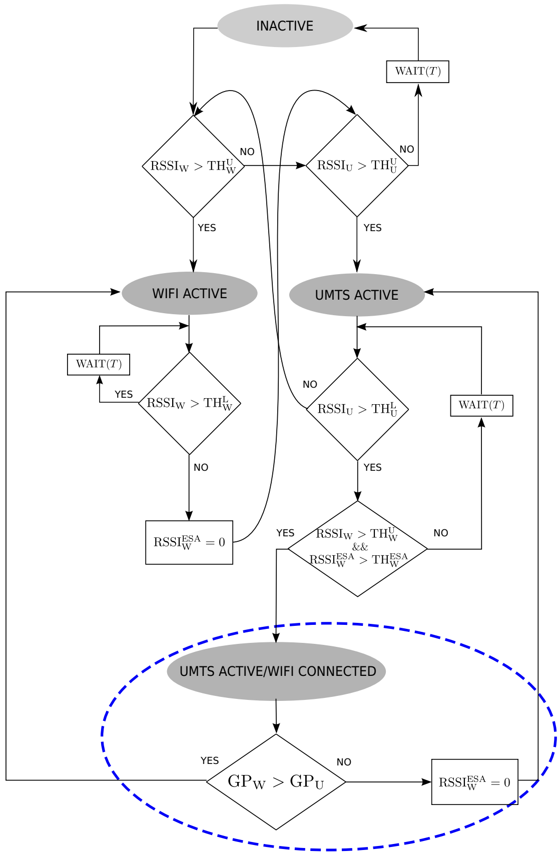

Figure 4. Dataflow of the low-complexity hybrid RSSI/goodput-based VHO algorithm.

5 Experimental Setup

The main goal of this work is the test of our VHO algorithm in a realistic environment, leveraging on commercially available connectivity service providers and using standard MT devices. In particular, we perform our test using a notebook running Windows 7 OS, equipped with a Broadcom IEEE 802.11g compliant network interface, and integrated by a UMTS compliant USB Huawei dongle.

IEEE 802.11 connectivity is provided by a hot-spot of one of the biggest Italian Wireless Internet Service Provider (WISP), namely Guglielmo S.r.l. [7]. The hotspot is composed by a Browan IEEE 802.11 access point, integrated with a captive portal, while the Authentication Server (AS) is remotely located, as in the standard WISP Roaming (WISPR) configuration [4]. The proprietary AAA procedure, sketched in Figure 5, foresees two additional message exchanges with respect to the WISPr directives [4], thus increasing the time needed to complete the AAA procedure. The UMTS connectivity was instead offered by the Public Land Mobile Network (PLMN) of Telecom Italia, one of the most important Italian mobile operator. The sequence of messages needed to complete the AAA procedure in a typical 3G network is sketched in Figure 6.[6] We observe that in both cases we have

[6]The AAA sequence adopted by Telecom Italia is not publicly available, but we are confident of its compliance with the 3GPP recommendations.

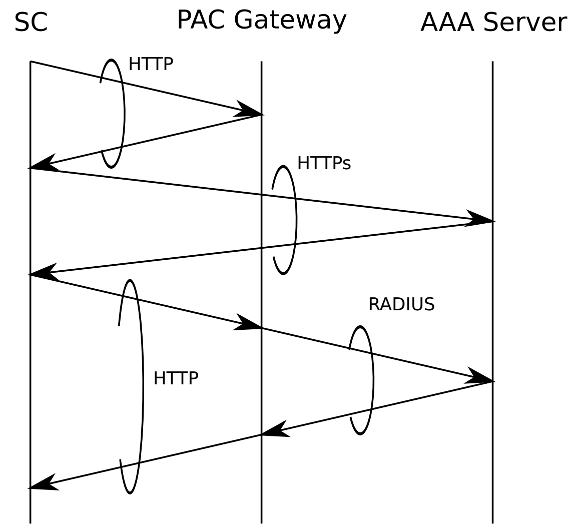

Figure 5. Sketch of the proprietary AAA mechanism used in the Guglielmo IEEE 802.11 network.

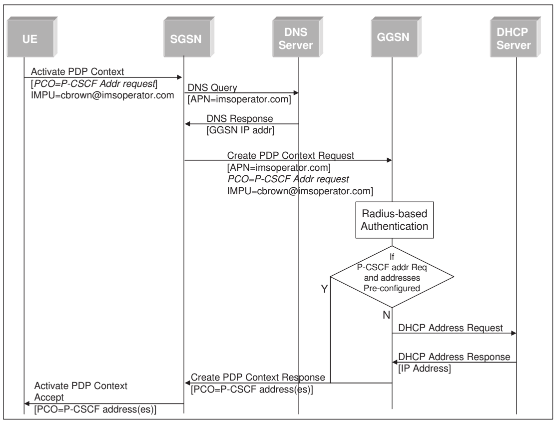

Figure 6. Sketch of the common AAA mechanism used in the UMTS networks.

not a direct control on the traffic generated by other users.

We have implemented the VHO mechanism described in Section 2 and its novel low-complexity modifications (presented in Section 3 and Section 4) on top of a so-called Smart Client (SC) software. According to the WISPR directives [4], a SC is an application studied for enhancing the user experience, making automatic the AAA procedure. The current implementation of the SC runs on a Windows 7 platform,[7] but porting on other development platforms (e.g., Android, iPhone, etc.) is the subject of current work. Basically, the goal of the SC is that of constantly monitoring the status of the available connections and executing the VHO algorithm described in Section 2. Additionally, once the MT initiates a VHO, the SC automatically has to take care of the proper AAA procedure. The SC controls both network interfaces, working with every IEEE 802.11 device able to provide real-time RSSI information, and with every 3G device (e.g., modem 3G, dongle USB) that supports the Microsoft Remote Access Service (RAS) API [1]. Due to the *make-before-break* approach,

[7]The SC also supports the Microsoft Vista OS.

Table 1. Parameters of the VHO algorithm.

Parameter	Value
v_1	0.08
v_2	0.15
v_3	0.77
T_s	0.5 s

the SC has also to manage the routing functionalities of the OS, in order to make non-critical the multi-homed situation that appears after the authentication with the second network interface [5, 25].

The parameters of the VHO algorithm used in the experiments are summarized in Table 1, where $\{w_i\}$ are the weighing coefficients used to compute $\mathrm{RSSI}_\mathrm{W}^\mathrm{ESA}$ according to (2). Our experiments were conducted in a building within the Department of Information Engineering of the University of Parma. The nearest UMTS base station is placed roughly at 1 Km from the building, and it guarantees a 2 Mbit/s downlink (384 kbit/s uplink) bandwidth, being compliant with the UMTS specifications. We have placed the hotspot in the WASN Lab (a room within the Department of Information Engineering), at 1 m above the ground. The hotspot is fed by an optical fiber network with 100 Mbit/s of symmetric bandwidth, but the hotspot imposes a symmetric limit on the available bandwidth equal to 2 Mbit/s, to replicate the conditions guaranteed to typical customers—despite the identical nominal downlink UMTS bandwidth (2 Mbit/s), the WiFi network has often outperformed, in our tests, the UMTS network. The test were performed by walking through the building, keeping the notebook on our hands and measuring (i) the time needed to perform the handover and (ii) the goodput variations. The tests were always performed during working hours, in order to obtain results associated with realistic daylife situations. Hence, we have measured the classical following metrics.

- *Handover time*, which refers to the duration between initiation and completion times of the handover process. The initiation corresponds to the instant when the VHO manager begins the AAA procedure to connect to a given network. In particular, we consider the instant at which the first data packet routed via the new connection is successfully acknowledged by the remote destination.
- *Goodput*, which refers to the data rate delivered to the mobile terminals on the network [26]. In order to measure the end-to-end goodput, we periodically download a 400 Kbyte file from a remote server (hosted by Google), using the HTTP over TCP protocol. Since the goodput test is performed during a walk, there is a tradeoff between the duration of the download and the accuracy of the estimate. In fact, the distance covered during a single test is inversely proportional to the effective data rate. In order to limit this effect, we impose a double timeout over the download test: (i) a timeout of 1 s over the establishment of the HTTP connection; (ii) a timeout of 1 s over the data reception from the remote server.

Table 2. Handover time for the VHO algorithm presented in Section 3 (mean, standard deviation, minimum, and maximum).

	WiFi → UMTS	UMTS → WiFi
Mean [s]	4.13	5.43
Std. Deviation [s]	1.76	3.30
Max [s]	10.72	15.69
Min [s]	2.41	1.22

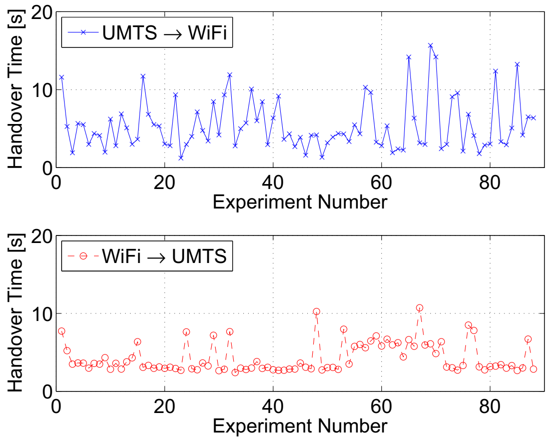

Figure 7. Instantaneous handover time of the VHO algorithm presented in Section 3.

6 Experimental Results

6.1 Low-complexity RSSI-based VHO Algorithm

In this subsection, we present the experimental results obtained while testing the VHO algorithm, introduced in Section 3, in the scenario described in Section 5. The handover time is automatically measured by the SC, and we average over 20 different runs, where in each run the path in the building and the corresponding handover instant have changed. In practice, we have collected the handover time values relative to 88 UMTS → WiFi and 88 WiFi → UMTS transitions.

In Table 2, the average handover time is shown (with corresponding standard deviation) for the WiFi → UMTS and the UMTS → WiFi transitions, respectively.

In Figure 7, the instantaneous values of the handover time are shown as functions of the considered transitions. From Figure 7, it emerges that WiFi and UMTS networks have very different behaviors. In particular, the UMTS network exhibits an almost constant handover time, around its average of 4.13 s (Table 2). However, there is a relevant number of samples also in the region between 5 s and 10 s, while the few values above 10 s can be considered as outliers. On the other hand, the WiFi network is definitively worse than the UMTS network, since it presents a higher average value of 5.43 s (Table 2) and a much greater standard deviation. At the same time, one should observe that the minimum value is very small.

For the sake of completeness, we have also estimated, upon time discretization in 0.25 s

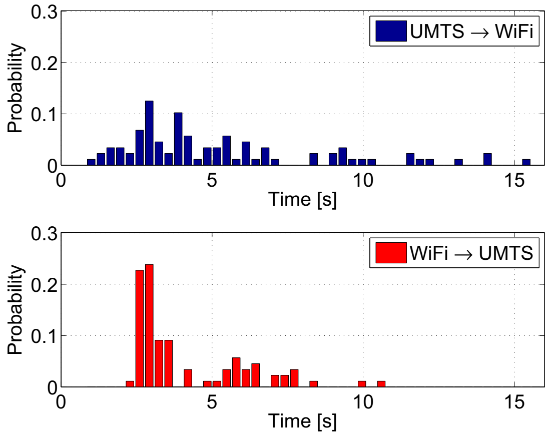

Figure 8. PMFs of the handover time of the VHO algorithm presented in Section 3: from UMTS to WiFi (upper) and from WiFi to UMTS (lower).

bins, the Probability Mass Function (PMF) of the handover time. The obtained PMFs, for the two VHO operations, are shown in Figure 8. Observing the upper subfigure in Figure 8, it seems that the handover time from the UMTS network to the WiFi network spreads between 1 s and 10 s. This relatively high variability has several motivations. First of all, in order to save energy, the MT is supposed to logout from a given network, once the VHO manager has selected the other network. Sometimes (more often in the WiFi network) the logout fails, and the remote authentication server keeps the authentication state for a certain timeout (roughly 60 s), before to automatically logout the user. In these cases, the UMTS → WiFi transitions can experience a small handover time since the MT is de-facto already authenticated to the network. Moreover, while the authentication procedure at MAC layer has, practically, no impact, the DHCP release of an IP address might be source of randomness. In fact, the RFC recommends that the demanding host has to wait a random time in the interval (0 s,10 s), determining a strong unpredictably. Moreover, the DHCP mechanism is managed by the OS itself, making it difficult to understand its impact. Finally, when the WiFi signal is received close to (metal) furniture, the RSSI experiences large oscillations that can slow down the AAA procedure. Conversely, the RSSI of the UMTS network is more stable, and it has a small probability of experiencing such large variations.

From the results shown in the lower subfigure of Figure 8, it can be observed that the handover time from the WiFi network to the UMTS network is generally shorter and more predictable (i.e., its PMF is more concentrated) than that in the opposite direction. However, due to the no-coupling and the lack of any optimization, the handover times are long, also in the case of transition to the UMTS network. This result has somehow to be expected, since the proposed VHO algorithm is designed to be used for slowly mobile MTs, e.g., people moving from a place to another, but not in a highly mobile scenario.

In order to measure the goodput, we focus on a single walking path, chosen among the experimental data set. The selected path is shown in Figure 9, along with the layout of the environment where the tests were performed (a portion of the Department of Information Engineering of the University of Parma). The bold solid lines represent reinforced concrete walls, that are source of a strong signal attenuation. In correspondence to a glass window or a door (where the bold solid lines are interrupted), the signal attenuation is clearly much

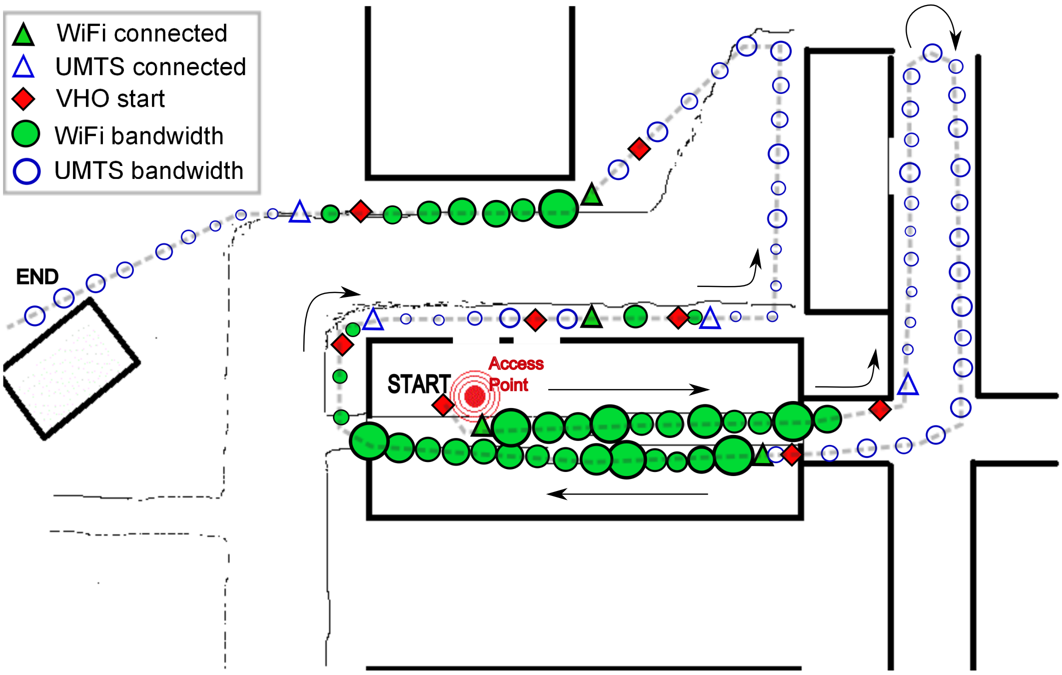

Figure 9. Goodput improvement using the low-complexity RSSI-based algorithm presented in Section 3.

weaker. The path followed by the user is represented by a dashed line and is delimited by the words "start" and "end." The circles drawn along the path represents the measured available goodput, which is proportional to the diameter of the circle. Filled circles indicate connection to the IEEE 802.11 network, while in correspondence to empty circles the MT is connected to the UMTS network. A (filled) diamond denotes the beginning of a VHO procedure, while the triangles indicate when the procedure has been successfully completed. The filled triangles indicates that the VHO procedure has established a WiFi connection, while empty triangles denotes the establishment of a UMTS connection. We stress the fact that between diamonds and triangles the MT is still connected with the old network, in order to avoid loss of connectivity before finalizing the VHO. Finally, the distance between the circles is directly proportional to the duration of the bandwidth test and, hence, it is inversely proportional to the available bandwidth.

Observing Figure 9, it can be concluded that the proposed VHO algorithm works well also in a complicated hybrid indoor/outdoor scenario, while walking between reinforced concrete walls. In particular, the dimension of the circles show that the goodput offered by the WiFi network, despite its high variability, is generally higher than that offered by the UMTS network. The UMTS network, instead, has shown a very homogeneous behavior along the entire path (both indoor and outdoor). From Figure 9, one can also observe that the presence of a window just in front of the WiFi access point is detrimental for the VHO algorithm. In fact, while walking in front of the windows, the MT receives a very strong WiFi signal for several meters, and then the VHO quickly invokes the handover procedure. Unfortunately, because of the long duration of the AAA to the WiFi network, the MT becomes connected to the WiFi network too late, when the user has already lost its "window" of good connectivity. We remark that this particular situation could not be

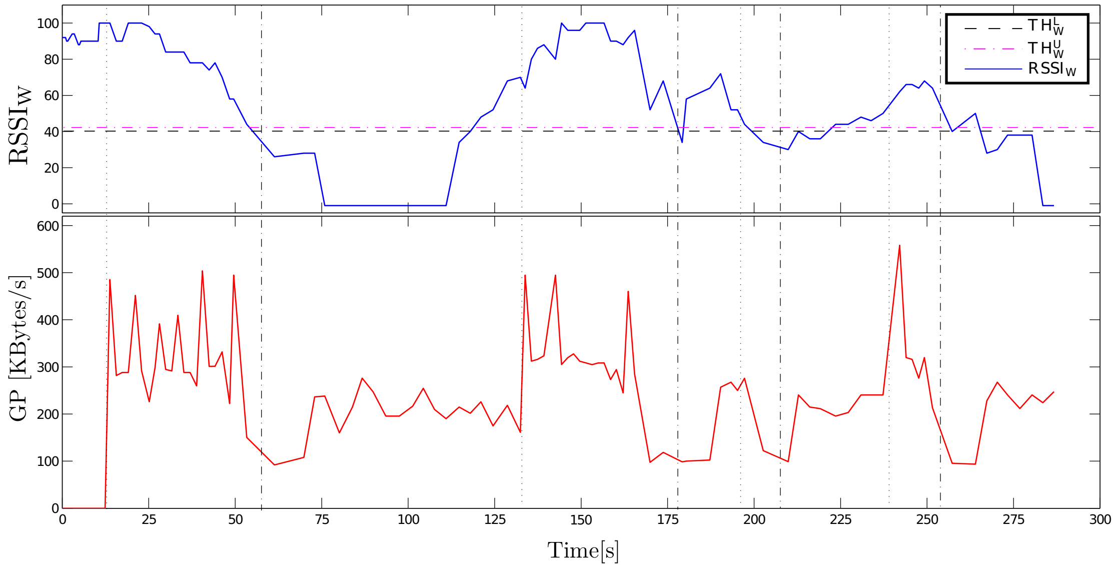

Figure 10. RSSI and goodput experienced by the MT following a sample path using the low-complexity RSSI-based algorithm.

counter-acted by our VHO algorithm. In fact, in order to prevent the two consecutive handovers that happen in front of the window, it would be necessary to change the coefficients of the ESA filter, thus yielding a higher handover latency. In other words, coping with this very particular case would degrade the performance in other circumstances.

In order to give more insights on the algorithm behavior, in Figure 10 we show[8] $RSSI_W$ (in the upper subfigure) and the goodput (in the lower subfigure) experienced by the MT as functions of time. Note that one discrete time corresponds to a position along the path shown in Figure 9. The goodput has a bimodal behavior, since it has a floor at roughly 800 Kbit/s, corresponding to the 3G connection, while it increases to a higher level as soon as the MT can use the WiFi connection. More precisely, the IEEE 802.11 goodput has a very irregular shape, but it is higher than that of the 3G network almost always. Looking at both Figure 9 and Figure 10, one can observe that, inside the building where the WiFi access point is placed, the RSSI of the WiFi signal varies slowly and the goodput is more regular and higher. On the other hand, in correspondence to the windows, when the handover procedure starts frequently, the goodput is more irregular and it is difficult to appreciate the benefits offered by a VHO solution.

6.2 Low-complexity Hybrid RSSI/Goodput VHO Algorithm

The performance of the hybrid VHO algorithm has been analyzed considering a slightly different path in the experimental scenario, shown in Figure 11. In this particular scenario, the assumption of a larger WiFi network bandwidth with respect to that of the UMTS network, is not satisfied. As in Figure 9, the diamonds in Figure 11 indicate the beginning of the handover procedure. In this case, the handover may fail with a higher probability, due to the additional goodput check. This motivates the presence, in Figure 11, of several diamonds not followed by triangles.

[8]We omit $RSSI_U$, since it is always higher than TH_W^L and practically constant.

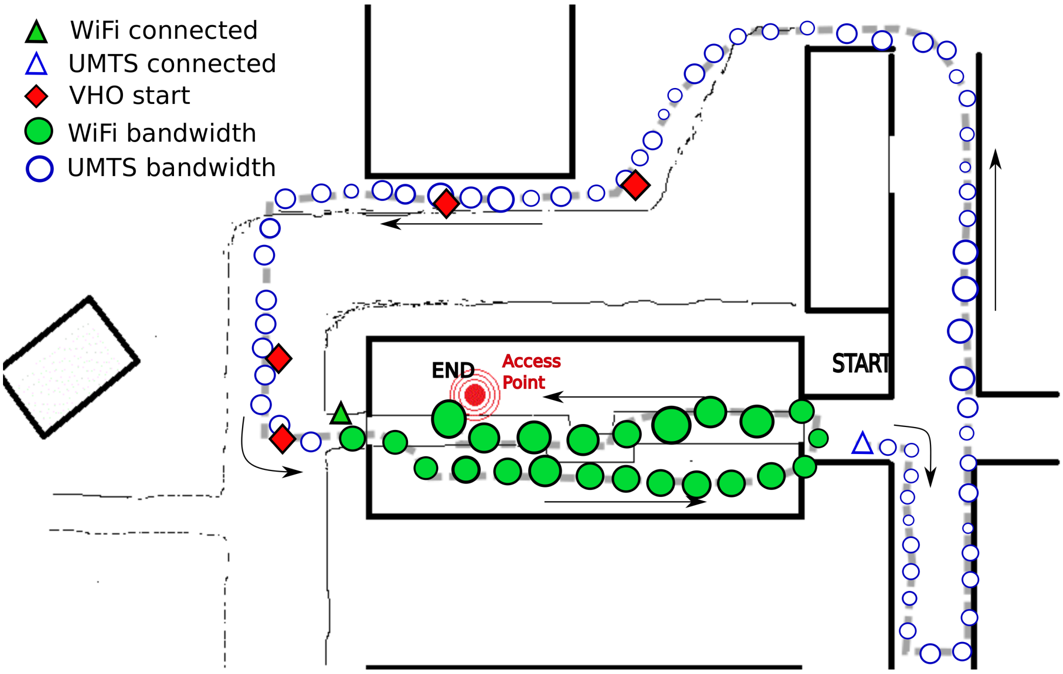

Figure 11. Goodput improvement using the low-complexity RSSI-based algorithm presented in Section 4.

In Figure 12, the RSSI and goodput, relative to the VHO algorithm introduced in Section 4, are shown as functions of time. For the sake of clarity, a direct comparison with the RSSI-based VHO algorithm is also considered. In the upmost subfigure, $\mathrm{RSSI_W}$ is shown together with the corresponding upper and lower threshold; in the lowest subfigure, the estimated goodputs $\mathrm{GP_W}$ and $\mathrm{GP_U}$ are directly compared; finally, in the middle subfigure the overall goodput guaranteed by the RSSI-based VHO algorithm (denoted as GP) and the hybrid VHO algorithm (denoted ad GP^H) are directly compared. According to the results in Figure 12, in the initial phase the MT is disconnected from the WiFi network, because the received power is too low. At a given point of the path, $\mathrm{RSSI_W}$ starts to quickly increase, and then it soon overcomes the threshold $\mathrm{TH_W^U}$. A few seconds later, therefore, the filtered RSSI also goes over its threshold ($\mathrm{RSSI_W^{ESA}} > \mathrm{TH_W^{ESA}}$). At this moment, the RSSI-based VHO algorithm begins the handover to the WiFi network, ignoring the fact that the effective goodput available in the WiFi network is lower. On the other hand, in the case of the hybrid VHO algorithm, the MT starts the bandwidth estimation process, after which it decides to keep the UMTS connection because it becomes aware of the guaranteed higher goodput. In other words, the hybrid VHO algorithm has shown to have better goodput performance than that of the RSSI-based algorithm, at the cost of a slightly longer handover time and a slightly higher complexity. These prices to be paid are due to the presence of a double connectivity situation, which requires to properly configure the OS routing table, in order to perform the bandwidth test in both networks, without penalizing the user.

In terms of handover time, the hybrid VHO algorithm has shown similar performance to the RSSI-based one, the only difference being a longer handover time in the UMTS $\rightarrow$ WiFi transition because of the time needed to perform the bandwidth test. The additional delay

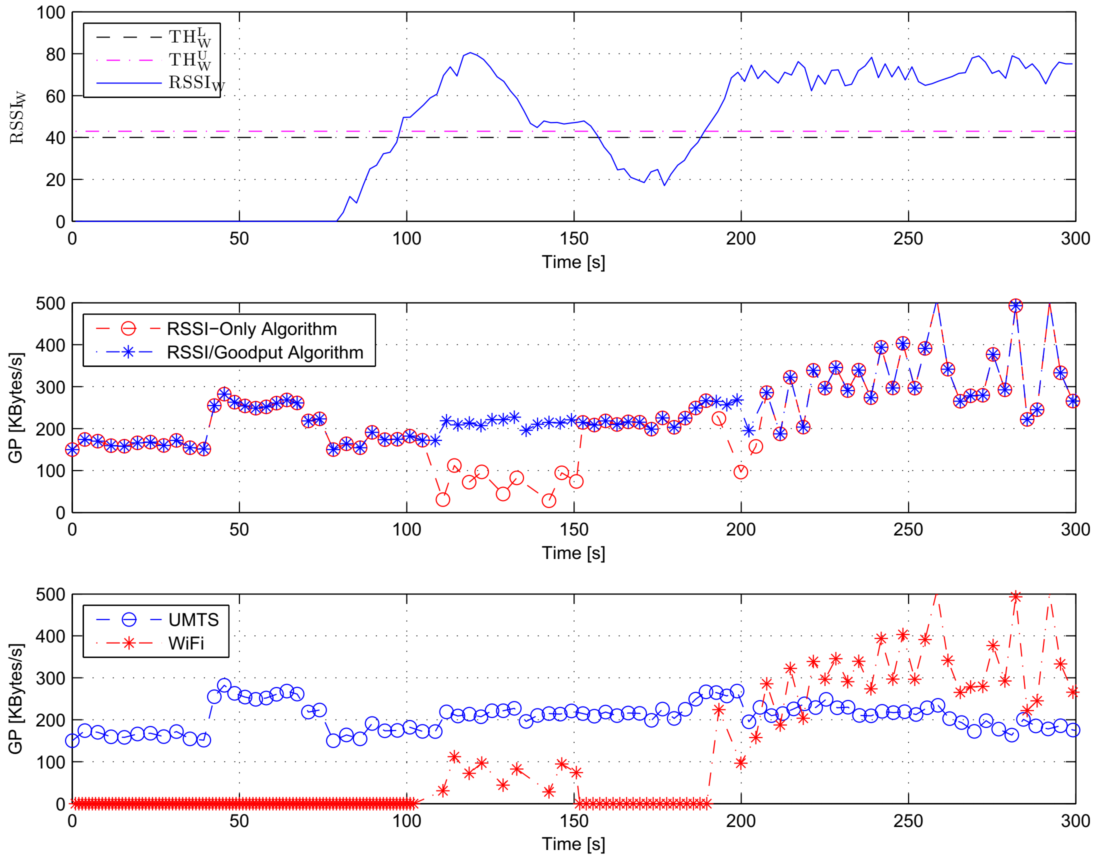

Figure 12. RSSI and goodput experienced by the MT following a sample path using the hybrid RSSI/goodput VHO algorithm.

is upper bounded by the sum of the two timeouts introduced in Section 5 (HTTP connection and data reception), which is approximately equal to 2 s in the standard configuration.

7 Conclusions

In this paper, we have proposed two simplified novel VHO algorithms (the first relying on RSSI measures and the second on RSSI and goodput measures) and analyzed their performance experimentally. It has been shown that the VHO procedure in loosely-coupled heterogeneous networks experiences a long handover time, mostly due to the latency induced by the AAA procedures currently under use in IEEE 802.11 and 3G networks. This problem is exacerbated in the handover from UMTS to WiFi networks. The proposed VHO algorithms, nevertheless, are effective in the presence of pedestrian mobility, e.g., when a user walks keeping his/her notebook/tablet in his/her hands. Although the goodput is difficult to accurately estimate in real environments, the second proposed "hybrid" VHO algorithm leverages on infrequent periodic goodput estimation to guarantee ABC conditions to the user.

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