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Context-aware network selection in heterogeneous wireless networks

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ABSTRACT

Today, most handheld devices including smartphones, tablets and notebooks are equipped with Wi-Fi, Bluetooth, LTE/4G radio interfaces that can allow connections to the Internet and other devices. However, given the properties changes of the radio environment and user mobility, an open question still lies in how to select the best access network interface, considering that the availability and characteristics of an access network will change in time. This paper describes a new intelligent interface selection mechanism based on analysis of contextual information obtained from the user, network environment, and device. To select the best available wireless network, the mechanism, named as CANS (Context-Aware Network Selection), allows for dynamic decision-making during the operation of a mobile device, taking into account different metrics such as price, local network capabilities, user preferences, and the mobile terminal capabilities. The evaluation of the proposed mechanism in a real environment shows that the adoption of selection strategies enables the best exploitation of the advantages on multiple access technologies, achieving a reduction in device power consumption and financial cost.

1. Introduction

The Internet is becoming well known for its services such as email, instant messaging, forums, social networks, voice over IP communication, video conferencing, and video lectures, among others. Access to such services has become more frequent by means of personal devices equipped with multiple wireless network interfaces like LTE, Wi-Fi, and Bluetooth.

One of the main characteristics desired is that these different access networks can work together in order to offer a satisfactory experience to users with the best bit rate, uninterrupted connectivity, and transparent mobility. In other words, the end-user wants to select the best available network at a given time, a concept defined as "Always Best Connected" (ABC) [1].

The literature around ABC networks [1–4] contains numerous network selection strategies that aim to choose the optimal access network and to provide seamless handover. All of these approaches provide a unified interface management strategy than trying to consider the specificity of each wireless technology covered by its solutions. However, in practice, the simple introduction of a new access network technology, or even the updating of existing technology is frustrated by the lack of modularity of the proposed approaches. Moreover, considering user mobility and radio environment variability, the availability and characteristics of an access network will change with time and are highly dependent on localization. As a result, the network access dynamic selection process will be necessary for any mobility management mechanism, responsible for maintaining session connectivity when the user moves or when the characteristics of available access networks change [2].

For this reason, context-awareness is the key ingredient in a solution development process that allows computing devices to take appropriate and timely decisions for users [4,5]. Context is any information that can be used to characterize the situation of an entity (person, place, or object), which is considered relevant to the interaction between a user and an application [3].

In particular, contextual information[1] is an essential part of a global roaming process in environments consisting of multiple wireless networks. Such systems must adapt to changes and user context variations, such as location, device capacity, characteristics of existing access interfaces on devices, network connectivity levels and application requirements.

Due to the diversity of the factors, it is very difficult to select the appropriate network and access interface for the user. The most traditional handoff mechanism uses received signal strength (RSS) as

[1] The term 'context' implicitly provide the meaning of 'information' according to the definition provided by [3]. Therefore, it is inaccurate to use the term 'context information' where 'information' is explicitly mentioned. However, research community and documents on the web frequently use the term 'context information'. Therefore, we also use both terms interchangeably.

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the only parameter for a handoff decision. However, in heterogeneous network environments, the use of a metric for handoff decision-making is not efficient [6]. To work around this problem, some handoff vertical decision algorithms consider multiple parameters together with the RSS metric such as Simple Additive Weighting (SAW) [7], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [8], and Analytic Hierarchy Process (AHP) and Gray Relational Analysis (GRA) [9]. These methods are simple and easy to implement, but inefficient in real-time applications [6].

In an attempt to make more efficient and intelligent decisions, some works have suggested the use of machine learning techniques such as neuro-fuzzy supervised learning approach [9], fuzzy logic method [10], and Markov decision process [10] to effectively improve the accuracy of vertical handoff decisions. Other works suggest the use of context-aware strategies to synthesize the networks and terminal information, as in [5,11–13].

To overcome the problems mentioned above, this paper proposes a new mechanism for the selection of access networks based on the user and device context analysis. This mechanism, named Context-Awareness Network Selection (CANS), is able to select the best communication interface based on the analysis of information collected from device usage, user displacement velocity, bandwidth consumption, and device energy.

The proposed mechanism allows that the user take advantage of access networks at any point time by choosing the most suitable network interface including the cellular network (e.g. UMTS and LTE), local area networks (e.g. IEEE 802.11 a/b/g/n) and also personal area network (e.g. Bluetooth). For instance, at home, a user could use their Bluetooth interface to access the internet (e.g. via ecodroidlink[2]) to save energy or even to reduce their monthly mobile costs.

Unlike of existent approaches, CANS is composed of specialized management modules dedicated to every network interface. This modularity makes our mechanism scalable allowing that the interface management strategies can evolve over time with the possibility of adding new modules (network interfaces) when needed. The main contributions of this paper are as follows:

1. Three new strategies for selection and management of following interfaces: Bluetooth, Wi-Fi and LTE/4G. These strategies aim to select the most appropriate networks for each access technology and manage the activation and deactivation of the interface based on context information.
2. A new interface selection algorithm based on analysis of user context information and device. The handoff decisions are based on explicit user-defined rules, i.e., policies. The algorithm identifies the current context and considers the tradeoff between different characteristics of the network such as bandwidth, access cost, and power consumption.
3. A new API for development of vertical and horizontal handoff strategies. The CANS API aims to help developers and researchers to develop new solutions and improvements in the handoff procedure. Such contribution is important so that more strategies can be discussed, implemented, and evaluated in real experimentation environments.
4. An application using the interface selection strategies, handoff decision algorithm and the proposed API. This application employs and evaluates the strategies for selection and management of interfaces on the user's mobile device, functioning as an extension to the native network manager of the operating system. Performance of our proposed mechanism is evaluated in a real environment. Numerical results show that the CANS mechanism obtains good performance and allows for dynamic decision-making during the operation.

[2] EcoDroidLink uses your home/office Internet router as the internet source (via a LAN cable), providing internet to Android phones and tablets via Bluetooth [http://www.clearevo.com/].

The rest of the paper is organized as follows. Section 2 provides an overview of recent work on vertical handoff decisions in heterogeneous networks. Section 3 describes our strategies for selection and management of interfaces and the handoff decision algorithm. Prototype and implementation issues are discussed in Section 4. The performance-evaluated results are presented in Section 5. Lastly, conclusions and directions for future work are given in Section 6.

2. Related work

The handoff procedure can be characterized in three phases [2]: information acquisition, handoff decision-making, and handoff execution. The information acquisition phase provides the necessary information for the evaluation process and selection of destination network. The handoff decision-making phase is responsible for implementing the selection strategies. Finally, the handoff execution phase effectively carries out changes to the new network access. In the handoff decision phase, a variety of access network characteristics such as throughput, availability, file transfer delay, reliability, power consumption, bandwidth, cost of service and user mobility have been considered in the decision-making schemes [4–28]. Such schemes have been designed based on different decision-making methods and, in most of them, the evaluation of the candidate network becomes a multi-criteria decision-making problem that involves a number of parameters and complex trade-offs between conflicting criteria.

One of the most widely used schemes to realize the network interface selection and handover decision is Multiple Attribute Decision Making (MADM). MADM algorithms refer to choose an option from a finite set of alternatives that are characterized in terms of their attributes. The most popular classical MADM methods are: (i) SAW (Simple Additive Weighting) [8], where the overall score of a candidate network is determined by the weighted sum of all the attributes values; (ii) TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [16], where the chosen candidate network is the one that provides the closest scores to an ideal solution; (iii) AHP (Analytic Hierarchy Process) [9] decomposes the network selection problem into several sub-problems and assigns a weight value for each sub-problem and GRA (Gray Relational Analysis) is used to rank the candidate networks and to select the one with the highest ranking. Similar to TOPSIS, GRA uses a score to describe the similarity between each candidate network and the ideal network. There are several other vertical handover decision algorithms that rely on a cost function or a utility function to calculate the cost of possible target networks from the available ones [4,25,26]. The basic idea of these algorithms is to choose a combination of decision making parameters for the network such as RSS, network coverage area, available bandwidth, service cost, reliability, security, and battery power, and define a cost function based on these factors to evaluate the performance of target networks.

Artificial intelligence approaches such as Fuzzy Logic and Artificial Neural Networks (ANN) has been used to improve the performance of handover in terms of throughput, latency, or unnecessary handovers. Generally, the fuzzy logic concept is used to combine and evaluate multiples criteria simultaneously i.e., the vertical handover decision is formulated as a Fuzzy MADM [17–19]. For instance, Jun et al. [20] propose a fuzzy inference system using input parameters of RSS, available bandwidth and the distance from the access point, to select an appropriate network and make a handover decision towards that. Similarly, a neural network has been successfully used to predict the behavior of the system in handover scenarios. Nasser et al. [21] propose a neural network based approach that retrieves network features that are used as attributes to feed to a neural network that is able to select the most appropriate wireless network. Although the Intelligent based Schemes (fuzzy logic and ANN) have been used to overcome the issues of handover performance they have certain disadvantages such as insufficient details on training process and parameter selection. Moreover, the algorithm suffers from training delay and system complexity is increased.

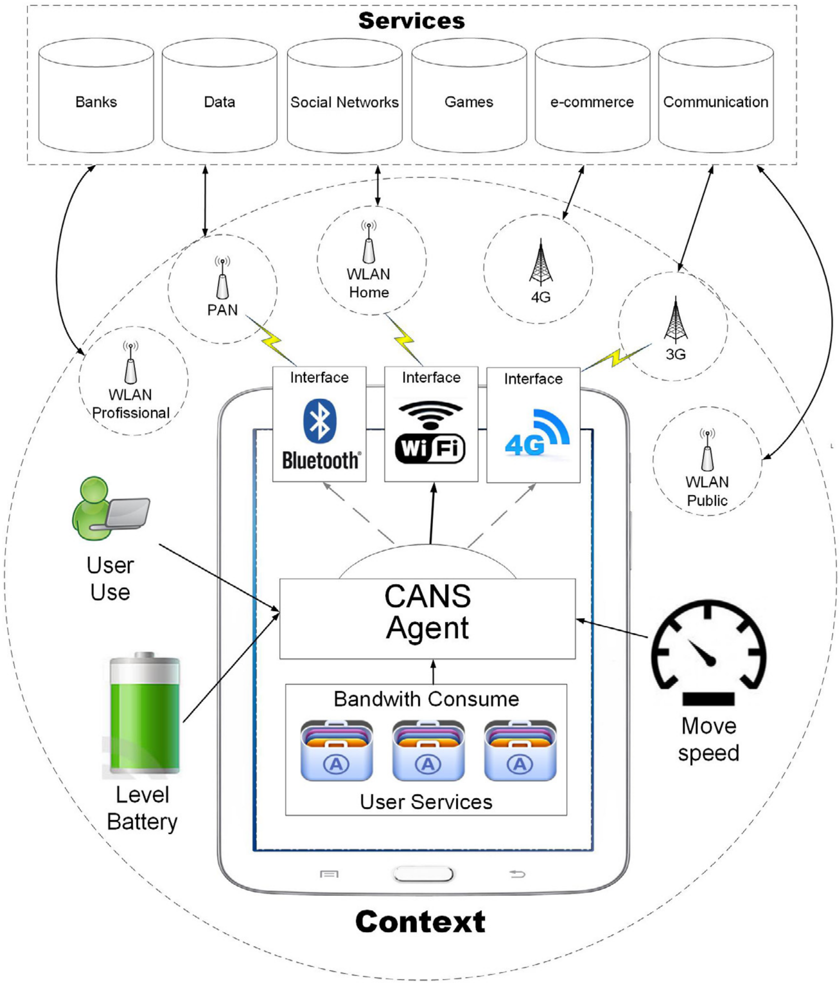

Fig. 1. CANS overview.

A context-aware handover procedure is one in which the handoff decision is selected based on the knowledge of the context information of the mobile nodes and the network. This information may include capacity, location, user preferences, network and user QoS, and coverage. Wei et al. [22] describe a mobile agent based handover decision mechanism in which, the contextual information coming from various parts of the network about the mobile nodes location changes and QoS of the current and available networks are used at the decision point. The QoS-aware network selection relies on Analytic Hierarchy Process (AHP) method that assists in applying user-perceived QoS for an optimal handover. Bi and Muntean [23] also propose a user location-aware network selection solution which aims at improving content delivery based on the existing network performance-related information and mobile user location and speed, the network that offers the best support for content delivery along the user path is selected as the target network and the handover is triggered. Mokhesi et al. [24] use a multi-criteria decision making model and a Bayesian Belief framework to support QoS-based mobility in the context of Bluetooth and WiFi networks. Handover decisions consider user and application preferences and a utility function that evaluates the cost of network changes.

Although there have been various vertical handoff algorithms proposed in the literature, our work differs from others by offering a modular framework. In general, the vertical handoff solutions applies a unique strategy for all the wireless access interfaces. The proposed solution applies different network selection strategies that are adequate to the user's context. Each network selection strategy aims to previously deliver the connected access interface and to be available for the interface selection strategy. This modularity allows other selection strategies to be punctually evaluated without compromising the solution architecture.

Additionally, although there are great contributions in simulated works, most simulated do not consider factors that can potentially affect a handoff solution. For example, in practice, some context information necessary for the interface selection phase are not acquired so easily as QoS parameters and bandwidth per application. Moreover, we cannot redirect application flows to different interfaces with IPv4 unless we use mobility support like Mobile IP or Media Independent Handoff In this work, we implement our solution using real devices and show the viability with real scenarios.

If we observe the strategies proposed by previous works, we surprisingly note the remarkable importance of knowing the real speed of movement of the mobile device to vertical handoff strategies, just as the SNIR is important for horizontal handoff. Certain access technologies are not suitable for high speeds such as Wi-Fi and Bluetooth, at low speeds the Wi-Fi can operate satisfactorily, however, the Bluetooth does not and when the device is stopped bluetooth becomes a good option to maintain connectivity with reduced power consumption. Thus the speed of the mobile device allows us to modularize the interface selection strategy, activating and deactivating interfaces according to the limitations of each access technology, this modularization allows only certain components (selection threads) to start operating when certain conditions of speeds are met, thus reducing the required processing cost and also reducing unnecessary spectrum spectra, which consequently impacts the reduction of energy consumption.

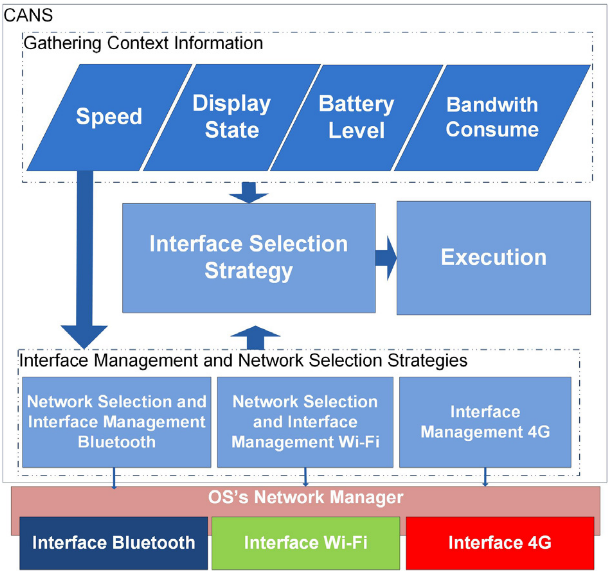

Fig. 2. CANS architecture.

3. Context-aware network selection

The Context-Aware Network Selection Mechanism (CANS) aims to conduct the dynamic selection of access networks for devices with multiple access interfaces (multi-homing devices) based on analysis of network characteristics, device and user.

As shown in Fig. 1, CANS acts as a software agent (a service) in the mobile communication device organizing the device information (e.g. power level), the user (e.g. displacement speed and device usage) and network (e.g. bandwidth). From the identification of context, the CANS is able to establish a preferential order to use the communication interfaces. Besides the interface selection process, CANS employs management strategies to Bluetooth, Wi-Fi, and LTE/4G interfaces.

The CANS architecture is illustrated in Fig. 2. Through Gathering Context Information Module, information like speed, display status, power level and bandwidth are collected and sent to management and network selections strategies. Each strategy selects the best interface and sent to interfaces selection strategy (Detailed Section 3.2). Once the CANS Agent recognizes the best interface, it performs changes the IP address of the gateway and the default interface in the operating system's routing table. The following sections provide details of the operation of each strategy used by CANS.

3.1. Network interfaces selection strategies

The CANS was designed to be a flexible and scalable mechanism, so that new access interfaces, selection strategies and management interfaces can be added easily. This modular feature of CANS allows each strategy to work in a timely manner in order to deliver the interface previously connected and with the Internet service available for the selection process.

To exemplify the modularity and flexibility of the solution, two access interfaces commonly used by users have been chosen. The 4G/LTE access interface was chosen for its wide access coverage, allowing the user to maintain an uninterrupted and transparent connection with the Internet. The Wi-Fi interface was chosen for being the most used in WLAN networks and for offering greater bandwidth, with a lower financial cost for the user. In addition, we added the Bluetooth interface, as recent developments in the Bluetooth SIG have made Bluetooth Low Energy (LE) a strong contender for the underlying wireless technology in many IoT applications. The key strengths of Bluetooth LE are very low power and widespread adoption. Recently, many indoor applications have turned to Bluetooth LE. The new Bluetooth 4.2 Core Specification and Internet Protocol Support Profile improves the IP capabilities of Bluetooth [29].

For this reason the Bluetooth interface is used in this work as a viable alternative to low energy consumption and financial cost to maintain the connectivity of the user, thus explaining that the CANS can support other types of communication interfaces, exploring its main advantages even if they do not have the main purpose of access to the Internet.

3.1.1. Bluetooth interface

The Bluetooth interfaces management strategy aims at identifying the availability of networks and devices with Bluetooth technology to enable connectivity to the network and Internet services with low power consumption.

Basically, the strategy (1) identifies when a user has an active interface, (2) starts the process of spectrum scanning to search for devices that have the Network Access Point (NAP) access profile, and (3) attempts to perform an automatic pairing, as shown in Fig. 3. This profile NAP allows the interface to be used as if it were an Ethernet access network interface, allowing for the use of the IP protocol. Although Bluetooth technology provides different device classes, which offer coverage of approximately 1 m (Class 3), 10 m (Class 2) and 100 m (Class 3), a majority of devices available in the market are of Class 2.

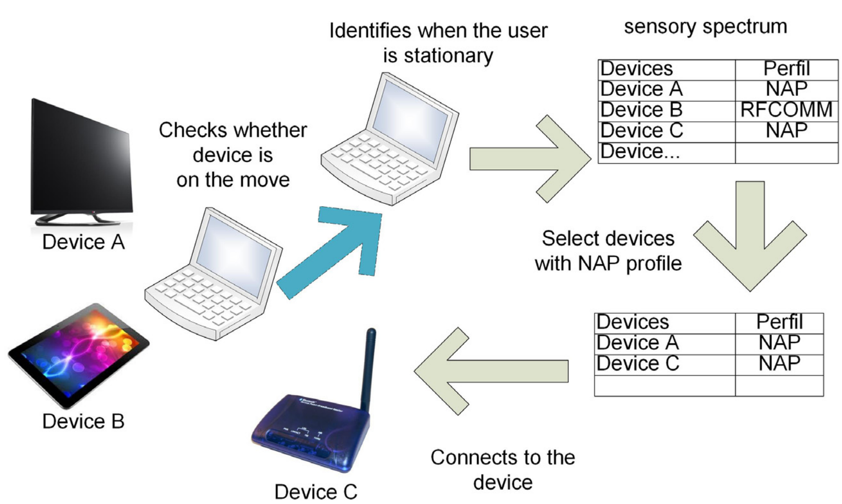

Fig. 3. Network selection strategy for Bluetooth interface.

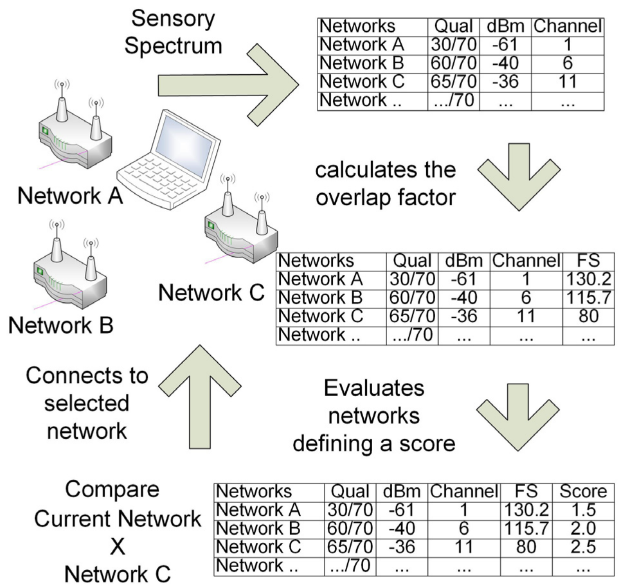

Fig. 4. Network selection strategy for Wi-Fi interface.

Considering the limited communication range of the Bluetooth technology, the interface selection strategy considers this access interface only when the user is stationary (i.e., when user's displacement speed is zero during the time interval of t minutes).

3.1.2. *Wi-Fi interface*

The strategy of interface management and Wi-Fi network selection works in a similar way to the Bluetooth interface strategy. However, instead of being executed only when the device is stationary, the management and selection of this interface occur whenever the user's displacement speed is less than or equal to 5 km/h or 1.388 m/s, corresponding with the speed of an adult walking [30]. This speed was chosen because is impracticable use Wi-Fi interface when possibly the user is driving or ride a bike in medium or high speed. Fig. 4 illustrates the strategy for selecting the most adequate Wi-Fi network.

As shown in Fig. 5, the strategy performs a spectrum sensing to collect the signal strength and the channel used on the adjacent access points. This data is used to calculate a wireless network score S_{R_n} using the Eq. (1), where Q_{R_n} is the network quality n, $RSSI$ indicates received signal strength of the network n, OF_{max} is the maximum overlap factor of the network n, Sens is the minimum sensibility level of the interface, and Q_{max} is the value of the maximum quality given by the operating system. Originally, the calculation to obtain the overlap factor between networks can be found in various channel selection algorithms [31–33]. The channel overlap factor of a network $O_F(i,j)$ is obtained by the ratio between the intersection range of the channels used by the APs i and j and the channel bandwidth. Thus, the overlap factor Of(i, j) is given by:

$$O_f(i,j) = \begin{cases} 1 - \frac{|F_i - F_j|}{W} & \text{if } fs(i,j) \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where F_i is the frequency of the channel assigned to the AP i, F_j is the channel frequency assigned to the AP j and W is the channel width. For example, the intersection factor $f_S(i,j)$ between channel 1 (2412 MHz) and channel 2 (2417 MHz) operating with channel width of 22 MHz is given by:

$$O_f(1,2) = \left\{ 1 - \frac{|2412-2417|}{22} = 0,772 \right. \tag{2}$$

$$S_{Rn} = \frac{Q_{R_n}}{Q_{max}} + \frac{RSSI - (-Sens)}{RSSI - Sens} + \frac{OF_{Max} - OF_{R_n}}{OF_{Max}} \tag{3}$$

After the score is calculated for all the networks, following strategies are used for selecting the network:

1. In case the device is not connected to any network, the strategy tries to establish a connection to a higher-score network.
2. In case the device is already connected to a network, a comparison is carried out between the higher-score network and the actual network to define whether the network switching is necessary.

The strategy makes sure that the network switching is only realized when the same network is detected with a higher score during a determined number of subsequent analyses. The objective is to avoid successive network exchanges that can lead to loss of network performance and user's QoS. In this work we adopt four consecutive samples of the SRn with 15 s of the interval, corresponding to a minimum time of one minute to exchange the current network to a network with the highest score.

3.1.3. *Management strategy for wireless interfaces for mobile communication*

Different from previous strategies, the mobile system strategy (wireless interfaces for LTE/4G networks) works only by managing the activation and deactivation of the interface. This occurs because the horizontal handover of the mobile LTE/4G access network is realized by a service provider, meaning that the CANS need only decide when to make the communication interface available or not.

Since this is the interface that provides the worst cost–benefit in relation to the access speed (throughput) and the access cost (MBytes/USS), the mobile access interface is selected as a last resort for access in the

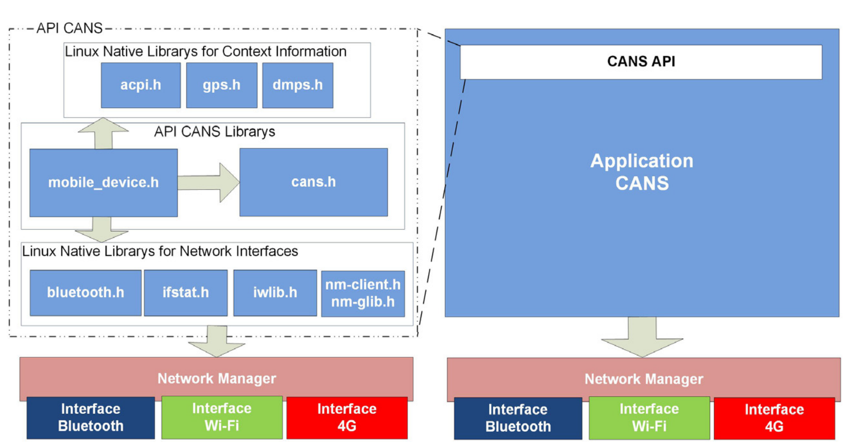

Fig. 5. Prototype architecture.

majority of contexts defined in this work. The strategy enters into action every time the other interfaces are not active or when they do not have Internet access. On the other hand, when the user is in high-speed displacement (for example, in a car) the mobile access network provides greater stability than local networks and personal wireless networks due to its wider coverage area. To identify the need to use the interface, the strategy verifies the activation state and service connection of other interfaces.

3.2. Interface selection strategy

Different criteria can be taken into consideration in the handoff decision step. Some of these criteria are related to network, user, device, and services in execution, and could be more relevant to others depending on the context. Prior to quantifying the advantages of using a specified interface, the proposed strategy for interface selection verifies three principal parameters before the selection process: the interface state (active/inactive), the connection state (connected/disconnected), and the service state (available/unavailable).

The interface state helps to identify whether the interface is active or not to be used in the handoff process. If a specific interface is not enabled, this can be disregarded in the assessment process. Thus, if only one access interface is enabled, the selection process is not executed and the active access interface is selected immediately.

The connection state verifies if the interface, even if active, has a pre-established connection with some access point. If the interface is not linked to any access point, it can be immediately discarded from the decision process. This scenario is very common when the user finds himself in access network coverage areas which do not possess the credentials (passwords) necessary for the connection to defined access points.

Finally, the service state allows us to identify whether any service is available at a particular network access point linked to a particular interface. For example, a device can be connected to an access point (e.g. Wi-Fi), but if the access point cannot access the service desired by the user, for example, the Internet (a common requirement in most cases), the interface is also ruled out of the decision process.

After verifying these three states and getting a confirmation that at least two interfaces can be used for the selection process, the strategy begins by identifying the context and choosing the appropriate interface.

The strategy looks at the device context, in order to guarantee that the user remains connected for most of the time with less financial cost and energy consumption. Every context is identified from the combination of four principal parameters: (i) displacement speed, (ii) device used by the user, (iii) consumption of total bandwidth used by active services, and (iv) current battery charge. The proposed interface selection strategy defines three context policies (access speed, energy economy, and coverage) that define the preference order for the use of the interfaces.

Table 1 presents the values and conditions necessary for the application of each of these policies. B_T (bandwidth threshold) is the reference value that establishes if the demanded traffic by the user is high ($> B_T$) or low ($< B_T$), and P_B (percentage battery) is the reference value that establishes the critical level of the battery for application in the policy of energy economy.

The "access speed" policy aims at approaching scenarios in which the user is using the device, and is found to be stalled or is at a displacement speed below 5 km/h. This policy defines the priority order of interfaces based on the access speed, offering users an access network with the best speed. The policy assumes that data transfer in real time or not can be executed in short time intervals or even simultaneously. Based on this assumption, interfaces with higher transfer speeds and networks that offer greater bandwidths are more adequate for these contexts.

The "power save" policy aims at maximizing energy saving when the device is not being used by the user, but it needs to maintain the devices connected at some access point due to the utilization of instantaneous message services as well as communication. With this understanding, this policy aims at helping the device to economize energy, prioritizing interfaces and access networks with low consumption, and preferentially maintaining a unique access interface with low available energy consumption.

The "coverage" policy approaches the scenario in which the user displacement speed is above 5 km/h. This policy defines the priority order of interfaces based on networks with higher coverage areas. This way, excessive handoff executions can be avoided, which can maximize the service availability and minimize communication interruptions. Table 2 presents the priority order of interface selection according to the presented context policies.

Table 1
Parameters x context police.

Parameters					Context police
Power source connected	Moving speed (km/h)	In use	Bandwidth use	Battery level	
Yes	v < 5	–	–	–	Access speed
	v > 5	–	–	–	Coverage
No	0	Yes	$> B_T$	$> P_B$	Access speed
				$< P_B$	Power save
		No	$< B_T$	–	Power save
	$0 < v < 5$	Yes	$> B_T$	–	Access speed
			$< B_T$	$> P_B$	Access speed
				$< P_B$	Coverage
		No	$> B_T$	$> P_B$	Access speed
				$< P_B$	Coverage
			$< B_T$	–	Coverage
	v > 5	–	–	–	Coverage

Table 2
Priority Order by Context Police.

Preferred order	Access speed	Coverage	Power save
1st	Wi-Fi	LTE	Bluetooth
2nd	LTE	Wi-Fi	Wi-Fi
3rd	Bluetooth	Bluetooth	LTE

4. Prototype

In this section, we describe a prototype that can be used in two ways. First, it can be used for validating the proposed methodology. Second, the CANS prototype can be used as an API by developers of handoff solutions, by end users through the application prototype presented below or by researchers as tools for monitoring the process of interfaces switching.

The implementation architecture of the CANS API, as shown in Fig. 5, consists of a set of libraries developed to facilitate the collection and analysis of interface information through the availability of structures and functions necessary for the handoff procedure. This way, the developer can use the CANS API to develop his/her own handoff solution based on the parameters used in this work. For example, using this API we develop an application (see Section 5 for details) that allows two different modes of operation: the monitoring mode that acts only as a tool for collecting context information; and handoff mode that collects, evaluates, and executes the handoff procedure (horizontal and vertical).

The CANS API was developed in C programming language. It uses following Ubuntu-based tools and methods for acquiring and processing

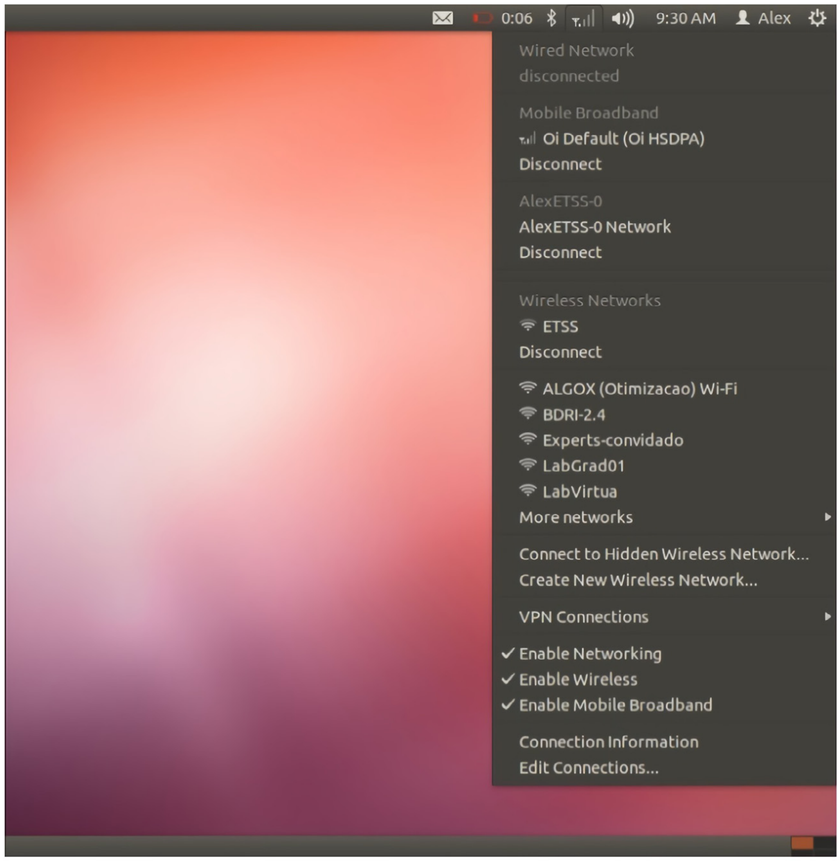

Fig. 6. Ubuntu network manager screenshot.

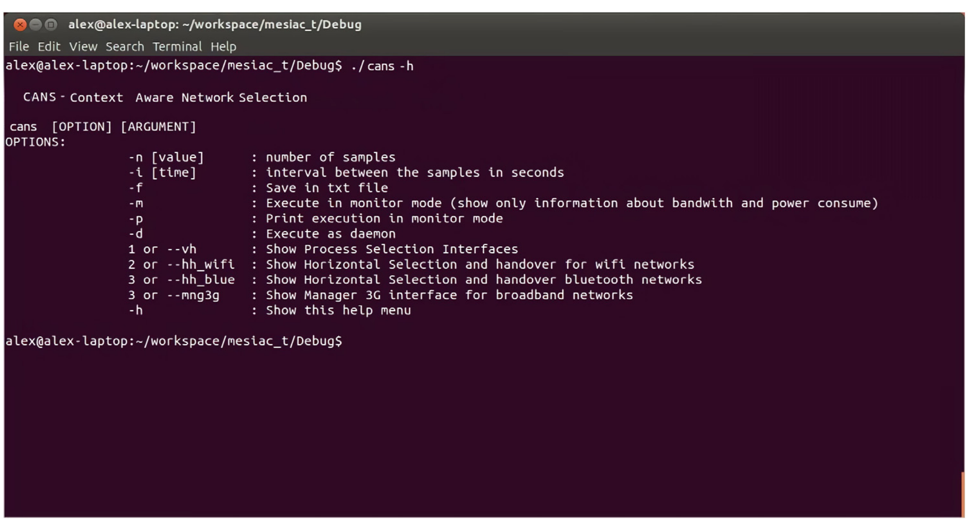

Fig. 7. Help menu screenshot of the CANS application.

context information of the access interfaces: gps.h (used to check speed), dmps.h (to check the display state), acpi.h (to check the battery status), ifstat.h (for interface bandwidth consumption), hci.h (Bluetooth interface information), iwlib.h (interface information and Wi-Fi networks), and nm-nm-util.h (information acquisition and interface switching through Network Manager).

In addition, the CANS API provides two other libraries that implement the handoff strategies ("cans.h") and the context information acquisition "*mobile_device.h*", as shown in Fig. 5 and detailed in Table 3.

The mobile_device.h library brings together the main data structure and functions relevant to the process of acquiring information and context selection. The data structure used in these functions consists of following data:

1. Idx: Run-index used to record and control.
2. Hostname: device network name.
3. Current_context: integer value of the current device context.
4. Best_interface: integer value that identifies the best interface in use.
5. GPSData: structure that stores position values and device travel speed.
6. bw_total: Total bandwidth consumption of all interfaces as Kbps.

Table 3
API CANS Library for gathering context information and handoff manager.

Library	Function	Description
mobile_device.h	gathering_infoctx (mobile_device_t)	Function to gather context information
cans.h	horizontal_handoff_Bluetooth (mobile_device_t)	Function to manage and select access points Bluetooth
	horizontal_handoff_Wi-Fi (mobile_device_t)	Function to manage and select access points Wi-Fi
	manage_ifaceLTE (mobile_device_t)	Function to manage LTE interface
	execution(mobile_device_t)	Function to run the network switch

7. energy_md: structure with information about the energy independence of the device.
8. Wi-Fine_select:-shaped structure linked list with the selected access networks for access.
9. best_ap: best selected Wi-Fi network.
10. cont_best_ap: number of times counter that the best network is selected.
11. Wi-Fi: structure with specific information from the Wi-Fi interface.
12. Bluetooth: structure with specific information from the Bluetooth interface.
13. ifaceLTE: structure with specific information from the LTE interface.
14. current_Wi-Finet: data structure that contains information about the current network of Wi-Fi.
15. current_bluenet: data structure that contains information about the current network of Bluetooth access.
16. host_ifaces: structure containing information on bandwidth consumption of each interface.
17. order_prefer: data structure that contains the order of preference of each access interface according to the context.

The library "cans.h" brings together all the relevant functions for implementing the handoff process. The horizontal_handoff_Bluetooth function takes as input the mobile_device_t data structure and decides on the need for horizontal handoff for wireless personal area networks (WPAN) based on the strategy described in Section 3.1.1. This function is responsible for checking the device displacement state, enabling or disabling the Bluetooth interface and for spectrum sensing for Bluetooth devices to share network services from the NAP profile.

The horizontal_handoff_Wi-Fi function decides on the need for a horizontal handoff on wireless local area networks (WLAN) based on the strategy described in Section 3.1.2. This function is responsible for checking the device displacement state, enabling or disabling Wi-Fi, and spectrum sensing the demand for access points with better signal level, quality, and less interference ($C_U F$). The function manager_ifaceLTE aims to manage the LTE interface according to the activation state of readings and connection interfaces Bluetooth and Wi-Fi. When at least one of the interfaces is available and depending on the context of displacement, the LTE air interface is disabled for power saving. If none of the interfaces is available, the LTE interface is activated immediately.

Finally, the execution function has the purpose of performing the selection of the proper interface. This function works in the routing table by setting the standard access route from the interface and the default gateway address of the chosen interface. Upon entering execution and selecting the better interface, the mechanism sends the response of the chosen interface to execution function.

5. Example application

In this section we describe an example of an application constructed using the CANS API. The AppCANS application acts as a support system to the operating system network management. The application was developed for the Linux Ubuntu platform that uses the Network Manager to manage the wireless interfaces and distribution connections. A Network Manager screenshot is shown in Fig. 6.

The functionalities covered by most network managers, including those provided by Linux and Windows operation systems, are restricted to registration and storage of connection information (and generally networks already connected by the user). Moreover, the whole process of activation/deactivation of interfaces or connection/disconnection of a new access network does not occur automatically, requiring that there is user interaction. In order to provide a better automation to this process, as well as the analysis and intelligent selection of network interfaces, the AppCANS makes use of APIs "libnm-glib" and "libnm-client" that allows management of interfaces by the Network Manager automatically based on the results adopted by the strategies.

Fig. 7 presents the help Menu displayed by AppCANS when the "cans -h" command is executed. This application has diverse parameters for exhibition and setting up, which can be tuned by users.

6. Experiments and results analysis

The purpose of this evaluation is to demonstrate our mechanism in a real use case example. We consider a heterogeneous network consisting of Bluetooth, Wi-Fi and LTE/4G mobile system to verify the handoff mechanism's performance.

The network infrastructure is composed of a Wi-Fi wireless router (N600 Wireless Dual Band Gigabit Router), a Bluetooth router implemented in a desktop running Ecodroidlink Agent [34] to provide support to the Internet using Bluetooth technology, and an LTE/4G cellular system. In the experiments, we have used a monthly 2 GB Data plan for 1 Mbps of speed provided by a Brazilian telecommunications provider. The regular service costs are R$ 39,00 for a mobile plan and R$ 69,90 for a Wi-Fi and Bluetooth for a rate of 70 GB per month [29]. The financial cost of kWh is considered the power utility in the current period from 04.19.2014 to 10.31.2015 in the amount of R$ 0.32081 [35].

6.1. Scenarios

Different test scenarios were devised to simulate the possible handoff events that occur in the day-to-day lives of users during displacement between two points.

The total displacement time considered was 1 h and 25 min, divided into 17 possible contexts with execution time of 5 min, as displayed in Fig. 8 where arrows pointing downwards indicate low bandwidth consumption, that is, consumption lower than $B_T = 1$ Mbps, while the arrows directed upwards indicate high bandwidth consumption, with values higher than B_T.

Table 4 presents speed values, the device state and bandwidth consumption for each experimental scenario and a brief description of how the strategy understands the context. Traffic generated on mobile devices corresponds to the download of different Ubuntu Operating System distributions, where the size of images varies from 616 MB to 1.1 GB. To perform bandwidth control in order to simulate the behavior of high and low consumption, a tool known as Linux Wondersharper [14] was used.

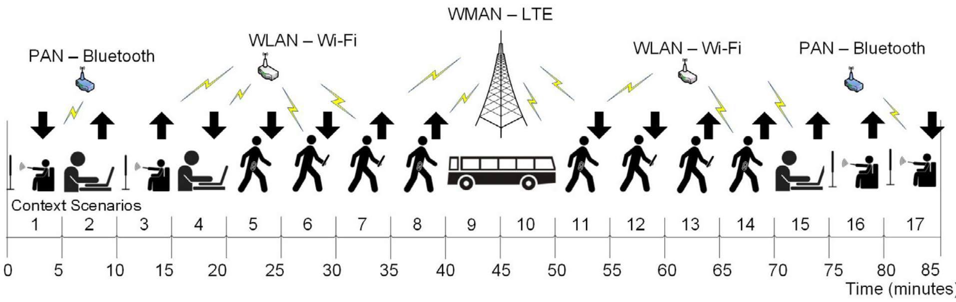

Fig. 8. Test scenarios.

Table 4
Context scenario descriptions.

Context	Speed	Device in use	Bandwidth consume Mbps
1 and 17	0	No	< 1
2 and 15		Yes	> 1
3 and 16		No	> 1
4		Yes	< 1
5 and 11	3.6	No	< 1
6 and 12		Yes	< 1
7 and 13		Yes	> 1
8 and 14		No	> 1
9	50	Yes	–
10		No	

6.2. Results

This section presents the results of throughput and energy consumption obtained by the CANS mechanism based on the scenario proposed in Fig. 8. First, we show the throughput obtained by each wireless access interface and throughput considering a mobile device equipped with multiple radio interfaces (Bluetooth, Wi-Fi and LTE/4G) using CANS mechanism. Next, we also show the results.

Fig. 9 shows a use case where only the Bluetooth interface is active and data is continuously transmitted and received. As expected, the interface remained operative between the ranges of 0 to 20 min and from 70 to 85 min. This operational period comprises precisely the time that the user device is displacement speed equal to zero or is parked. Despite the Bluetooth interface specification informing a theoretical transfer of up to 2 Mbps, the experiments showed lower transfer values of less than 1 Mbps and it fits within the B_T 1 Mbps benchmark adopted by CANS that differentiates the bandwidth consumption as high or low.

We also repeated these experiments for the Wi-Fi 10 and LTE/4G interfaces 11. Fig. 8 shows the throughput obtained when only the Wi-Fi interface was activated. As expected, this interface remains inoperative during the time interval in which the user's travel speed is greater than 5 km/h. The periods between 10 and 30, 50 and 60, and 80 and 85 min comprise intervals in which the user is stationary or moving and using the device with lower traffic B_T, as in the contexts 4, 5, 6 and 17 of Fig. 8.

Finally, Fig. 11 shows the throughput obtained when the user uses only a LTE/4G interface. Despite the fact that the LTE/4G networks do not present any point of unavailability during the user travel, their access speed is limited to the access plan contracted with the operator, which in this case is 1 Mbps.

Next, we show data transfer rates obtained when a multi-homed device and the CANS mechanism are used. Fig. 12 shows that the interface selection strategy proposed by CANS allows the user constant access availability. The variation in data transfer rates was due to the access interface changes caused by the changes in user displacement speed. These interface changes were made based on the context of changes observed by CANS as shown in Fig. 13, which represent the relationship between identified context (see Table 4), time and interface chosen. In the illustration, it is noted that during the first (0 to 5 m) and the last connection (80 to 85 m) the selected access interface was the Bluetooth interface, during the contexts 3, 5, 8 and 11, the interface chosen was the Wi-Fi, and in the contexts 6, 9, 12, and 13 the interface is chosen was LTE/4G, totaling seven vertical handoffs.

Fig. 14 presents the percentage of availability for interface connection (without CANS) and using CANS for the proposed scenarios. This percentage is obtained by considering the connection time available divided by the total time for experiments (1 h 25 min). The results show that the average connectivity provided by CANS reaches up to 95.13% of connection availability, being inferior only to LTE interfaces with an availability of 99.2%.

This difference is mainly given by handoff procedures (horizontal and vertical) conducted by CANS arising from context changes stipulated in the evaluated scenario. Fig. 15 shows the interruptions brought about by interface changes. In order to minimize the exchange time that could interrupt the data traffic, the target interface is prepared 5 s before, during this time both interfaces: the current and the destination are enabled simultaneously until the interface exchange succeeds. In some cases, the device's downtime varies between 10 ms and 20 ms. When interface exchange occurs, the IP address of the default gateway is changed, causing the active TCP and UDP connections of the applications to be broken. So after the interface exchange, the active applications are forced to re-establish their connections. This trade-off was already foreseen in the scope of this proposal because it does not have a mobility management.

Fig. 16 presents the amount of data transmitted and access speed provided by each interface, and by CANS usage. The average quantity of data transferred by the interfaces with CANS usage was 1.8 GB, while the average total of data transferred by Bluetooth, LTE and Wi-Fi interfaces was 150 MB, 515 MB and 6.1 GB respectively.

The high throughput obtained by the Wi-Fi interface without CANS usage occurred because the proposed interface selection strategy aims to identify the best access interface not only considering data throughput, but also other factors such as energy saving and financial cost, as described in 4.

Fig. 17 shows the average power consumed by the device during the experiments considering a mobile device using a radio interface all the time (Bluetooth, Wi-Fi or LTE/4G) and with multiple access interfaces using the interface selection strategy proposed by CANS. The graph shows the power consumption curve, using the CANS, with the data below the device using only the Wi-Fi interface and above the device using the Bluetooth and LTE interfaces. The Figure shows a comparison of the energy consumption demanded by the three interfaces individually and when using CANS.

Table 5 lists the values of the total consumption, the average power consumed, the cost of energy per MByte, and the estimated range. The results show that proper choice of access interfaces depending on the user context provided by the use of the CANS, allowed a larger energy saving and increase in the battery lifetime. The CANS provided battery autonomy higher (20 min) when compared to the scenario with only the Wi-Fi interface.

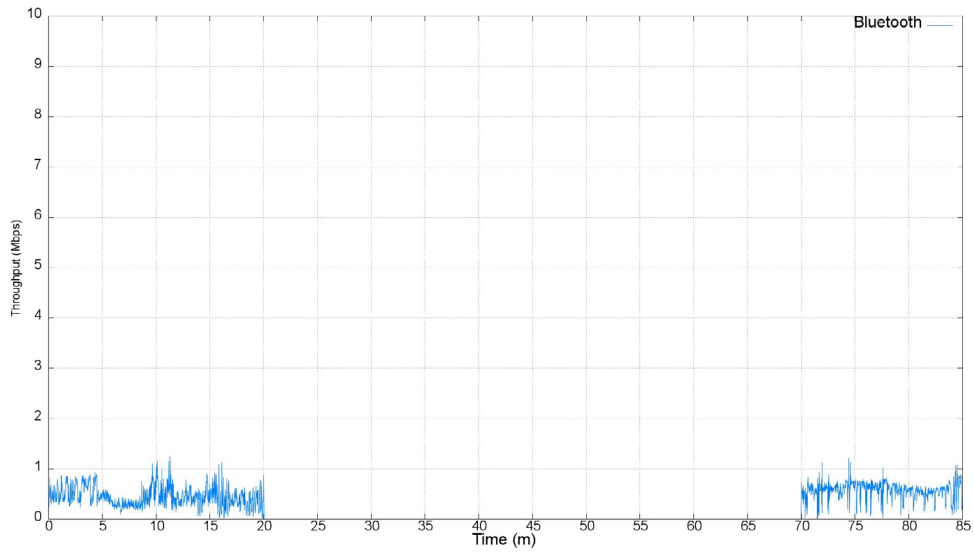

Fig. 9. Throughput obtained by Bluetooth interface.

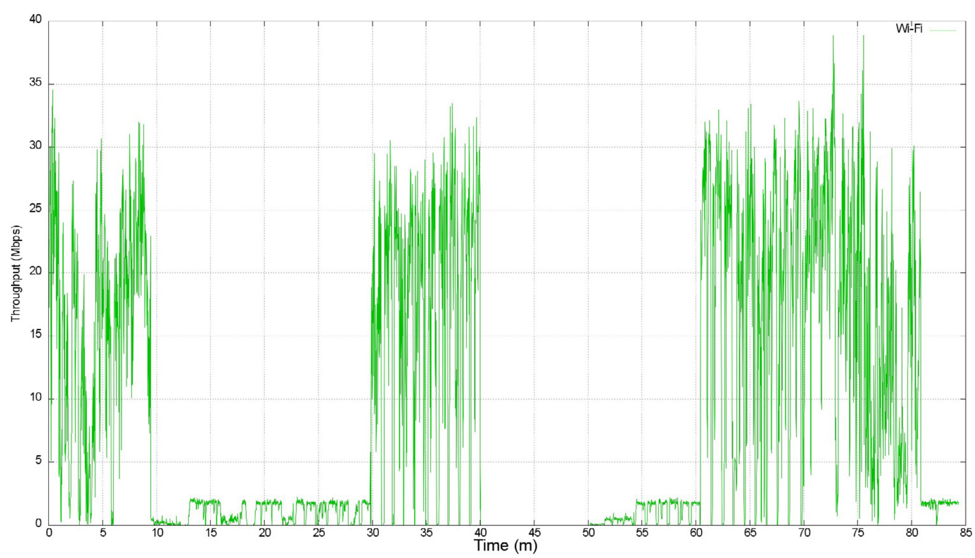

Fig. 10. Throughput obtained by Wi-Fi interface.

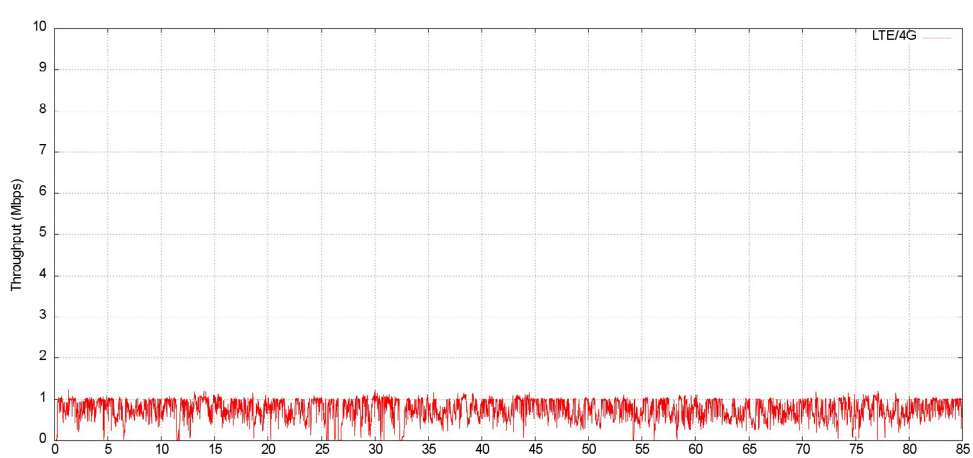

Fig. 11. Throughput obtained using LTE/4G interface.

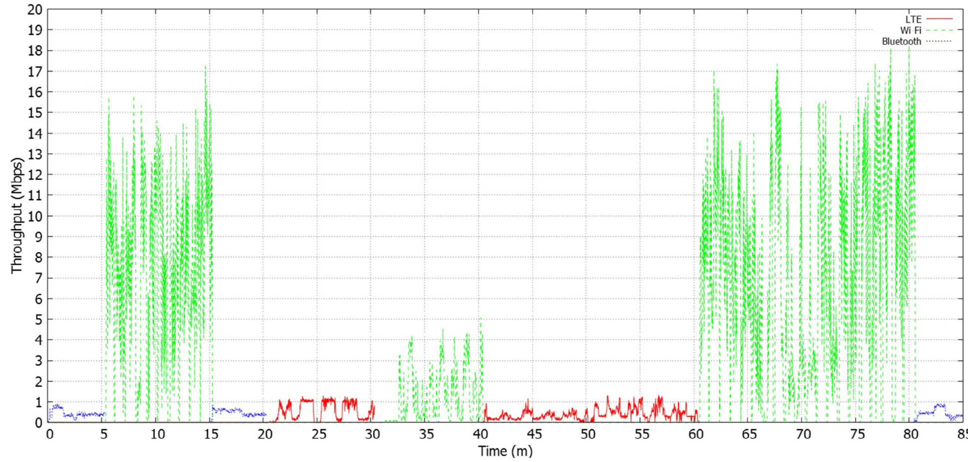

Fig. 12. Throughput provided by CANS mechanism.

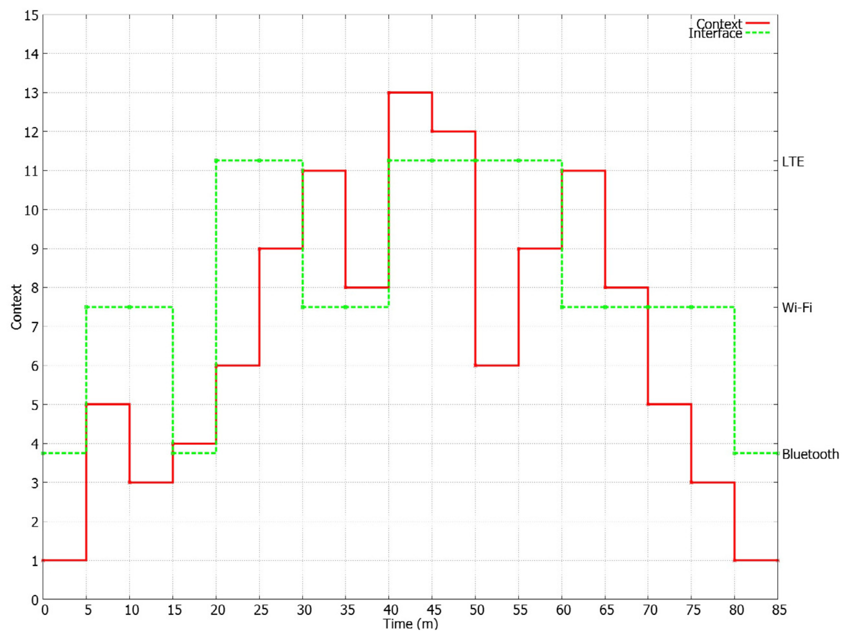

Fig. 13. Context changes and interface swap in time.

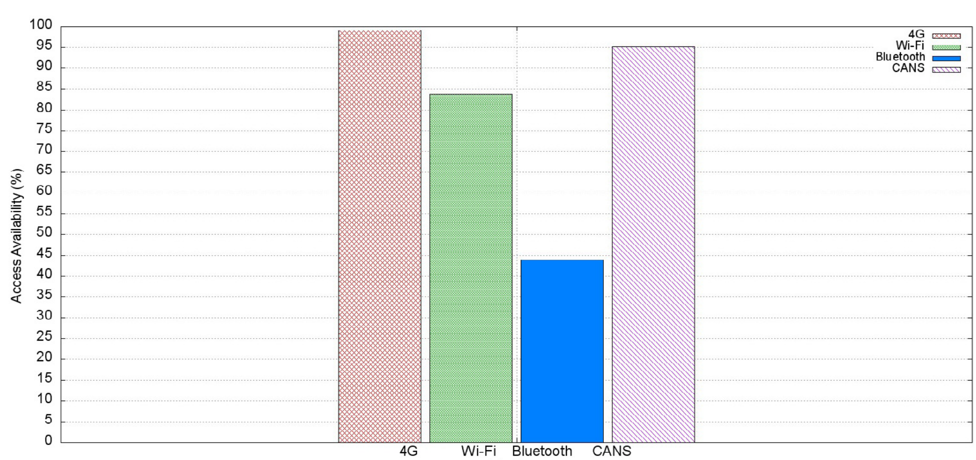

Fig. 14. Connection availability obtained by interfaces with and without CANS management.

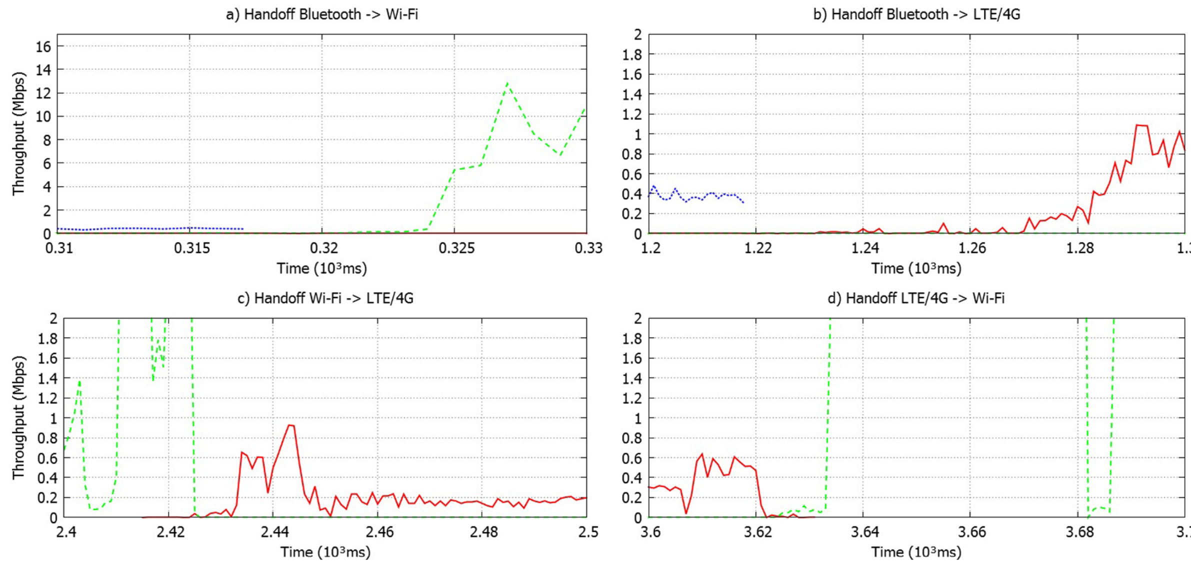

Fig. 15. Interruptions caused by vertical handoff: (a) presents the interface change that occurred between the Bluetooth and Wi-Fi interfaces, (b) interface change that occurred between the Bluetooth and LTE interfaces, (c) interface change that occurred between Wi-Fi and LTE (d) interface change that occurred between LTE and Wi-Fi.

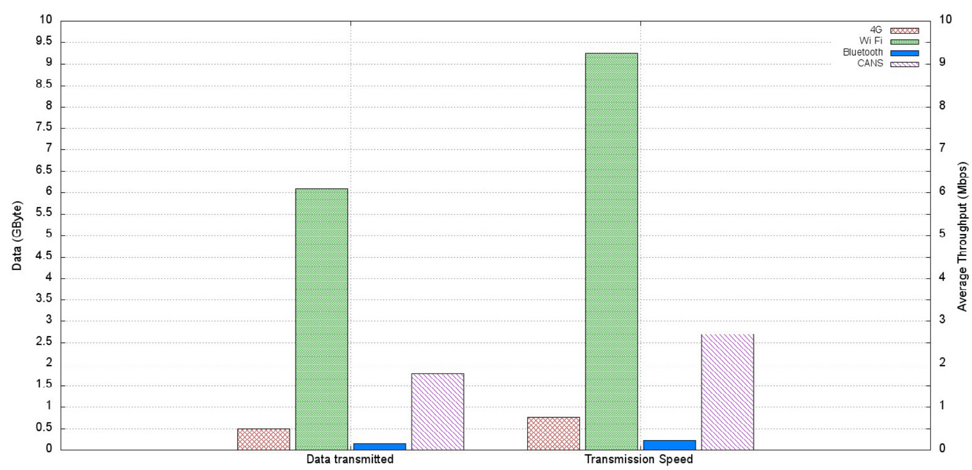

Fig. 16. Amount of data transmitted and access speed per interface and using CANS.

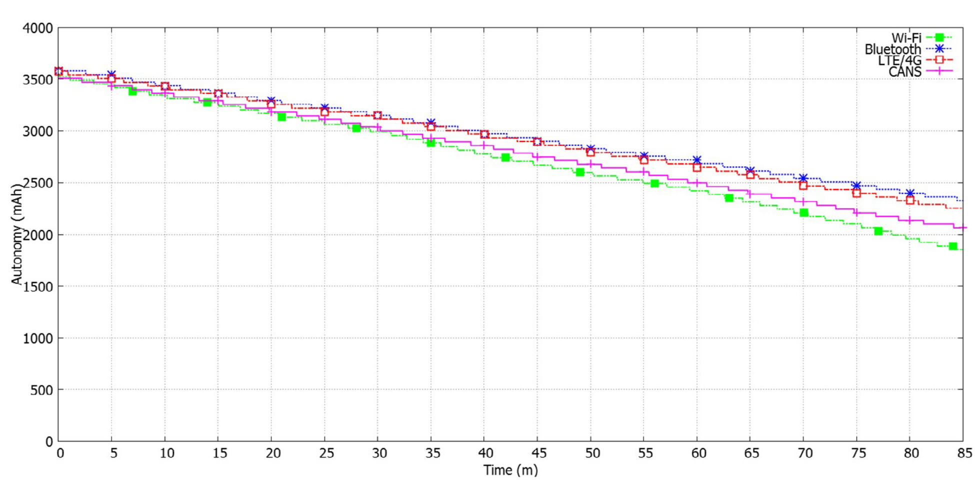

Fig. 17. Device energy consumption using different access interfaces.

Fig. 18 shows the measured power consumption ratio given in milliampere hours per MByte transmitted. It can be seen that consumption of mAh/MB is less when the device uses the Wi-Fi and CANS interface. The energy consumption per MB for Wi-Fi interface is justified due to the bandwidth provided by the interface. In the case of CANS, the efficiency of this relationship is due to the selection strategy that selects

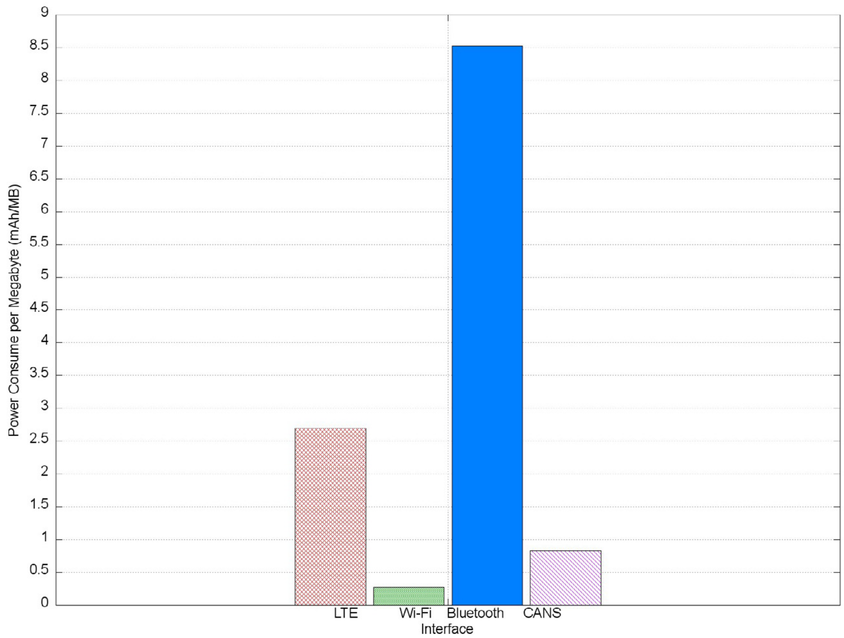

Fig. 18. Power consumption per interface.

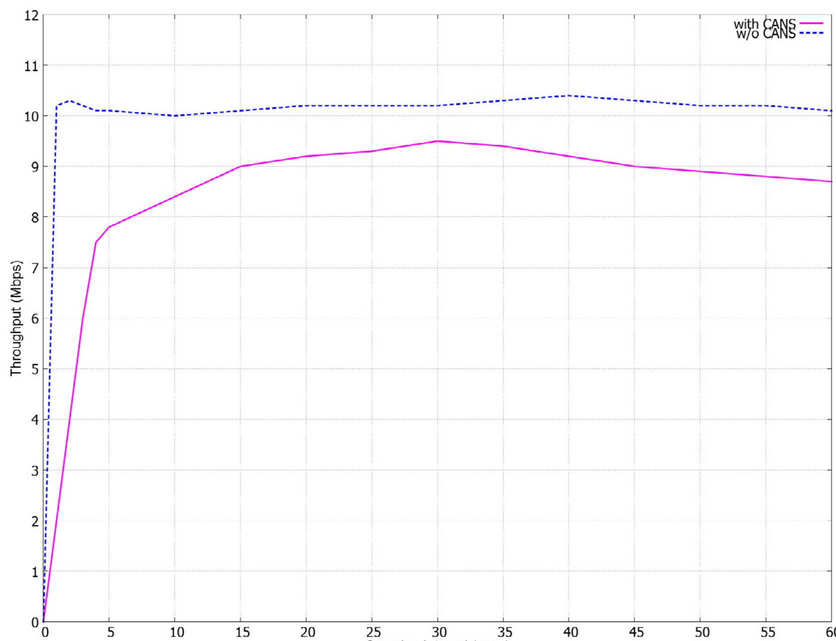

Fig. 19. Wi-Fi interface throughput.

Table 5
Comparative table on power consumption.

	Bluetooth	Wi-Fi	LTE	CANS
Total consumption (mAh)	1288.00	1708	1394	1515
Average current (mA)	1038.71	1377.42	1124.19	1221.77
Cost per MB (mAh/MB)	8.52	0.27	2.70	0.83
Estimated autonomy (h)	3:25	2:34	3:10	2:54

the interface according to the user-required bandwidth. The ratio less efficient of energy consumption per MB transmitted is attributed to Bluetooth due to low bandwidth provided by the interface.

The financial cost is given by the cost of energy (energy used to recharge the device) and the cost of traffic demanded by the user. To quantify the financial cost of energy, the cost per milliamp hour was converted into Watt-hour (Wh) and multiplied by the value of the current rate of R$ 0.32081 per kWh [36]. The mobile device uses an average voltage of 11.7 V. The total consumption Wh is listed in Table 6.

The proposed mechanism provided a monthly financial savings of 11.3% (R$ 0.42) in relation to energy consumption obtained using the Wi-Fi interface. Another important improvement was the possibility of reducing the financial cost related to traffic, while from the use of LTE and Wi-Fi interfaces would be respectively R$ 10.29 and R$ 6.24, the

Table 6
Power and traffic prices.

Type	Cost	Bluetooth	Wi-Fi	LTE	CANS
Power	Watt-hour	15.07	19.98	16.31	17.73
	Financial R$ (10^{-3})	4.83	4.83	5.23	5.68
	Monthly R$	2.81	3.72	3.04	3.30
Traffic	MegaByte R$ (10^{-3})	9.98	9.98	20	2.06
	Traffic GB	0.151	6.25	0.515	1.82
	Financial R$	0.08	6.24	10.29	3.77

cost provided by CANS was R$ 3.77, providing a savings of 64% for LTE interface and 39% for the Wi-Fi interface.

7. Discussion

The implementation of CANS involved two main issues: the first one was to deal with the cost of processing and energy consumption resulting from the collection and processing of user context information. The second issue was the maintenance of active TCP/UDP connection sessions.

Continuous collection of context information can increase the cost of processing, so it was necessary to develop an effective strategy to reduce the number of samples based on key information. Knowledge of the user's displacement speed is the first parameter to reduce the overhead generated by the continuous collection of context information. CANS uses this parameter to enable or disable the interface selection process. For example, the Wi-Fi interface is not designed to handle user mobility scenarios with high-speed displacements (> 5 km/h). This way, when the user is in a high-speed displacement the best access interface is LTE/4G, it is not necessary to activate and run the selection process in the other access interfaces. Thus the speed of the mobile device allows us to modularize the interface selection strategy, activating and deactivating interfaces according to the limitations of each access technology. This modularization allows only network selection strategies to start operating when certain conditions of speeds are met, thus reducing the cost of processing required and also unnecessary spectrum sensing, which consequently impacts the reduction of energy consumption.

In addition, to reduce the overhead generated by the continuous collection of context information (battery level, bandwidth consumption, display state), CANS acquires context information that is already available in the OS from APIs such as Advanced Configuration and Power Interface (ACPI) and NetworkManager. With regard to information about user speed, CANS uses the reading of GPS coordinates, however, it is possible to capture user mobility contextual information through other sensors embedded in mobile devices such as accelerometers and magnetometers that could reduce energy consumption.

To further minimize the overhead introduced by CANS, we evaluated the sampling interval for the interface selection process. Fig. 19 shows the amount of transmitted data by Wi-Fi network interface using CANS. The results show that sampling intervals after 15 s, the Wi-Fi access interface is less influenced by the CANS, the average overhead introduced by CANS is 1.05 Mbps. In this work, we adopted the sampling interval of 15 s to allow the CANS to identify the context of the user more faster.

As for the problem generated by session breaks, this proposal aims to evaluate and perform the selection of interfaces based on user context information. Therefore, this work assumes that the user's applications have appropriate to deal with breakage and reestablishment of sessions. To minimize these problems, it is suggested to use mobility management protocols, such as Mobile IPv6 [37]. The use of these protocols together with the CANS will allow the realization of the complete handoff process in a transparent way for the users and their applications.

8. Conclusion

This article presented a new mechanism for access network selection based on context analysis. The proposed mechanism evaluates the states of the device and network, as well as user's displacement speed and proactively attributes an access network to the device which best suits the user context. More specifically, CANS collects context information such as user's displacement speed, device state (on/off), bandwidth usage and device battery level, among others, in order to determine the most adequate user access interface in a defined moment.

We have built a prototype system and have performed a series of experiments, using roaming among Bluetooth, Wi-Fi and LTE/4G as examples, to verify and demonstrate the properties of the proposed mechanism. The experimental results show that the use of proposed strategies enables not only an increase in connectivity but also a reduction in energy consumption of the device.

We are currently working to extend CANS to include others network interfaces. We also intend to perform feasibility studies of the implemented solution in terms of scalability, QoS, and throughput under other mobility scenarios. Moreover, we are evaluating the use of learning algorithms for building smart network selection algorithms based on patterns of connections and activities between different users. Pattern recognition and relationships between locations, networks, and user context can allow for the development of more robust and accurate strategies that satisfactorily meet the needs of users.

Acknowledgments

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