A Unifying Perspective on Context-aware Autonomic Network Selection

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Abstract

The growing market of wireless devices with multiple connectivity technologies - Wi-Fi, Bluetooth, and UMTS - is pushing toward the necessity of seamlessly selecting the proper connectivity network at any time. That selection should consider several elements, at different abstraction layers, from bandwidth requirements to network congestion, from connectivity costs to user preferences, in other words, it should be context-dependent. Relevant research work has recently addressed different aspects of context-dependent network selection. We claim it is time to offer a comprehensive survey with a unifying perspective (and a derived uniform terminology) to better point out similarities and specific aspects of solutions in the literature. In particular, the paper aims to achieve the twofold goal of i) identifying the primary design choices emerging from available solutions, together with corresponding tradeoffs, and ii) better positioning the wide variety of related work in a single classification. To that purpose, it introduces an original model to represent solution architectures, by showing how the model facilitates the understanding of the notable examples of 4th Generation and Always Best Connected networks. In addition, the paper proposes a novel taxonomy able to cluster any state-of-the-art solution along three classification directions: deployment scenarios, evaluation process, and continuity management.

1. INTRODUCTION

The diffusion of mobile devices is continuously growing, pushed by their rising and enhanced capabilities coupled with their decreasing costs. To achieve network connectivity while preserving mobility, current mobile devices can exploit several heterogeneous wireless technologies with different characteristics, such as available bandwidth, transmission range, allowed client mobility, power consumption, ... This heterogeneity is also justified by the specific suitability of different connectivity solutions for different deployment environments: for instance, GPRS/UMTS for Wireless Wide Area Networks (WWAN), IEEE 802.11 for Wireless Local Area Networks (WLAN), Bluetooth for Wireless Personal Area Networks (WPAN or simply PAN).

Today, it is very common that one portable device hosts client equipment of multiple wireless technologies and, when needed, can exploit more than one of them simultaneously. For example, most laptops and Personal Digital Assistants (PDAs) are already equipped with both IEEE 802.11 and Bluetooth cards; UMTS/GPRS smart phones can usually exploit also infra-red and Bluetooth connectivity, while the additional Wi-Fi option is emerging as a crucial market element due to the envisioned diffusion of Wi-Fi Voice over IP telephony. In addition, even if a PDA does not provide GPRS/UMTS capabilities, it could be interested in taking advantage of the network connectivity offered by a 3G mobile phone in proximity, for instance exploited as a Bluetooth modem.

That widespread availability of mobile devices with many wireless connectivity options calls for novel support solutions to exploit the dynamically available networks in the most appropriate manner, e.g., by selecting an IEEE 802.11 network if a running application requires large bandwidth and the Wi-Fi cell is not congested, or by choosing Bluetooth if the client is willing to preserve its battery and the running applications have compatible bandwidth requirements, or by connecting to a Bluetooth modem freely offered by a peer node if UMTS connectivity is too expensive in that area.

As pointed out by these cases, the choice of the most suitable connectivity solution at a given time depends on a large variety of elements, from user preferences to application requirements, from runtime environment conditions to expected stability in the availability of peers offering connectivity. In other terms, the choice of which connectivity to exploit should depend on context, intended as any information that describes the user (preferences, needs, location, ...) and the environment where she is operating (date, time, resource state, on-going service sessions, ...) [Bellavista et al. 2006b]. In particular, we define Context-aware Autonomic Management of Preferred network Opportunity (CAMPO) the integrated management, with full context visibility, of all connectivity solutions dynamically available at clients. For instance, a CAMPO system should be capable of enabling a single (the most suitable) network interface at a client in some context conditions, e.g., in low-battery situations, while deciding to dynamically exploit multiple interfaces simulta-
nously for different running applications in a different context.

Lots of recent research papers and activities, from both academia and industry, can be regarded as relevant but partial contributions to the wide CAMPO area: although state-of-the-art related papers share the same ultimate goal of smartly exploiting the set of dynamically available connectivity options, they exhibit many differences. In particular, they assume some specific network architectures and/or wireless technologies, by missing to identify uniform/similar aspects that could bring to a unifying perspective in this research field. In addition, they tend to adopt different vocabulary and, even worse, the same terms with different meanings. An illustrative example is the plethora of words exploited to describe envisioned CAMPO scenarios: 4th Generation (4G), Beyond 3G (B3G), 3G and Beyond (3GB), and Always Best Connected (ABC) are frequently used as synonyms, even if we claim that they should identify different forms, with specific aspects and characteristics, of possible CAMPO deployment scenarios. The lack of both a unifying perspective and a unique shared vocabulary represent non-negligible obstacles for beginners to orientate themselves in the CAMPO research area and for researchers/expert practitioners to correctly position their work in the field.

For these reasons, the paper aims to provide a comprehensive survey of all different CAMPO aspects with a twofold goal. On the one hand, by following a top-down approach, this survey intends to precisely identify which are the available points of choice to be considered by system/middleware/application developers working on CAMPO systems, so to simplify the determination of suitable tradeoffs and to guide proper CAMPO implementations. On the other hand, based on a bottom-up approach, the survey aims to depict how the wide variety of proposals in the field can be clustered according to a comprehensive taxonomy, by clearly showing the commonality of solution guidelines and system characteristics in the same clusters of that grid. The classification should considerably facilitate the understanding of the evolving CAMPO research field and the real differences among proposed solutions, thus providing a clarifying perspective on the area. We claim that only this twofold approach can achieve the double objective of identifying CAMPO principles and solution guidelines within a unifying synopsis and of putting together existing solutions in uniform categories to better identify the specific aspects of each contribution.

To that purpose, the paper introduces both a novel simple model to represent the wide variety of solutions in the CAMPO area and a comprehensive taxonomy to cluster state-of-the-art CAMPO systems. The proposed model permits, on the one hand, to precisely and univocally define basic terms, such as horizontal and vertical handover, and, on the other hand, to provide a very general and coarse-grained grouping of CAMPO solutions based on their architecture principles, as better detailed in the following. Moreover, our original taxonomy identifies three primary criteria (deployment scenarios, evaluation process, and continuity management) that permit to classify all CAMPO solutions in the literature. Deployment scenarios identify the set of considered wireless technologies/capabilities that should be available at clients and/or within the support infrastructure. The evaluation process category relates to the quantitative measurement of context-dependent suitability of the available network connectivity options. Continuity management is in charge of actually performing connection management operations (and choosing when to trigger them) needed to seamlessly switch between different connectivity options and providers, by preserving service continuity.

Let us stress that this survey represents an original, and we hope valuable, generalization effort if compared with already available tutorial papers in the literature, all focusing on specific aspects of either 4G or ABC networks, as extensively detailed in the related work section. In addition, differently from already published work, this survey provides a unifying overview and a thorough classification that can include both infrastructure-based deployment scenarios, with pre-deployed network attachment equipment (IEEE 802.11 access points, GPRS/UMTS base stations, …), and peer-to-peer scenarios where connectivity options are offered by opportunistically encountered peers, e.g., smart phones working as Bluetooth modems to the UMTS network.

The rest of the paper is structured as follows. Section 2 presents our original model for CAMPO system architectures. Section 3 exemplifies the usefulness of the proposed model in the notable case of pointing out similarities/differences between 4G and ABC solutions. Then, Section 4 describes our novel comprehensive taxonomy, by detailing the motivations driving the choice of the three adopted classification directions. Both the introduced model and taxonomy are exploited in Section 5 to characterize and classify all recent CAMPO research activities. By following the indications of the related work analysis, we are working on an original Mobility-Aware Connectivity system, overviewed in Section 6, which takes into account several context aspects, e.g., expected joint mobility of peers offering connectivity, to seamlessly adapt network selection. Finally, envisioned directions of future research and conclusive remarks end the paper.

2. A Unifying Architecture Model for CAMPO Solutions

The lack of both a common description model and a shared vocabulary Relevantly complicates the description of currently available CAMPO systems. In state-of-the-art papers, researchers are often involved in defining and re-defining even basic wireless terms, such as vertical handover. For these reasons, we claim the need for a simple but powerful model to represent a general CAMPO architecture, to classify both more usual cases of infrastructure-based wireless connectiv-
ty scenarios and emerging cases of opportunistically discovered peer-to-peer access to the Internet.

We propose the comprehensive general model reported in Figure 1. Any CAMPO system is modeled in terms of relationships between three types of entities only: applications, interfaces, and connectors. Each application represents a running service client at a user terminal and actively requests connectivity to fulfill its applicative goals, e.g., to download a hypertext from a Web server. Interfaces model the wireless hardware equipment available at the client side, e.g., Wi-Fi and Bluetooth client cards. Interfaces can be active/inactive (switched on/off, not stripped/stripped in the figure). Connectors are the entities actually providing client nodes with connectivity by interworking with client-side active interfaces (graphically, in the figure, a connector is compatible with an interface if the profiles of the two representing shapes match). Connectors include both fixed Access Point (AP) equipment of infrastructure-based networks (IEEE 802.11 APs, Bluetooth APs, GPRS/UMTS base stations, …) and mobile wireless peers, either offering Internet connectivity or temporarily playing the role of servers in a peer-to-peer interaction.

We claim that any deployment scenario where CAMPO solutions operate can be modeled in terms of two kinds of relationships: between applications and interfaces (interface selector) and between interfaces and connectors (connector selector). On the one hand, when requiring connectivity, an application should associate with an active interface. In simple and widespread current environments, an application statically associates with a single interface, already active before application launch (the interface selector relationship is static and 1-to-1). On the other hand, for any active interface, more than one connector may be available. For instance, a client with its switched-on Wi-Fi card can have visibility of more than one Wi-Fi connector (near Wi-Fi APs or peers in ad-hoc mode). Also in this case, nowadays most environments associates one interface with one single connector in a static way (the connector selector relationship is static and 1-to-1).

According to the model, we call channel the triple \{application, interface, connector\} that describes both the interface and connector relationships currently established for a running networked application client. Therefore, in traditional systems one application is usually involved in only one channel. We will see that all CAMPO solutions have the ultimate common goal to properly manage multiple channels for an application (or a set of applications) and of dynamically updating those channels depending on context.

Let us sketch an ideal provisioning scenario: we would like to have the most proper and dynamic channel selection (and consequent runtime update) with no impact on the design and implementation of both service clients and servers, which should focus only on the application logic, by possibly integrating also with legacy service components. In addition, it is desirable that also interface and connector implementations are not affected by relationship establishment and runtime modifications, in order to exploit any already deployed equipment and support. In other words, a CAMPO system is expected to be responsible for both interface and connector selections (multiplexing vertical black lines in the figure), possibly in a completely transparent way for application clients/servers, interfaces, and connectors.

At least any CAMPO solution should select the most proper interface(s) and connector(s) for an application statically, i.e., at application launch. Obviously, the context conditions determining channel determination may vary during service provisioning. A crucial aspect is, therefore, how a CAMPO solution reacts to dynamic variations in context conditions involving active channels (abrupt bandwidth/latency/jitter degradation due to congestion or client mobility, availability of new connectors with better quality, …). Simpler CAMPO solutions are only static and take interface/connector selection decisions simply at channel instantiation, without any further control and action. Sometimes, it is impossible even to change interface/connector when the channel is either broken or so degraded to produce service interruption. More flexible and relevant CAMPO systems, instead, are dynamic, i.e., they manage active channels at runtime, by modifying relationships among applications, interfaces, and connectors, in order to exploit available networks at best at any time. In that case, a crucial point is to avoid service interruptions and/or loss of service sessions while re-configuring active channels at provisioning time. Let us note that, as in any management system that performs corrective operations in response to variations of monitoring indicators (here, the possibly wide set of context conditions of interest), CAMPO solutions should carefully consider the tradeoff between responsiveness in channel updating and related costs, avoiding the risk of possible thrashing due to continuous relationship modifications.
Before next section thoroughly discusses how the proposed model can permit to better catch similarities and differences between 4G and ABC solutions, let us rapidly observe that the common meaning assigned to usual terms, such as horizontal/vertical handover and micro/macro-mobility, can be clearly defined and better understood by means of our model. For instance, our model permits to univocally define horizontal handover as the process of updating a channel by modifying an interface-connector relationship while maintaining the same interface (the application-interface relationship is unchanged). In particular, in intra-horizontal handover (or micro-mobility) situations, a CAMPO system should replace the origin connector with a new destination connector in the same network domain (dashed oval in Figure 2, part a), i.e., in the same subnetwork under the same administration realm. This is the usual behavior embedded in Wi-Fi client cards that automatically switch between different APs belonging to the same domain depending on the value and time-evolution of Received Signal Strength Indicators (RSSIs) from all APs in visibility. Differently, we define inter-horizontal handover (or macro-mobility) the situation, always without interface modification, where the change of connector also produces a domain modification, e.g., among Wi-Fi APs of different WLANs as in Figure 2, part b. Vertical handover, instead, is a channel update where the exploited interface is changes, thus usually forcing to a modification also in the selected connector(s), as depicted in Figure 2, part c.

Note that in current wireless systems the underlying network equipment usually manages inter-horizontal handover in an application-transparent and embedded way, e.g., in IEEE 802.11 or UMTS roaming, by adopting not modifiable strategies/mechanisms for connector selection. On the opposite, intra-horizontal and vertical handovers often require additional network/service management actions (external to the wireless equipment implementation) for channel re-configuration, e.g., client IP address change, re-start of client Authentication Authorization Accounting (AAA), and seamless transfer of service sessions. In particular, in infrastructure-based deployment scenarios, IEEE 802.11 APs and GPRS/UMTS base stations support inter-horizontal and vertical handover through re-routing mechanisms usually transparent to mobile clients, while in peer-to-peer connectivity there is typically the need for application peers to participate in an explicit end-to-end re-addressing. In the following, we will use the term continuity management to indicate the wide set of mechanisms, tools, and algorithms, from re-addressing to re-routing, from AAA to session transfer, that provide the building blocks to enable dynamic channel update without perceivable interruptions in service provisioning, possibly in a seamless way for wireless clients and final users. Given the wide heterogeneity of involved wireless technologies, in terms of both interfaces and connectors, there is a large spectrum of different continuity management mechanisms in the CAMPO literature. Our model also tends to give a unifying perspective on that plethora of support mechanisms, by identifying common goals and interworking opportunities/requirements (see Section 4.3).

Fig. 2. Intra-horizontal (a), inter-horizontal (b), and vertical (c) handover represented according to our proposed CAMPO model.

3. Exploiting the CAMPO Model to Characterize 4G and ABC Solutions

With the goal of exemplifying the application of our model to notable CAMPO cases in the literature, this section analyzes which are the main differences and points of contact between 4G and ABC systems by modeling them according to our proposal. That should contribute to reduce the confusion and imprecision in the current usage of the two terms.

Figure 3 represents the simplest, and today most common, working environment for a CAMPO solution. Even if several interfaces are potentially available for clients, only one of them is usually active at a time. That active interface is associated with any running application and with only one connector that is selected, among the ones available for that interface, according to an enforced strategy. In other words, if the running applications at client are N, all of them exploit the same interface, and that interface associates with only one connector, the same for every channel. In the following, we will use the expression \(<N:1:1>\) for the channel triple to indicate the fact that the interface selector relationship is N-to-1 and the connector selector relationship is 1-to-1.

In that scenario, the burden of interface selection is usually delegated to the user who can manually switch on/off the interfaces mounted on her client terminal. In this case the only CAMPO role is the choice of the most proper connector for the switched-on interface. Often, that choice is directly embedded in the implementation of client connectivity equipment, e.g., the client card implementation of the IEEE 802.11 MAC layer that may select the Wi-Fi AP with maximum RSSI. Typically there is no support to seamless interhorizontal and vertical handover. Only intra-horizontal handover is usually allowed with no impact on application implementation: its support is completely delegated to wireless client cards and to special-purpose infrastructure-side components for re-routing and/or re-
addressing, e.g., via standard signaling protocols between IEEE 802.11 APs.

Let us observe that the above simple case represents a poor CAMPO working environment, which does not exploit at all the wide set of possibilities offered by multiple connectivity technologies possibly available at the client side. For instance, in that scenario, even client connectivity depends on users in charge of switching on the suitable interface depending on locally available networks. On the contrary, we claim that a CAMPO solution should be capable of exploiting the different wireless interfaces available at clients at best, even in a synergic way, by automatically selecting the most suitable channel for each application depending on current context conditions and by supporting seamless channel switch during service provisioning.

The simple environment depicted in Figure 3 is still usual in current wireless systems. To overcome its limitations, several recent research activities, from both industry and academia, have proposed a large number of CAMPO solutions, with different characteristics and responsibilities, as extensively detailed in Section 5. Nowadays, 4G and ABC are the terms most frequently used to generally indicate CAMPO systems that go beyond the above simple case. However, in several state-of-the-art papers, the two terms are used in a confused way, sometimes as synonyms, without stressing their peculiar characteristics and their differences. We claim that 4G and ABC should identify two specific and differentiated families of CAMPO solutions and their precise definitions could benefit from our CAMPO architecture model to clearly point out specific properties and assumptions.

In particular, by adopting our model, it is easy to identify that, differently from ABC solutions, 4G systems respect the constraint that all applications at a 4G client have to exploit only one interface at a time (see Figure 4). CAMPO systems for 4G are in charge of two main management actions: i) selecting the interface to activate at any time and ii) performing vertical handover, i.e., commanding the continuity management support to seamlessly update all active channels when there is the need to change the currently switched-on interface. That typically occurs because there are no alternate connectors available for the previously activated interface, for instance, because a Wi-Fi-connected client is moving and entering an area not covered by IEEE 802.11 APs.

![Fig. 4. Usual 4G solutions can be modeled as <N:1:1> wireless environments that can dynamically change the activated interface.](image-url)

To perform vertical handover, 4G clients and infrastructure-side support components collaborate to gather the context information required for proper interface selection (see Section 4.2), e.g., signal quality, level of congestion, and estimated jitter. 4G selection strategies may pursue either a local client-specific goal, e.g., continuous channel availability or QoS maintenance, or a global goal, e.g., load balancing among overlapped cells. Occasionally, 4G systems also aim at providing support for inter-horizontal handover, while intra-horizontal handovers are generally performed by network equipment in a transparent way in this kind of CAMPO solutions. On the contrary, connector selection (typically considering only infrastructure-based equipment, such as APs or base stations) is completely embedded in interface implementation and application-transparent.

In summary, in any case 4G solutions associate all applications running at a client with the same interface and, therefore, typically consider client node requirements as a whole to choose the most suitable interface. The cardinality for interface/connector selector relationships in 4G is <N:1:1> as in the simplest case of Figure 3, but these systems add the primary capability of dynamically changing the activated interface.

On the contrary, we claim that the ABC term should be used to indicate more flexible CAMPO solutions where multiple interfaces may be simultaneously active and the main goal is to activate and update the most suitable channels for any running application. The motivation is that different applications usually have different service-specific requirements in terms of bandwidth, latency, and sustainable discontinuity intervals. Thus, the possibility to have channels with different interfaces for different applications at the same time can significantly improve the exploitation of available networking options.

By exploiting our CAMPO architecture model, it is possible to identify two main categories of ABC solutions depending on the cardinality of the connector.
selector relationship. On the one hand, there are ABC systems where each activated interface associates with a single connector (<N:M:M> ABC systems). <N:M:M> solutions are responsible for activating the proper interfaces among the set of available ones and for selecting/updating the most suitable connector for each of them. On the other hand, more complex ABC systems additionally consider the possibility of associating multiple connectors with each active interface, thus enabling applications that exploit the same interface but different connectors (<N:M:L> solutions).

Figure 5 depicts the case of <N:M:M> CAMPO systems. Differently from 4G, here the interface/connector selection strategies should consider the requirements of any application and not of the client as a whole. In addition to interface activation and initial connector selection for each active interface, <N:M:M> systems are typically in charge of channel updating when new interfaces become more suitable than the currently used one. Therefore, these CAMPO systems generally include continuity management mechanisms for per-channel re-addressing and for communicating endpoint modifications to application clients/servers. On the opposite, <N:M:M> systems usually do not automatically update the choice of the connector for each interface, by delegating that selection to the embedded behavior of network equipment. For instance, once activated, the client UMTS card autonomously selects the base station where to attach among the ones in visibility depending on an embedded strategy.

![Fig. 5. Usual ABC solutions can be modeled as <N:M:M> wireless environments.](image)

<N:M:L> ABC solutions are even more flexible and can actively select not only the interface but also the connector for each channel (see Figure 6). In addition, these CAMPO systems are often able to consider an enlarged set of potential connectors. They can take into account not only traditional infrastructure-side network components, such as IEEE 802.11 APs and GPRS/UMTS base stations as in 4G, but also nearby peers in wireless ad-hoc connectivity mode behaving as connectivity bridges. Notwithstanding that flexibility, in some real <N:M:L> systems the possibilities of connector selection may be reduced due to possible limitations in communication technology capabilities. For instance, Bluetooth allows concurrent interworking with connectors residing in different networks (scatternet) and ad-hoc-configured IEEE 802.11 permits to simultaneously interact with different connectors in the same ad-hoc network, provided that the nodes have the same Extended Service Set Identifier. On the contrary, IEEE 802.11 in infrastructure mode and most cellular technologies provide very limited or null capabilities to control connector selection, thus forcibly limiting the selection space available for CAMPO systems developed on their top.

Similarly to <N:M:M> systems, <N:M:L> solutions are in charge of implementing continuity management mechanisms for per-channel re-addressing, even if in these systems mobile nodes are often responsible for invoking these mechanisms at channel updates (end-to-end visibility of channel modifications). For instance, mobile nodes may be requested to notify their new IP addresses after a channel update by exploiting CAMPO signaling facilities. In addition, differently from other ABC systems, <N:M:L> solutions should be able to manage the increased complexity stemming from the need to simultaneously monitor a large set of connectors for different interfaces in order to command channel updates when better connectors are available. Moreover, these solutions should address the challenging issue of considering and evaluating the possible unreliability of peer connectors to operate proper channel decisions: differently from APs and base stations, peer connectors may abruptly become unavailable due to mobility or power shortage, thus forcing frequent channel update operations (and the consequent overhead).

![Fig. 6. Flexible ABC solutions support <N:M:L> cardinality for interface/connector selector relationships.](image)

4. An Original Comprehensive Taxonomy for CAMPO Solutions

CAMPO systems may pursue goals at different abstraction levels and with different flexibility, by considering even very diverse assumptions on their working environments. After the introduction of the proposed architecture model and first examples of general 4G and ABC features, here we aim to provide an exhaustive description of all the possible differentiated characteristics of CAMPO systems, organized in a structured classification that permits to clearly position all CAMPO contributions in the literature.
Figure 7 graphically depicts the proposed comprehensive and original taxonomy for CAMPO solutions. Our taxonomy is structured according to three main categories: deployment scenarios, evaluation process, and continuity management. In short, deployment scenarios represent and define the characteristics of target execution environments. The evaluation process specifies how to instantiate and update channels (interface and/or connector selection). Continuity management identifies the set of mechanisms, algorithms, and tools to actually operate horizontal/vertical handovers, possibly in a seamless way notwithstanding runtime client mobility. Figure 7 shows how our taxonomy refines each primary category by identifying first-, second-, and third-level sub-classes, structured in a hierarchical tree organization. The characteristics, relevance, and CAMPO system coverage for each subclass will be described in the following sub-sections.

We claim that our articulated taxonomy can clearly classify the whole set of CAMPO systems, by facilitating the identification of similarities/differences between the various contributions. In fact, on the one hand, the three primary categories address all the primary aspects of state-of-the-art CAMPO solutions, even if those aspects are sometimes identified with different terms in the literature. On the other hand, they represent the three crucial families of design choices to consider for researchers and developers when designing novel CAMPO solutions. Other support functions, e.g., quality management, that may be employed in CAMPO systems but are not specific of the CAMPO research field, are outside the taxonomy, which aims to center the specificity of the area.

To permit the full understanding of the sub-class structuring detailed in the following sub-sections, let us first introduce what we intend exactly for the three taxonomy categories. We define deployment scenario as the set of assumptions and related constraints that a CAMPO solution adopts depending on its expected and/or current working environment. In other words, the deployment scenario category relates to working environment characteristics such as the set of selectable channels (possibility to choose either interface or connector or both), the number of interfaces that may be
simultaneously active at clients, and the role/location of support components, e.g., to locally/remotely trigger handovers and to perform session transfer.

While the deployment scenario identifies the addressed working environment, evaluation process and contingency management categorize the primary operations that a CAMPO system must perform to provide final users with suitable and updated channels (see Figure 8). In particular, the evaluation process is in charge of gathering context information and consequently providing a quantitative estimation of the suitability of available channels according to an adopted metric. Any metric consists of three main parts, which determines its expressiveness: input, processing method, and output. The input sub-class defines the level of abstraction and variability of the exploited context information, e.g., the continuously changing bandwidth offered by a connector or the more static user-level indications about preferred interfaces. The processing method mainly influences metric flexibility (ability to vary the adopted metric at provisioning time) and the scope of CAMPO goals (e.g., the global objective of optimal load sharing among all access networks). The output sub-class defines the granularity of selected entities and the result type provided by the evaluation process, e.g., the most suitable interface or a set of values quantifying the suitability of any potentially available connector.

![Fig. 8. The primary sub-components of evaluation process and continuity management.](image)

Finally, continuity management relates to all the mechanisms, tools, and strategies to actually perform the update of active channels at provisioning time without user-perceivable service interruptions. As depicted in Figure 8, continuity management not only decides when and how to update channels depending on the evaluation process output (trigger component) but also provides the support mechanisms to seamlessly switch among interfaces and/or connectors at runtime (switcher component). Let us note that first simple CAMPO systems did not include continuity management facilities at all, or sometimes a very limited capability subset, by leaving application developers the burden of addressing the challenging continuity issues associated with channel update. We claim that, nowadays, the availability and flexibility of continuity management solutions are crucial aspects of CAMPO systems because of the growing relevance of mobile continuous services, such as mobile multimedia. That is the reason why we have decided to originally devote one whole specific category of the taxonomy to that demanding aspect.

Most state-of-the-art CAMPO systems only concentrate on one of the three categories and adopt solutions proposed by other CAMPO researches for the remaining two. For instance, many contributions have focused on identifying original strategies for interface/connector selection by delegating to Mobile IP the burden of partially solving continuity issues. Other CAMPO systems propose innovative continuity management solutions by leaving to mobile nodes the burden to evaluate when, where, and which type of handover should be performed. Moreover, as better detailed in the following, some CAMPO proposals provide seamless horizontal/vertical handover of service sessions by imposing specific constraints on deployment scenarios, i.e., by assuming the presence (and full visibility) of needed support components in specific locations. Anyway, in general, even if the three categories are not strictly correlated, some assumptions in a category may limit the space of potential design choices for the remaining two. In other words, the chosen deployment scenario subclass may limit the available design choices for CAMPO developers by making some evaluation and continuity solutions not viable. For instance, it is hard to pursue a global objective in a deployment scenario where CAMPO components are located only client-side, global context information is often not available, and continuity management is usually performed in an end-to-end way.

The following subsections extensively describe and discuss the three adopted taxonomy categories, by pointing out the associated design options for CAMPO developers.

### 4.1. CAMPO Deployment Scenarios

The variety of state-of-the-art CAMPO solutions also depends on the fact that they focus on different target deployment scenarios. It is possible to identify three main categories of deployment scenarios where CAMPO solutions take decisions based on i) the only information about available interfaces (and possibly associated connectors) at each client node, ii) the additional data about working channels and overall node capabilities/requirements for each client node, and iii) the additional knowledge about the whole execution environment, including the infrastructure side, such as the presence of auxiliary CAMPO-related support components.

CAMPO systems in the first category establish and update channels on a node depending on interface scope, i.e., the set of static/dynamic characteristics of the interfaces (either active or not) available at the node. These CAMPO solutions can only consider aspects such as possibilities of interface control and programmability: in fact, some network interfaces only allow to be switched on/off, while in other cases dynamic interface management is possible with a finer control degree, e.g., by deciding when and to which connector to command the horizontal handover of an interface. By focusing on the second sub-category (mobile node scope), these CAMPO solutions can consider the whole client node environment to guide their decisions. Depending on the whole set of not only ac-
Interface scope CAMPO solutions may be classified into two primary types: interface-only and interface-connector. Interface-only systems can select only the interface to exploit (possibly by switching on inactive interfaces), by delegating any other interface management action to the embedded and not-modifiable firmware/hardware of the selected interface. In other words, interface-only CAMPO systems address deployment scenarios where, given an interface, the selection of its associated connector is outside control. On the contrary, interface-connector CAMPO systems can additionally select the connector to exploit via interface-embedded capabilities, which could depend on client card implementations. For instance, as already sketched in Section 3, UMTS does not enable the choice of a specific base station (interface-only), while ABC solutions usually permit to switch to a selected connector (interface-connector).

By focusing on related design choices, the decision of assuming a target deployment scenario with interface scope significantly limits the design possibilities for CAMPO developers. In very simple CAMPO solutions of this class, the choice of the connector for a given interface is completely delegated to the embedded behavior of low-layer communication components. For instance, the selection of a specific IEEE 802.11 AP among the set of APs in visibility is typically embedded in Wi-Fi card implementations. Only very simple metrics can be specified: for instance, if the most important requirement is to minimize power consumption, a CAMPO system gives priority to the activation of low consumption interfaces, such as Bluetooth, without considering any other context indicator. In slightly more flexible cases, interface scope CAMPO solutions can also decide which connector to exploit among the available ones for a given interface, for instance the AP connector with minor congestion among the trusted ones. That is obviously possible only when interface implementation also supports connector selection. In these cases, CAMPO systems are in charge of comparing not only interface capabilities (often statically pre-defined) but also connector-related performance indicators, such as currently offered QoS level, thus calling for resource-demanding runtime monitoring functions.

Let us note that interface scope CAMPO solutions usually consider no more than infrastructure-based connectors, such as IEEE 802.11 APs or UMTS base stations. Only recently, first CAMPO proposals have started to work on the possibility to exploit also nearby client nodes as peer connectors. A peer connector can either behave as a bridge between the client and the fixed Internet infrastructure or directly offer services in a peer-to-peer fashion. The possibility to consider peer connectors provides a deployment scenario that greatly differs from traditional infrastructure-based environments, by requiring to take into account peer characteristics of various nature. In fact, while infrastructure-based connectors are usually fixed and reliable, peer...
nodes may be mobile, statically unknown, and with variable levels of trust. Moreover, clients and peer connectors should share a common goal to make their connectivity convenient for nearby peers. In addition, peer connectors typically provide connectivity in an intermittent way since i) their offer produces additional computational, networking, and energetic loads for them, and ii) their possible mobility increases the probability of connectivity loss for their associated clients. These challenging aspects represent state-of-the-art open issues and call for original approaches to manage novel forms of context, e.g., peer mobility indicators (see Section 6).

Finally, let us rapidly observe that the CAMPO architecture model presented in Section 2 can also apply to the case of peer connectors, which in their turn can exploit channels to connect to the Internet or to other peer connectors. In the simple example of Figure 11, indeed, a client hosts only the Bluetooth interface, which is used to connect to a nearby peer connector offering Internet connectivity, e.g., via its Wi-Fi interface connected to a free IEEE 802.11 hotspot (second connector, in pipeline with the first one).

Fig. 11. An example of deployment scenario with peer connectors.

4.1.2. Mobile Node Scope

By focusing on the second category of our deployment scenario classification, CAMPO systems with mobile node scope may concentrate on exploiting either only one network interface at a time (single-on) or several interfaces simultaneously (multiple-on). For instance, 4G solutions usually exploit only one interface at a time: every channel uses the same interface, the currently active one. On the contrary, ABC solutions can take advantage of several interfaces simultaneously and can establish different channels by exploiting different, concurrently activated interfaces.

The choice between single-on and multiple-on deployment scenarios is probably the most important aspect affecting CAMPO design choices. Sometimes that decision is forced by the addressed execution environment. In fact, the possibility of having multiple active interfaces at the same time usually depends on client capabilities. Limited mobile nodes often prefer simple, lightweight, and energy-preserving CAMPO solutions, e.g., there should be only one active interface at a time, selected according to a static priority order. As resource availability on common clients is increasing, CAMPO systems start to favor smarter and more resource-consuming solutions, e.g., which exploit several interfaces at the same time to widen the available bandwidth or to provide continuous connectivity via duplicated data flows during vertical handovers [Shenoy and Montalvo 2005].

In addition, the single-on/multiple-on deployment category influences other relevant design choices. For instance, CAMPO single-on solutions have to choose the only one interface to activate at a node by taking into consideration the requirements of the whole set of running applications and trading among them. Multiple-on solutions, instead, are inherently more complex because they must allow the simultaneous management of multiple interfaces. Anyway, in single-on solutions the decision to change the activated interface implies evaluating the costs to update all channels, while multiple-on solutions can activate new interfaces independently of other working channels.

4.1.3. Whole Environment Scope

To the purpose of proper channel selection/update, CAMPO solutions may additionally consider the possible availability of support components with different roles (evaluation process and continuity management) in the execution environment, located either on the client side or distributed on both client and infrastructure sides.

About the role of support components in the execution environment, the variegated set of mechanisms and tools of interest for CAMPO systems span from QoS channel monitoring to more general context gathering, from metric evaluation to the triggering of continuity management operations, from context transfer in response to handovers to AAA support. Here, we do not provide the exhaustive description of CAMPO support mechanisms because they will be extensively detailed in the following sections devoted to evaluation process and continuity management.

About the location where support components execute, some CAMPO solutions privilege the exploitation of only client-side components, while other approaches include components distributed both at clients and in the network infrastructure. Client-side support
components are generally simpler and focused on switching between available interfaces. Usually, both client- and infrastructure-side components interwork to collect monitoring information about connectors, especially in flexible CAMPO systems where monitored context includes data from the whole execution environment. In addition, when infrastructure-side components have also the role of interface/connector selectors, they can take into account not only client capabilities/requirements but also global network objectives, such as load balancing. Continuity management components are usually deployed on both the client side, e.g., pre-fetching buffers to sustain streaming continuity during handovers, and the infrastructure side, e.g., Session Initiation Protocol (SIP) servers for session transfer.

As for the other deployment scenario categories, also the role and location of support components in the execution environment may depend on deployment constraints and are inter-related with CAMPO design choices. For instance, by referring to the already examined notable examples of 4G and ABC, 4G systems usually aim to maintain mobile nodes simple, by delegating to infrastructure-side components as many tasks as possible, e.g., vertical handover triggering and traffic re-routing. ABC solutions, instead, tend to favor limited coupling between mobile nodes and the network infrastructure: clients are usually smarter and directly manage interfaces/connectors. More generally, on the one hand, deploying special-purpose support components on mobile nodes is often the simplest way to CAMPO realization from the perspective of network providers because it does not force to modify network infrastructures, by imposing all the burden of hardware/software adoption to interested end points. However, given the often limited capabilities of mobile nodes, the client-side approach does not enable flexible CAMPO solutions. On the other hand, the availability of a highly open and dynamic network infrastructure would permit to deploy special-purpose components on powerful infrastructure nodes, where and when needed, with obvious potential advantages in terms of performance. For instance, it would allow IEEE 802.11/UMTS integration by dynamically injecting the needed continuity support capabilities in the UMTS network equipment at the edges with the Wi-Fi LANs of current interest. Network infrastructures, especially today’s telecommunication ones, often lack the needed degree of openness and dynamicity to achieve that goal, and there is the need of interacting with external support components, such as Mobile IP servers outside the UMTS infrastructure, to enable seamless network switching.

4.2. CAMPO Evaluation Process

The goal of CAMPO evaluation process is to quantitatively, in a homogeneous and comparable manner, the current suitability of possibly heterogeneous interfaces and/or connectors to be included in active channels. That comparison is necessary whenever a decision is important, either at channel set up time (when an application starts and requires the instantiation of a new channel) or to update active channels during service provisioning (change of interface and/or connector). Figure 14 gives a high-level simple representation of the CAMPO evaluation process as the pipeline of three successive steps: the collection of input values describing the current and applicable context, the evaluation of a metric that processes context input, and the delivery of the output result produced by the processing step. Input, processing, and output are the three sub-classes of the evaluation process category of our taxonomy and will be extensively described in the following sub-sections.

![Fig. 14. CAMPO evaluation as a three-step process.](image)

More traditionally, it is possible to define the evaluation process as the set of operations needed to evaluate an adopted metric, represented by the cost function:

\[ \text{resultType} \ C (\text{inputType}, \text{staticContext}, \text{inputType}, \text{dynamicContext}) \]

where the \text{staticContext} and \text{dynamicContext} input parameters are current values of entities of interest in the applicable context, respectively with less frequent or more frequent modifications, and \text{resultType} can largely vary in nature and represents the recommendation for channel instantiation/update, as better explained in the following. The distinction of input parameters depending on their expected change rate is crucial to enable effective CAMPO solutions, e.g., which continuously monitor only a limited set of context indicators while assuming fixed per-session values for static context parameters.

The definition of a suitable evaluation process for a CAMPO system is a complex task. A primary issue is to properly choose the context input parameters to consider. Input parameters should be easily measurable and comparable for the different interfaces/connectors available at runtime. In fact, to guarantee openness and easy extensibility, the evaluation process should not depend on any particular communication technology (and should be applicable also to newly introduced connectivity solutions). In addition, different evaluation processes may exhibit very differentiated complexity, changeability, and expressiveness, with a significant impact and correlation with the addressed deployment scenario. Roughly speaking, very expressive processing with complex goals, such as fairly distributing bandwidth to clients in a network domain, may require frequent interactions with the deployment environment to collect monitoring indicators (to be included in the context input) and call for frequent re-evaluations (output result updates). On the contrary, simple evaluation processes, such as minimizing client power consumption by always exploiting the least con-
summing interface, can be provided very easily with a
pre-defined priority order for interfaces/connectors,
with minimum overhead.

4.2.1. Input

Input data may have different degrees of dynamicity
and be at different layers of abstraction (variations
and abstraction level sub-classes of our taxonomy). About
variations, input data can be classified as either static
or dynamic. Static context information, such as average
power consumption for an interface, maximum data
 throughput for a connector, user preferences and appli-
cation requirements, either slowly changes or does not
 vary at all for a given channel during a service session.
Dynamic context data, such as the bandwidth/delay/jitter
currently provided by a connector, tends to vary frequently,
also within the same service session, thus requiring proper context monitoring sup-
port.

About levels of abstraction, context input may in-
clude physical-, network-, or application-layer infor-
mation. Physical context data usually relates to dynam-
ic monitoring information such as RSSI or Signal to
Noise Ratio (SNR). In addition, it may include static
properties of a communication technology, e.g., aver-
age power consumption or maximum data throughput.
Network-layer data comprise currently provided band-
width, delay, and jitter, which typically are very dy-
namic context indicators. Application-layer data, in-
stead, include user-related context (user requirements,
priorities, history, …), terminal-related capability con-
text (client hardware and software capabilities), and
connectivity provider-related context (such as the en-
forced pricing model).

As already stated for other CAMPO taxonomy cat-
egories, the choice of input parameters for the evalu-
ation process depends on the target deployment envi-
ronment and may strongly influence several CAMPO
design choices. Since most gathering/processing activi-
ties are performed at clients in usual CAMPO solu-
tions, simple evaluation processes exploiting static
input parameters better fit mobile nodes with limited
capabilities. Clients with richer resource availability
permit more dynamic and expressive input data, so to
promptly react to even complex context variations,
such as changes in client location and speed. Open/rich
deployment scenarios with infrastructure-side compo-
nents usually permit to monitor a larger set of state
information about eligible connectors, e.g., the amount
of currently served mobile nodes or the available
bandwidth. In an evolutionary historic perspective, let
us note that first CAMPO approaches simply consider
low-layer context information, by basing their choices
over traditional and locally measurable input values,
such as network latency and RSSI, e.g., by choosing
always the IEEE 802.11 AP with greatest RSSI. The
trend in advanced CAMPO solutions is to include
higher-layer input data to perform channel manage-
ment decisions with full awareness of more expressive
context information.

4.2.2. Processing

The choice of the processing method to adopt remark-
ably influences the expressivity and complexity of the
evaluation process. Our claim is that the most impor-
tant processing aspects are the level of flexibility (the
capability to modify and adapt processing methods at
runtime, either embedded or extensible) and the scope
of the pursued objective (either local or global).

About flexibility, embedded processing methods
permit to define how to combine input data only before
starting CAMPO execution; any metric variation re-
quires stopping and restarting the CAMPO system.
Extensible processing methods, instead, are modifiable
also during service provisioning. For this reason, most
state-of-the-art proposals offer extensible processing
solutions, either function-based or policy-based. Func-
tion-based metrics typically calculate output as a linear
function of context input data and of weights, which
may be adaptively configured also at service provision-
ing time. To further increase processing flexibility,
some CAMPO solutions propose general frameworks
to define metrics depending on high-level declarative
obligation policies. Policies are activated by specified
values of context input and may be specified/modified
at runtime, with no impact on the implementation of
CAMPO system and of service logic.

About the processing objective scope, in the case of
local goal, the processing method has visibility and
tries to fit only the local requirements expressed by the
client node, such as minimizing client power consump-
tion and maximizing network throughput. In the case of
global objective, the processing method aims to
achieve a network-wide objective, such as balancing
network load among available connectors at all clients.
and maximizing the global throughput of a network, e.g., by preferring connectors currently involved in the minimum number of channels.

Also in this case, the flexibility and the objective scope of the processing method affect CAMPO design choices and are influenced by the addressed deployment scenario. Even if less intrusive from the overhead point of view, embedded solutions seem unsuitable for highly dynamic CAMPO scenarios; some recent research activities even claim the impossibility of adopting effective static definitions of general-purpose processing methods because it starts to be recognized that metric suitability also depends on user/application-level requirements. Usually there is the need for a high level of processing expressiveness when exploiting rich input data, in order to exploit at best the deep context visibility to achieve sophisticated interface/connector selections. Simpler processing methods are usually coupled with less complete context awareness and the willingness to achieve lightweight CAMPO solutions. In general, more complex and flexible the processing method, more context information needed (by generally requiring the execution of monitoring components with non-negligible overhead), and more expressive the resulting output, as detailed in the following.

4.2.3. Output

The evaluation process output may be of various nature. On the one hand, CAMPO solutions may differ on the type of entity provided as processing method result type (either interface or connector). On the other hand, and orthogonally, they can either directly provide their result as the best interface/connector/channel (value sub-class) or produce a set of values that continuity management can then exploit for channel update decisions (evaluation set sub-class). For instance, that set of output values may be the list of available interfaces in prioritized order, the list of available connectors in prioritized order, or a set of numerical values quantitatively evaluating any potentially available channel.

Let us rapidly note that, in any case, the processing output is only the input data for the following continuity management stage and may differ from the final handover decision taken by the CAMPO system. For instance, the continuity trigger component, described in the following section, can decide not to command the switching towards the first channel in the output prioritized list because that channel was recently used. CAMPO continuity management solutions may adopt hysteresis time intervals to prevent channel update bouncing.

The chosen sub-class of evaluation process output affects the design and implementation complexity of a CAMPO system. In the case of interface selection, the output is simply the result of the evaluation of all the interfaces available at the client node, by considering or not the currently switched-off ones. In the case of connector selection, the set of possibilities to take into account is noticeably larger: CAMPO systems have to evaluate all connectors associated with any interface (in most CAMPO solutions also non-active ones). In addition, the ability to select connectors tends to increase the CAMPO complexity because it requires both managing the heterogeneity of interface features and deeply interacting with them, e.g., to extract context information about both IEEE 802.11 APs and GPRS/UMTS base stations. Moreover, the choice of an output result type may affect the level of abstraction of the context information to consider: in the case of interface selection, physical- and network-layer context is usually considered adequate; when the result type also includes connectors, there is usually the need for full visibility of more complex and articulated application-layer context, thus pushing towards more flexible CAMPO design choices.

4.3. CAMPO Continuity Management

After the initial phase of channel setup, there is the need to reconsider and possibly update working channels depending on context variations, including interface/connector availability. In CAMPO solutions, continuity management components are in charge of receiving the output of the evaluation process, of consequently deciding channel updates, and of seamlessly performing interface/connector switches at service provisioning time, for instance by ensuring content streaming continuity in despite mobile node movements between a Wi-Fi covered area and another location with only UMTS connectivity.

Continuity management components can be grouped into two main classes, as depicted in Figure 8: triggers and switchers. On the one hand, triggers may reside on either the client- or the infrastructure-side and play the role of monitoring active channels, by commanding channel update operations to switchers when needed. Triggers are clients of the evaluation processing output: they either gather evaluation results via polling or wait for event notifications related to context variations. On the other hand, when commanded by triggers, switchers perform all network/service management operations to maintain service session continuity notwithstanding runtime channel modifications. Trigger classification and design choices are strongly inter-related with evaluation output sub-classes and the paper has already discussed that point in the previous section. For that reason, here we focus on switcher mechanisms, crucial for continuity.
management, and on their classification and deriving design choices.

Switcher solutions have been and still are one of the primary open points of investigation in CAMPO research activities. Switcher proposals in the literature may be classified along three primary directions: level of integration with the execution environment, granularity, and level of client visibility. Integration represents the relationship among origin and destination connectors when performing handovers. In particular, from the integration point of view, connectors may be either tightly or loosely coupled. Tightly integrated connectors are deployed in the same administrative domain, are supposed to know each other, and can communicate directly, e.g., via special-purpose protocols, thus reducing the complexity and the duties of switcher mechanisms. Loosely integrated connectors, instead, are deployed in different administrative domains, typically communicate via standard IP-based channels, and require intra-domain agreements in order to cooperate effectively.

Granularity defines the target of the continuity management process. When triggered, per node switchers migrate every active channel between connectors involved in the handovers, by adopting a coarse-grained approach and exploiting the most suitable interface/connector for the whole mobile node. On the contrary, per channel switchers can migrate even only one channel per time, in a finer-grained manner, thus enabling each channel to exploit its most suitable interface/connector.

Client visibility permits to identify the degree of involvement of mobile clients in the continuity management process. Transparent CAMPO continuity solutions usually perform their management actions on the infrastructure side, without any direct client involvement, thus enabling simple and lightweight mobile clients. On the contrary, end-to-end approaches tend to minimize infrastructure-side requirements, by delegating the needed continuity management operations to mobile clients.

4.3.1. Tight/Loose Integration

Network providers, especially cellular operators, have recently spent significant efforts to address CAMPO integration issues, in particular with the specific challenge of WLAN/cellular integration in mind. Possibly biased by the experience of telecommunications providers, these solutions aim to extend the operator network infrastructure, often in a close and proprietary way, to seamlessly include additional connectivity opportunities, such as Wi-Fi. On the contrary, there is a recent emerging trend in integration systems that aim to provide seamless interworking of different connectivity solutions without deploying any novel equipment on the operator-side part of the network infrastructure. The advantages are obvious in terms of dynamicity and easy deployment.

Guided by the two exemplifications above, we have decided to classify continuity management CAMPO solutions in two integration sub-classes: tight integration solutions, e.g., where WLAN APs should be deployed as novel equipment inside a proprietary cellular network, or loose integration solutions, e.g., where WLAN APs are deployed outside a cellular network, typically at the boundaries between the cellular network and the traditional Internet, with no impact on the already installed network equipment [ETSI 2001]. Only to mention a notable example, according to the proposed taxonomy, IEEE 802.11 APs are classified as tightly integrated within a GPRS/UMTS network when deployed as a part of the GPRS/UMTS infrastructure and seen as proprietary network equipment belonging to the telecommunication provider infrastructure. On the contrary, the same APs could be deployed in a loosely integrated way, when installed outside the operator infrastructure and possibly managed by a third party.

First CAMPO solutions were focused on tightly integrated scenarios. By adopting primarily the network operator point of view, the most relevant issues they addressed was to find the optimal location where to deploy and integrate connectors inside the already available telecommunication infrastructure (usually WLAN connectors in a cellular network) in order to provide continuity management capabilities.

Most recent CAMPO literature is changing the point of view. It mainly focuses on loosely-coupled integration of heterogeneous networks, by assuming few or no capabilities at all to intervene on already deployed proprietary networks. That change of focus has also influenced a terminology change: first CAMPO solutions classified handovers as intra/inter-domain depending on the possible change of administrative domains between origin and destination networks, usually managed in a proprietary way by their operators; currently, most CAMPO papers use the terms intra-horizontal, inter-horizontal, and vertical handover (see the definitions in Section 2) to move the accent on the characteristics of evaluation process and continuity management.

The set of needed switcher actions strongly depends on the integration relationship between origin and destination connectors. In tightly integrated scenarios, intra-domain handovers require a limited set of support mechanisms. In fact, since connectors belong to the same administrative domain, it is possible to assume that network-related client characteristics do not change, first of all client IP address. The only needed
action is to update client location, i.e., to propagate the identity of the currently accessed connector in order to correctly re-route packets; that usually involves only lower layers of the OSI protocol stack. On the contrary, inter-domain handovers usually force to change several network characteristics and require the coordination of connectors deployed in different administrative domains, probably handled by different network operators. For instance, to support seamless connectivity for final users, origin and destination connectors have to agree on a common AAA mechanism to transparently migrate client credentials; in this case, packet re-routing usually interests also the higher layers of the OSI stack. In any case, in tightly integrated scenarios, all switcher operations on the client-side are delegated to embedded firmware, which transparently migrates active channels among interfaces. In addition, in loosely integrated scenarios, intra-horizontal handovers require the same mechanisms adopted for intra-domain handovers, while inter-horizontal and vertical handovers are similar to inter-domain ones. However, let us note that in the case of vertical handovers switcher mechanisms on the infrastructure-side do not change considerably while on the client-side there is the need to perform several additional actions, specifically designed to effectively and seamlessly migrate active channels without affecting the lower layer implementation of the exploited interfaces.

Also the decision of tight/loose integration relevantly influences the design choices available for effective CAMPO solutions. Tight integration solutions usually require low-layer interface integration and are characterized by little or no handover control capabilities propagated up to the application level. Both interface and connector selection are usually delegated to embedded solutions, e.g., interface firmware. In addition, tightly integrated environments are possible only if promoted by network infrastructure providers (for instance, by cellular operators) because they require the exploitation of special-purpose integration equipment directly deployed in the cellular network. However, tightly integrated solutions are usually characterized by better performance, e.g., smaller handover completion times, because origin and destination connectors can benefit from the homogeneity deriving from belonging to the same administrative domain. On the contrary, usually loosely integrated CAMPO solutions only require the deployment of special-purpose components on mobile nodes, e.g., to evaluate when and to which network to make a handover, and/or on auxiliary distributed support components added with no impact on the cellular network, e.g., intermediary proxies working as care-of-addresses for mobile nodes. In addition, loosely integrated solutions may take advantage of already available standard supports for continuity management, e.g., Mobile IP and SIP, thus facilitating and accelerating the deployment of CAMPO systems. Notwithstanding the potential limitations in terms of achievable performance, flexibility and easy deployment make loosely integrated CAMPO solutions definitely more suitable in the execution environments envisioned for the near future.

### 4.3.2. Granularity

![Fig. 19. Continuity management granularity.](image)

From the granularity point of view, switching operations may be categorized in two main sub-classes: per node and per channel. Shortly, in per node CAMPO solutions the main continuity management goal is to seamlessly re-route the whole node traffic from the origin to the destination network. In the case of per channel switching, instead, the CAMPO continuity support is in charge of updating any single node channel, possibly independently from one another.

Per node switching requires reconsidering and possibly reconfiguring the whole set of resource bindings of a mobile node transparently, e.g., to autonomously discover a new printer in the destination network and to maintain updated references to remote resources such as network file systems. In addition, there is the need to disseminate information about node location, since a network change usually delves into location-related modifications such as IP address change. Moreover, there is the need to manage traffic flows during handovers, e.g., by maintaining streaming continuity at the expense of additional computing/network overhead via bi-casting to both origin and new destination networks. Finally, the provisioning of common AAA/billing mechanisms could be indispensable for seamless handovers between networks owned/administered by different operators.

Per channel switching tends to require only a subset of the above continuity management operations. First of all, there is no need to consider possible updates for any active channel. In addition, since several interfaces may be simultaneously active, in the case the channels exploiting one of them become abruptly interrupted, CAMPO solutions can quickly update them with one of the other active and working interface. The main continuity management issues are how to correctly update channel references at end-points and how to perform per channel switching by minimizing packet loss while limiting computing/traffic overhead.

The adoption of either per node or per channel solutions is strongly interconnected with the chosen target deployment scenario, in particular with the adopted mobile node scope, and relevantly influences the CAMPO design choices. Single-on CAMPO systems exploit only one interface at a time and the adoption of per node continuity management is the only possible
choice for them. Deployment scenarios based on more powerful client nodes often push for the adoption of multiple-on solutions, and that is often connected with the possibility of having per channel continuity management granularity. For instance, per node granularity is the usual solution in 4G single-on scenarios where the evaluation output generally triggers the interface change for all the channels active at a node. That is typically achieved by exploiting infrastructure-side support components, e.g., Mobile IP to achieve care-of-address and traffic re-route. Per channel granularity, instead, is more common in ABC scenarios where continuity management support performs channel re-addressing and must inform involved clients of any change in channel end-points, e.g., by exploiting SIP as the signaling protocol.

4.3.3. Client Visibility

By focusing on the perspective of client involvement in continuity management switching operations, it is possible to identify two extremes: either transparent or end-to-end switching. Transparent continuity solutions completely hide mobile nodes from the actions performed to update channels. For instance, infrastructure-side switchers may redirect traffic from the origin to the destination interface, without requiring any client awareness. On the contrary, end-to-end continuity management solutions request full client visibility: for instance, peers with active channels usually have to inform their clients in the case of interface change, possibly by communicating also how to reach them after the modification. Most continuity solutions lie between these two extremes: often infrastructure-side components operate transparent traffic re-routing, while mobile nodes are partially involved in triggering handover procedures.

To achieve the goal of decoupling client actions as much as possible from continuity operations, several recent CAMPO solutions, with both transparent and end-to-end visibility, are based on the adoption of intermediary support components, i.e., proxies, especially to handle the case of vertical handovers. For instance, continuity management proxies are used to predict vertical handovers in order to anticipate the associated management operations. The goal is to accelerate handover completion as much as possible to better support time-continuous service provisioning, such as interactive multimedia streaming. Some proxy-based continuity management proposals simply adapt and exploit support mechanisms non-strictly designed for CAMPO, e.g., by exploiting DNS or SIP to communicate new IP addresses to mobile nodes. Other solutions adopt Mobile IP for care-of-addresses and dynamic traffic re-routing.

The adoption of either a transparent or an end-to-end continuity management solution primarily depends on CAMPO objectives and considerably affects its design choices. For instance, the main goal of a network operator could be to provide seamless handovers between its cellular network and other connectivity solutions in order to provision services despite the actually exploited network interface. In this case, transparent continuity management is desirable and to that purpose network operators may deploy special-purpose continuity management components on the infrastructure side, thus minimizing the needed modifications at clients to maximize the immediately available market of potential users. On the contrary, if it is impossible to modify the core cellular network infrastructure or in the perspective of CAMPO service providers, the most suitable solution is end-to-end or proxy-based. Let us note that, in addition to the already sketched advantages in terms of flexibility and dynamicity, continuity management solutions close to the end-to-end extreme of our classification can relatively reduce the required initial CAMPO investments: in fact, these approaches tend to share costs among interested users, who are requested to buy new client devices or to extend/update them in order to benefit from continuity management support.

5. Classifying the CAMPO Literature according to the Proposed Taxonomy

The CAMPO area is currently one of the most interesting and actively investigated fields in wireless research. Nowadays, as the continuously emerging novel CAMPO proposals demonstrate, the complex and articulated issues of seamless integration of heterogeneous wireless technologies are not yet fully addressed. Despite the still dynamic evolution of the area, some first survey papers have been published. However, as better clarified in the following, they are focused on either some specific challenges or categories of solutions, without the ambition of providing a comprehensive unifying CAMPO overview.

For instance, most proposed classifications only focus on infrastructure-based 4G systems, by missing to point out the similarities with peer-based connector solutions, and only provide a coarse-grained category classification. [Akyildiz et al. 1999] represents a relevant seminal contribution about heterogeneous network integration: it is the first paper to analyze handover management by identifying three phases, handover initiation, generation of new connections, and data flow control. [Pahlavan et al. 2000] proposes another simple handover taxonomy based on two dimensions: handover architecture (which component is in charge of han-
dover decision and which is the supported degree of continuity? and evaluation processing methods (which metric, by exploiting which handover indicators?). [Nasser et al. 2006], instead, proposes a handover classification based on network types, number of connections, number of administrative domains, and possibilities of user control, but not considers at all continuity management solutions. [McNair and Fang Zhu 2004] describes handovers as three-stage processes: handover decision, link transfer, and channel assignment. [Kappler et al. 2007] provides a cellular operator point of view, by delineating five primary steps to integrate heterogeneous networks: wireless medium sensing, discovery, establishment of security and internetworking relationships, composition negotiation, and composition realization. [Niyato and Hossain 2005] only partially relates to CAMPO systems and specifically presents a survey about call admission control in heterogeneous wireless environments.

In addition to the above papers about infrastructure-based 4G solutions, a very few other contributions, considering also ABC and with some survey content, exist in the literature. [Gustafsson and Jonsson 2003] discusses user experience and business relationships in ABC scenarios: its main contribution is the decomposition of solutions in functional blocks but it does not provide any CAMPO classification. [Ferreira et al. 2005] presents a high-level integration analysis by focusing on the simultaneous usage of services from different systems and operators. [Cavalcanti et al. 2005] is partially devoted to discuss open issues to integrate cellular networks, WLANs, and mobile ad hoc networks: the paper briefly and simply classifies the related literature according to different layers of abstraction.

Some other papers with survey content specifically concentrate on continuity management, without considering deployment scenarios and evaluation process issues, thus providing a very partial CAMPO perspective. [Reinbold and Bonaventure 2003] overviews main differences between micro- and macro-mobility, by only comparing primary micro-mobility protocols. [Saha et al. 2004] provides a slightly more articulated classification, by differentiating contributions into micro-, macro- and global-mobility. Other contributions adopt traditional layering classifications: [Akyildiz et al. 2004] distinguishes continuity management solutions in link-, network-, and cross-layer approaches, while [Banerjee et al. 2003] additionally takes into consideration transport and application layers. [Roberts et al. 2006] and [Lampropoulos et al. 2005], instead, focus on cellular networks: the former surveys cellular technologies by pointing out main issues for link- and network-layer integration; the latter specifically addresses WLAN-cellular handovers by pointing out how required management actions strongly depend on network integration levels.

Let us stress that, if compared with the above papers, our survey originally provides a unifying architecture model and a more comprehensive and fine-grained CAMPO system classification. In particular, the evaluation process category and the consideration of both infrastructure- and peer-based connectors represent relevant innovative aspects of our taxonomy. In the following, the paper describes the most important CAMPO contributions in the literature, by presenting them in the grid of our taxonomy and by focusing on the specific aspects that make the examined proposals exemplar for their categories.

5.1. Deployment Scenarios
CAMPO-related papers usually do not explicitly point out the deployment scenario they specifically address. However, each contribution has some relevant aspects that implicitly position it in a specific deployment subcategory of our taxonomy.

5.1.1 Interface Scope
In the perspective of interface scope, available CAMPO solutions can be classified according to their capability to select among either interfaces [Stemm and Katz 1998; Minji Nam et al. 2004] or interface-connector pairs [Cheng Wei Lee et. al 2005]. The latter case also includes CAMPO systems that can consider peer connectors [Hung-Yu Wei and Gitlin 2004; Lera et al. 2005; Luo et al. 2003; Frattasi et al. 2006; Seung-Seok Kang and Matt W. Mutka 2005; Chunyan Fu et al. 2006].

At the cost of imposing precise assumptions on deployment requirements, some CAMPO solutions give mobile nodes the only possibility to select interfaces. For instance, the scenario proposed in [Stemm and Katz 1998] is based on the wireless overlay network assumption: the network technology with wider coverage provides connectivity everywhere and continuously, usually with limited bandwidth; other wireless technologies cover only limited and eventually spatially discontinued areas, but providing a larger bandwidth. [Stemm and Katz 1998] has the main goal of always exploiting the available network with larger bandwidth. As a consequence, vertical handover is performed only depending on the availability/unavailability of networks themselves, in an interface scope manner; it takes into account finer RSSI-based connector scope considerations only in horizontal handovers. Wise Interface SElection (WISE) adopts a slightly widened scope, by primarily concentrating on interfaces and secondarily on connector scope [Minji Nam et al. 2004]. In particular, WISE considers, with decreasing priority, mobile node requirements (with an interface scope, to minimize power consumption according to interface nominal characteristics) and network infrastructure requirements (with a connector scope, to redistribute network load when performance degrades).

Most common CAMPO solutions in the literature offer both interface and connector selection. For instance, [Cheng Wei Lee et. al 2005] monitors performance indicators of the currently used network and of other current connectivity (WLANs and cellular net-
works). That enables mobile nodes not only to choose the most proper interface but also the most proper interface-connector pair, at the expense of maintaining an almost updated view of context indicators describing the current state of the execution environment.

The exploitation of peer connectors requires additional deployment scenario capabilities and introduces further complexity in context evaluation. [Hung-Yu Wei and Gitlin 2004] proposes a two-hop-relay architecture, based on Relay Gateway (RG) nodes that can behave both as usual mobile nodes and as cellular gateways. They can seamlessly switch interfaces depending on network availability. In addition, they can improve WLAN coverage by exploiting cellular interfaces where WLAN connectivity is not available. Mobile nodes have to explicitly request for RG-based connectivity, in a non-transparent way. [Lera et al. 2005] proposes a similar approach based on two-hop paths towards the fixed Internet infrastructure. Other CAMPO solutions propose more flexible and complex multi-hop organizations. In [Luo et al. 2003] a peer connector, namely the Proxy Client, can interwork with both cellular and IEEE 802.11 ad-hoc networks. Differently from previous examples, in [Luo et al. 2003] mobile nodes can interact with Proxy Clients not only directly but also via intermediate peer connectors, namely Relay Clients, in a multi-hop ad-hoc manner. [Frattasi et al. 2006] provides several deployment scenarios for peer- and infrastructure-based connectors, by identifying associated service classes of primary relevance: for instance, cooperatives services, such as resource sharing, that exploit single-hop peer coverage; local retransmission services where peer connectors operate local multicast retransmissions; improved QoS support services where multimedia streams are split into several parts, each one processed at a distinct peer.

With still a greater degree of peer involvement, there are a very few CAMPO proposals aiming at the coordination of a set of mobile nodes to create Mobile Ad-hoc Network (MANET) connectivity opportunities. Cooperating ad Hoc networking to Support Messaging (CHUM) dynamically elects one node to play the role of gateway between MANET and the fixed network infrastructure [Seung-Seok Kang and Matt W. Mutka 2005]. In particular, CHUM exploits WLAN connectivity on the MANET side and 3G on the infrastructure side. [Chunyan Fu et al. 2006] provides a similar example of MANET-3G integration, where SIP is exploited as the node-gateway signaling protocol.

In short, interface-only CAMPO solutions are certainly simple, e.g., because they exploit only rather static context information such as interface nominal capabilities. First CAMPO systems exploited this approach to accelerate their prototyping, to simplify their implementation, and to accelerate their adoption. However, the need of a deeper context consideration and of a full exploitation of interface capabilities has rapidly emerged. In fact, most current CAMPO proposals belong to the interface-connector deployment scenario category. In particular, most of them exploit only infrastructure-based connectors. However, increasing mobile node capabilities are opening new scenarios where mobile nodes are also exploited to offer connectivity opportunities, and thus the class of peer-based interface-connector solutions is gaining relevance. We claim the crucial importance of considering also peer connectors in envisioned wireless environments and, for this reason, here we have devoted relevant space to the few related proposals in the literature. Most state-of-the-art papers focus instead on more traditional infrastructure-based connectors, and will be extensively described also in the rest of the section.

5.1.2. Mobile Node Scope

By focusing on mobile node scope, the crucial decision point for CAMPO systems is the capability to exploit either only one interface at a time (single-on solutions such as [Buddhikot et al. 2004]) or several interfaces simultaneously (multiple-on solutions such as [Ylitalo et al. 2003; Chebrolu and Rao 2006; Kristiansson and Parnes 2006]).

[Buddhikot et al. 2004] is an exemplar case of CAMPO single-on solutions. It supports a Simple IP operating mode where each mobile node can activate a single interface at a time; there is no support at all for continuity management and ongoing sessions are lost whenever a vertical handover occurs. In addition, it offers a richer Mobile IP operating mode where, even if only one interface is actually exploited for communication purposes, multiple interfaces are kept active to prepare handovers in background. In that way, it is possible to proactively perform handover management, by anticipating new IP address requests to destination networks in order to accelerate handover completion.

Multiple-on solutions offer the additional capability of allowing each running application to exploit the available interface that best fits its specific requirements. For instance, [Ylitalo et al. 2003] uses multihoming (see Section 5.3.3) to simultaneously enable multiple interfaces, even for the same application, and to update interface selection for each channel independently. In Bandwidth A Ggregat ion (BAG) the focus is on widening the bandwidth available for an application by splitting its traffic over different channels with simultaneous exploitation of different interfaces [Chebrolu and Rao 2006]. In addition, at the same time BAG simplifies seamless node mobility and enhances channel reliability because applications can send multiple packet copies through different channels.

Finally, Simulcast represents an original hybrid solution between single- and multiple-on CAMPO systems [Kristiansson and Parnes 2006]. When different networks with similar suitability (according to a Simulcast embedded metric) are available, an application can exploit several interfaces simultaneously, even for the same traffic flow. On the contrary, Simulcast forces the exploitation of a single channel when it is evaluated as the most suitable one (largely better than the others according to the metric). Simulcast vertical handovers may be time-consuming because the system does not
perform any handover prediction operation. Other multiple-on solutions are similar to the ones above and are listed here for the sake of completeness [Gazis et al. 2005; Fodor et al. 2003; Xing and Venkatasubramanian 2005; Adamopoulou et al. 2005; Jun-Zhao Sun et al. 2005].

In the perspective of identifying related trends in CAMPO system evolution, similarly to infrastructure-based connector proposals examined in the previous sub-section, single-on CAMPO solutions are certainly the most common ones in the literature. The primary reason is of limiting both power consumption and development complexity (e.g., multiple-on solutions require finer-grained and more complex channel management). We claim that multiple-on CAMPO systems will be the most adopted ones in future wireless environments. In fact, the increasing mobile node capabilities and the always growing bandwidth/reliability/continuity requirements of envisioned applications push towards the research and the industrial realization of multiple-on systems. For this reason, we have devoted wide space in this sub-section for the overview of the few multiple-on systems currently available.

5.1.3. Environment Scope
When considering the environment scope - the wider degree of visibility in the deployment scenario category - CAMPO proposals may differ in terms of adopted components, their deployment location, and their role. Here, we present most representative related contributions, by starting with solutions deployed only on the client-side ([Jun-Zhao Sun et al. 2005; Minghui Shi et al. 2004]), then describing distributed CAMPO components ([Vidales et al. 2005; Akyildiz et al. 2005]), and finally presenting proposals based on deployment in the cellular infrastructure ([Inoue et al. 2004; Karetsos et al. 2005]).

Connectivity Middleware Management provides an API to enable adaptive connectivity in an end-to-end fashion by working primarily on mobile clients [Jun-Zhao Sun et al. 2005]. In particular, it offers functions for event-based monitoring of available interfaces and for commanding channel switching. [Minghui Shi et al. 2004] belongs to the same category but specifically deals with authentication management, by proposing an end-to-end scheme to maintain communication privacy notwithstanding the change of exploited access network.

Other CAMPO solutions deploy their components on both mobile clients and the access network infrastructure. Policy-based system to ROam Transparently among Overlay Networks (PROTON) deploys highly demanding processing tasks related to policy specification/deployment in the infrastructure, while it operates policy enforcement on mobile nodes [Vidales et al. 2005]. Similarly to PROTON, Architecture for ubiquitous Mobile Communications (AMC) offers functions for evaluation process but originally adds support for continuity management [Akyildiz et al. 2005]. In particular, continuity management support functions are provided by infrastructure-side components for interoperability between heterogeneous networks of different operators, including authentication, accounting, and billing facilities. AMC performs evaluation in a distributed way: client-side components gather information about network conditions and determine which is the best channel depending on exclusively local considerations; infrastructure-side components have a global state view and may override local choices for optimal traffic distribution.

Differently from the above proposals, [Inoue et al. 2004] and [Karetsos et al. 2005] are based on component deployment on the infrastructure side. [Inoue et al. 2004] performs handover triggering, network discovery, and AAA operations by exploiting ad hoc components installed in the cellular infrastructure, transparently from the client point of view. Mobile nodes only have the burden to register themselves to request for seamless handover-transparent channels, to update their preferences, and to notify their location changes. In [Karetsos et al. 2005] infrastructure-side components are organized hierarchically and provide both evaluation process and continuity management. In the case of network degradation, e.g., traffic congestion, [Karetsos et al. 2005] tries to locally manage the situation by exploiting support components in the local network; if not enough, it involves global infrastructure-side components with multi-network visibility, e.g., to redistribute traffic among overlapping heterogeneous networks.

In short, with regards to role and location of CAMPO components, we do not observe any major evolution trend in state-of-the-art contributions. Client-side CAMPO solutions require greater resource availability on mobile nodes, in terms of both computing and energy power. More distributed CAMPO solutions require a certain degree of control on the network infrastructure, not always easy to achieve especially in cellular networks. However, the growth in mobile node capabilities coupled with the proliferation of heterogeneous wireless networks is pushing for privileging client-side CAMPO systems, mainly to facilitate CAMPO development and deployment over open wireless environments. In particular, recent solutions are encouraging client-side evaluation process to achieve scalability, while continuity management is often performed in a distributed way because, to some extent, some level of infrastructure-side involvement is useful to provide effective seamless connectivity, e.g., to broadcast packets to both origin and destination connectors during handovers.

5.2. Evaluation Process
The evaluation process is one of the most important, characterizing, and widely investigated aspects of CAMPO systems. Within the evaluation process category, most CAMPO proposals focus on processing methods, in particular by identifying solutions with growing degrees of flexibility; a smaller set of solu-
tions concentrate on local/global objective distinction. On the contrary, a very few papers in the literature explicitly point out their characteristics in terms of input and output sub-categories.

5.2.1. Input
As already stated, most CAMPO solutions do not clearly describe which are the characteristics of their evaluation process input, by rapidly and implicitly assuming it depending on the exploited processing method. However, we claim the relevance of the input subcategory to understand the complexity of input gathering and the correlated monitoring costs. For this reason, we have thoroughly examined the CAMPO literature and chosen to present here some exemplar contributions exploiting simple input information ([Stemm and Katz 1998], physical-level input about the status of wireless communications ([Minji Nam et al. 2004; Mohanty and Akyildiz 2006]), and more expressive, complex, and innovative input at the application level ([Cheng Wei Lee et. al 2005; Qian Zhang et al. 2003]).

Finally, the section describes two CAMPO contributions explicitly working on input characteristics ([Stavroulaki et al. 2006; Balasubramaniam and Indulska 2004]).

Simplest CAMPO solutions, based on the overlay network assumption, exploit a static priority order among available interfaces; the only dynamic input data to consider is network availability, often based on beacon frames [Stemm and Katz 1998]. Most evaluation process proposals, instead, exploit more dynamic input information [Minji Nam et al. 2004; Mohanty and Akyildiz 2006; Cheng Wei Lee et. al 2005; Qian Zhang et al. 2003]. Some contributions focus on a small set of physical-level network parameters. [Minji Nam et al. 2004] primarily considers power consumption and, secondarily, network conditions. In particular, the evaluation process performed at mobile nodes exploits visibility of static physical information, such as interface power consumption in transmit/receive/idle state, and of variable communication states (mainly network residual bandwidth). Similarly, Cross-layer Handoff Management Protocol (CHMP) is primarily based on physical context input, i.e., current RSSI of APs in visibility and interface-embedded RSSI thresholds for handover triggering [Mohanty and Akyildiz 2006].

Differently from [Minji Nam et al. 2004], CHMP presents a more articulated handover mechanism taking into account different signaling delays for intra- and inter-domain handovers. Moreover, threshold values can vary dynamically, depending on mobile node speed and on handover failure probability requirements.

Other CAMPO solutions consider more expressive and complex input data [Cheng Wei Lee et. al 2005; Qian Zhang et al. 2003]. [Cheng Wei Lee et. al 2005] dynamically evaluates performance indicators for both WLAN APs and cellular network base stations. In the case of WLAN, it monitors RSSI variations (physical layer) and residual bandwidth (network layer), which are derived from direct measurements of throughput, channel utilization, and frame loss rate (the last two indicators available in QoS BSS beacon frames [IEEE 802.11e 2005]). In the case of cellular networks, it exploits statically defined nominal values. [Qian Zhang et al. 2003], instead, applies the Fast Fourier Transform to RSSI values of APs in proximity to quickly and accurately detect signal decay. In addition, it exploits network-level information: the Network Allocation Vector provided by IEEE 802.11 APs is used to infer bandwidth and access delay. In that way, given a set of eligible APs with RSSI over a threshold, it can select the one currently less loaded.

Finally, only a very few proposals explicitly describe their context input. [Stavroulaki et al. 2006] considers as input data user profiles (subscribed services, corresponding QoS requirements, and maximum price allowed), terminal profiles (client device hardware/software capabilities), network offers (currently available services, supported QoS levels, and corresponding costs), and configuration costs (time and, more generally, resources required to perform channel reconfiguration). Let us note that, while user and terminal profiles are rather static, network offers and configuration costs may be very dynamic indicators. [Balasubramaniam and Indulska 2004], instead, presents a precise description of context input data, classified into static and dynamic. Static information relates to the mobile node as a whole and covers different abstraction layers, from device capabilities to personal settings such as user-defined interface priorities. Dynamic information can be either associated with the whole mobile node, e.g., user location, or differentiated for each channel/interface, e.g., currently available bandwidth.

By summarizing, only very first CAMPO solutions proposed the adoption of exclusively static input parameters, based on the overlay network assumption. In fact, the relevance of exploiting dynamic input to perform connector evaluation has rapidly emerged and is now widely recognized. Several CAMPO solutions still adopt only physical input data, e.g., RSSI and SNR, mainly inspired by the traditional evaluation processes for horizontal handovers. To provide effective evaluation processes with a proper trade-off between complexity of input gathering and expressiveness, some systems have claimed the inclusion of traditional QoS indicators in context input. Most recent solutions additionally exploits application-level input information, which better describes the characteristics of terminal, user, and environment context. However, at the current stage it is not yet fully addressed the issue of efficiently retrieve from context and exploit in the evaluation process information at a high level of abstraction.

5.2.2. Processing
The processing method is certainly the most characterizing aspect of the evaluation process. Here we present CAMPO contributions taking into primary consideration the flexibility of their processing methods: first embedded methods ([Stemm and Katz 1998; Hongyang Bing et al. 2003; Hou and O’Brien 2006; Wei Song et
and O'Brien 2006], instead, provides an embedded but
ways prefers WLAN connectiv ity if available. [Hou
client, and its RSSI overcomes a threshold. UMTS
low a threshold, a UMTS base station is close to the
handovers are triggered whenever the AP RSSI is be-
vertical handovers from UMTS to
and base stations in visibility and their distance from
restituting handover management actions depending on
processing methods, either local or global, are pre-
Embedded processing methods are usually based on
fixed priority order among available interfaces, as in
CAMPO systems based on the overlay network as-
sumption, thus providing limited flexibility. For in-
stance, [Stemm and Katz 1998] triggers an upward
handover, from the current to an alternative
wireless technology with smaller bandwidth and wider
coverage, whenever the current interface becomes un-
available; similarly, downward vertical handovers are
triggered whenever new interfaces with better perfor-
ance and more limited coverage become available.
Instead, the RSSI comparison is exploited to trigger
horizontal handovers. [Hongyang Bing et al. 2003]
adopts a slightly more complex processing method by
taking into account also some simple indicators to es-
timate QoS. In particular, it considers RSSIs of APs
and base stations in visibility and their distance from
mobile nodes. A vertical handover from UMTS to
WLAN occurs when the target AP is close to the client
and its RSSI overcomes a threshold; WLAN-to-UMTS
handovers are triggered whenever the AP RSSI is be-
low a threshold, a UMTS base station is close to the
client, and its RSSI overcomes a threshold. UMTS
RSSI is not considered at all because the proposal al-
ways prefers WLAN connectivity if available. [Hou
and O'Brien 2006], instead, provides an embedded but
slightly configurable solution. It enables different ver-
tical handover strategies between two extremes: the
former triggers a handover as soon as the correspond-
ing channel is interrupted, the latter waits for a fixed
time interval after channel interruption before starting
handover execution. [Hongyang Bing and O'Brien 2006]
decides which handover strategy to perform and with which
delay by adopting fuzzy logics to model input uncer-
tainty, e.g., probability of link interruption, probability
of handover failure, size of unsent messages.
Let us note that the goal of [Stemm and Katz 1998;
Hongyang Bing et al. 2003; Hou and O'Brien 2006] is
local: they aim to select the most suitable channel from
the mobile client point of view, by considering only
context input evaluated at mobile nodes. Always within
the embedded processing sub-category, other CAMPO
solutions target a global objective, e.g., monitoring the
performance of each considered network and optimally
distributing load. For instance, [Wei Song et al. 2005]
provides call admission control capabilities by taking
into account network residual bandwidth and by diffe-
rentiating handover management actions depending on
traffic type, either voice or data: voice calls are prefer-
ably allocated to cellular networks, more suitable in
terms of delay and coverage; data traffic is directed to
WLANs, preferred for their larger bandwidth.
To deal with dynamically variable requirements
and network conditions, most state-of-the-art CAMPO
proposals exploit general-purpose function-based
processing methods. The processing function in Termi-
nal Management System (TMS) considers quality
and cost of eligible connectors and a user-specified
priority order among operators and interfaces [Adamop-
poulo et al. 2005]. TMS evaluates the processing
function for any available connector: each function
term is weighted according to user-specified priorities,
which can change at service provisioning time. Also
Vertical Handoff Decision Function (VHDF) provides
users with the capability to specify a priority order
among different network characteristics, by defining a
proper weight set [Hasswa et al. 2005; Nasser et al.
2006]. The VHDF processing function exploits the
weight set to evaluate a linear combination of network
conditions, network performance, service cost, power
requirements, security, proactive handoff, and client
speed for each active interface.
Other CAMPO proposals exploit more complex
processing methods, based on the knapsack algorithm
([Xing and Venkatasubramanian 2005; Gazis et al.
2005]) and on the Analytic Hierarchy Process (AHP
- [Qingyang Song and Jamalipour 2005; Ahmed et al.
2006]). Knapsack-based solutions try to address the
channel-to-interface or channel-to-connector assign-
ment issue in a per-channel fashion. For instance,
[Xing and Venkatasubramanian 2005] exploits the
knapsack algorithm to minimize average power con-
sumption and user dissatisfaction in terms of distance
from traffic requirements. Each traffic flow is modeled
as the set of its associated bandwidth/delay require-
ments and a partitionability flag; any available network
is represented by its maximum bandwidth, maximum
delay, and power consumption indicators. [Qingyang
Song and Jamalipour 2005] exploits AHP to decide
weights for the considered criteria and Grey Relational
Analysis (GRA) to rank channel alternatives. AHP
splits a complex problem, in this case the provision of
the best QoS as a local objective, into a number of de-
cision factors: availability (decomposed in RSSI and
coverage area), throughput, timeliness (delay, response
time, and jitter), reliability (BER, burst error, and aver-
age retransmissions per packet), security, and cost. On
the one hand, GRA normalizes and compares UMTS
and WLAN QoS parameters; on the other hand, it ex-
ports AHP to determine Grey Relational Coefficients
and thus to chose the most suitable interface. Also [Ki-
bria and Jamalipour 2007] exploits AHP and GRA,
while [Bari and Leung 2007] adopts the TOPSIS algo-
rum to perform connector ranking by considering the
distance between evaluated metric parameters and their
desired values. The above function-based processing
methods pursue a local objective, often dependent on
user requirements represented by weight sets. On the
contrary, [Luan Huang et al. 2006] aims at a global objective: while the problem statement is similar to the knapsack one, [Luan Huang et al. 2006] tries to aggregately maximize the set of utility functions representing the level of satisfaction of every user currently connected to the system.

To further improve flexibility and extensibility, some CAMPO systems propose the adoption of policy-based processing methods. [Ylitalo et al. 2003] continuously monitors context input and checks whether there are conditional clauses that apply in the current set of enforced policies; the verification of a condition clause triggers a management action to perform, and each action associates with an ordered list of network interfaces. PROTON is a more complex and articulated example of policy-based CAMPO solution [Vidales et al. 2005]. PROTON exploits policies as event-condition-action rules, i.e., declarative rules that specify actions to execute whether conditions apply, with events that trigger condition evaluation. Context input data are not considered aggregately, as in many function-based metrics: PROTON breaks down context into fragments and allows the specification of independent normalization functions for any fragment. In particular, PROTON permits to define tautness functions that evaluate how tautly a condition fits to an event: the closer is the returned value to 0, the tauter a condition is to a specific event.

Other relevant policy-based solutions are [Wei Zhuang et al. 2003], [Wei Song et al. 2007] and [Jun-Zhao Sun et al. 2004]. [Wei Zhuang et al. 2003] proposes differentiated policy-based management depending on the integration degree between origin and destination networks. [Wei Song et al. 2007] performs policy decision and enforcement on both the client- and the infrastructure-side; the primary overall objective is to balance networking load among overlapping cellular and WLAN networks. [Jun-Zhao Sun et al. 2004] adopts a context-aware policy solution that permits the definition of policies with different scopes (interface, channel, or application). Let us finally note that, independently of the fact they involve or not infrastructure-side components, [Ylitalo et al. 2003], [Vidales et al. 2005], and [Jun-Zhao Sun et al. 2004] pursue a local objective, while [Wei Zhuang et al. 2003] and [Wei Song et al. 2007] target a global objective.

By summarizing, the processing method objective scope, either local or global, simply represents a design choice that depend only on developer purposes. On the contrary, the evolution trend in CAMPO processing flexibility is worthwhile of some additional considerations. Initial CAMPO research efforts adopted embedded processing solutions: they share the common non-negligible limitation of not allowing to change processing method requirements at runtime. That imposes strict static constraints that usually prevent taking optimal choices: for instance, the overlay network assumption usually does not apply, thus making impossible the adoption of a static priority order [Vidales et al. 2005]. Embedded processing solutions are still of some limited interest because of their efficiency and scarce overhead, especially for mobile nodes with limited capabilities; however, their decreasing relevance is a clear trend.

To provide greater flexibility, most recent CAMPO systems are proposing function-based solutions, which mainly differentiate in relation to the exploited mechanisms (from simple sums of addends to knapsack and AHP/GRA algorithms). Their objective is to achieve the optimal trade-off between flexibility and computational complexity. For instance, in most cases function-based processing permits to change parameter weights at runtime but statically imposes the number and type of parameters. Recently proposed policy-based solutions offer even greater flexibility, but are still in their infancy by often providing valuable policy frameworks but omitting to propose actually effective metrics in terms of imposed overhead. Our opinion is that the additional complexity of policy frameworks and the potentially limited efficiency imposed by policy management and evaluation at runtime are not sufficiently justified by current practical deployment scenarios. Therefore, we expect that function-based processing methods will continue to be the most adopted ones also in next generation CAMPO systems.

5.2.3. Output

Even if the current CAMPO literature usually skips over the explicit description of the main evaluation output characteristics, it is possible to identify two major groups of contributions: a category of CAMPO solutions provide quantitative values that measure the suitability of eligible channels; another category of proposals directly returns the most suitable channel to either activate or switch to.

Function-based processing methods ([Adamopoulos et al. 2005], [vho15]) and AHP-based solutions ([Qingyang Song and Jamalipour 2005; Ahmed et al. 2006]) typically belong to the first group. Sometimes the set of output values is available to the application level, e.g., to enable direct decisions by the running applications; in other cases, at default, the output result is only the identification of the best channel, but applications can optionally request the output values describing all the currently available connectivity opportunities. Embedded and policy-based processing methods usually belong to the second group: applications on their top typically do not have any visibility of output values to compare eligible channels.

Let us note that most current CAMPO solutions are in this second group and completely hide the application layer from low-level evaluation process details. While a transparent approach is commonly desired to minimize application development complexity, at the same time it may significantly reduce application capabilities, thus making difficult to develop context-aware services. In particular, we claim the suitability of middleware-level CAMPO solutions that manage low-level CAMPO implementation details but with some advanced and hybrid forms of visibility propagation up to
the application layer, as processing methods that offer output values do. For further details about the proper tradeoff between transparency and visibility in both context information gathering and evaluation process output, please refer to [Bellavista et al. 2006a].

5.3. Continuity Management
Several CAMPO contributions address the increasingly relevant and challenging issue of continuity management in order to fully support seamless node mobility in heterogeneous networks even while accessing continuous services. State-of-the-art solutions greatly differ in terms of integration level, granularity, and visibility. Research activities coming from the telecommunication area often adopt a tightly integrated perspective, while loosely-coupled CAMPO solutions are recently becoming more and more popular. Granularity aspects include both per-node continuity management mechanisms, mostly adopted in 4G systems, and per-channel ones, more appropriate for ABC solutions. The visibility category, instead, mainly affects the architecture of continuity management CAMPO solutions, i.e., end-to-end, proxy-based, or mainly transparent.

5.3.1. Integration
The industrial efforts accomplished in the last years to provide a standardized architecture for heterogeneous connectivity integration have primarily adopted a cellular operator point of view. The main issue was to tightly integrate heterogeneous wireless networks by effectively including WLANs inside cellular networks. In particular, [3GPP 2002] identify six differentiated environments with a rising level of requirements: i) common billing and customer care, ii) common access control and charging, iii) WLAN-accessible cellular services, e.g., a Wireless Application Protocol (WAP) service available via WLAN connectivity, iv) service continuity, e.g., the possibility to access the same WAP service after cellular-WLAN handovers, v) seamless service, i.e., service continuity achieved in a completely user-transparent way, and vi) access to traditional circuit-switched cellular services via WLAN.

By concentrating on loosely-coupled integration proposals, they share the primary goal of minimizing required modifications to GPRS/UMTS and WLAN deployment environments. For instance, to this purpose [Jyh-Cheng Chen and Hong-Wei Lin 2005] exploits special-purpose gateways deployed at the boundaries between GPRS and WLAN networks. Similarly, [Buddhikot et al. 2004] proposes the deployment of gateway integrators over WLANs and connected to the integrated cellular network via Internet, while [Bernaschi et al. 2005] exploits externally deployed Mobile IP support.

Several recent CAMPO contributions tend to position themselves somewhere in the middle between the two extremes of tightly- and loosely-coupled integration. They usually implement hybrid solutions where there is the possibility to choose the level of integration at system deployment time [Salkintzis et al. 2004; Lera et al. 2005]. For instance, the [Salkintzis et al. 2004] tightly-integrated operating mode enables seamless service continuity independently of WLAN/GPRS roaming, by also enabling the reuse of GPRS AAA. The architecture is mainly based on two components, one deployed at mobile nodes (WLAN Adaptation Function, WAF) to transport GPRS signaling/data over IEEE 802.11 WLANs; the other on the infrastructure side (GPRS Interworking Function, GIF) to offer a standardized interface to the GPRS core network, thus hiding WLAN peculiarities. By exploiting that tightly-integrated architecture it is possible to implement the first five scenarios identified in [3GPP 2002]. In addition, [Salkintzis et al. 2004] can work in a loosely-integrated mode by exploiting the possible availability of an IP network internal to the cellular operator network: in that case, WLAN data traffic is carried by the internal IP network and does not pass through the GPRS core infrastructure as it would in tightly-integrated CAMPO solutions. [Salkintzis et al. 2004] exploits Mobile IP for service continuity; it faces AAA and billing issues with an operator perspective, by introducing authenticator components for WLAN users that permit to reuse the same AAA/billing mechanisms exploited in the cellular network. [Lera et al. 2005] is another valuable example of hybrid approach where both tight and loose integration are supported. The integration is based on a special-purpose UMTS/IEEE 802.11 gateway accessing the Internet via UMTS and providing mobile clients with IEEE 802.11 connectivity. However, differently from [Salkintzis et al. 2004], that gateway may also be a peer connector. In the case of tight integration, [Lera et al. 2005] deploys the gateway inside the UMTS network, as if it were an UMTS device; in the loosely-coupled integration case, the gateway acts as an IP router in its WLAN and does not require any intervention on the UMTS network.

To briefly sum up the above aspects, first research work on CAMPO solutions, especially coming from the industrial telecommunication field, has primarily followed a cellular operator perspective, by consequently adopting a tight level of integration. In particular, tightly-coupled CAMPO solutions were mainly motivated to minimize modifications needed at the client side, thus allowing operators to be the primary actor pushing for innovation. The current evolution trend, instead, is assigning growing and growing relevance to loosely-coupled integration, since it can enable the integration of several heterogeneous networks in an easier and more open way, by favoring heterogeneity also in terms of involved network operators. Let us note that most state-of-the-art CAMPO systems in the previous sub-sections tend to position themselves closer to the loosely-integrated extreme: they typically assume limited or no capability to intervene on infrastructure-based connectors, which are managed as not modifiable legacy components.

5.3.2. Granularity
The granularity continuity management category dis-
criteriates per-channel and per-node CAMPO solutions, respectively better fitting ABC and 4G systems.

Most spread per-channel ABC systems propose re-addressing mechanisms for contingency management, especially for application-specific provisioning environments, such as multimedia streaming. The Multipath Smooth Handoff scheme activates multiple channels along multiple paths from the stream sender to its receivers [Yi Pan et al. 2004]. The primary idea is to exploit multiple paths simultaneously and, once evaluated path performance in an end-to-end fashion, to select the most suitable paths depending on service requirements. The main support components related to continuity management are i) a path management module running at both sender and receiver, which exploits Mobile IP simultaneous binding [Perkins 2002] and route optimization [Johnson and Perkins 2001], and ii) rate control modules at each path endpoints that perform the on-line bandwidth monitoring for each channel. [Luo et al. 2003], instead, is a per-channel ABC solution specifically focused on re-routing capabilities. It supports both infrastructure-based connectivity (assumed as always available but possibly with a low data rate) and ad-hoc multi-hop networking (to explore the possibility of higher data rates, when needed, via peer connectors to the cellular infrastructure). Whenever an ad-hoc path is broken, e.g., due to an intermediate node failure or movement, the interested client passes to infrastructure-based connectivity while starting the simultaneous discovery of other possible paths with greater QoS. Finally, an interesting per-channel ABC proposal is presented in [Ghini et al. 2005], where it is possible to exploit re-routing among not only different interfaces of the same mobile node, but also different mobile nodes belonging to the same group, e.g., from a specific user’s PDA to her car radio.

Notwithstanding the relevance of the above ABC solutions, most CAMPO systems still provide simpler and less flexible per-node granularity. That is the case of 4G CAMPO contributions, despite their proposed architecture is either loosely or tightly integrated. Several 4G continuity management mechanisms deal with packet forwarding, AAA, and billing [Marques et al. 2005; Ahmavaara et al. 2003; Hui Luo et al. 2003; Koen and Haslestad 2003]. As a general property, however, per-node CAMPO solutions exhibit a greater maturity if compared with the analogous continuity management support mechanisms available in per-channel systems.

In this sub-section we have devoted more space to the overview of contingency management aspects related to per-channel CAMPO systems, while continuity management support in 4G solutions will be more extensively described in the following sub-section. In fact, the family of 4G CAMPO systems is relevant not only because it is a notable example of per-node granularity but also for the associated degree of continuity management client visibility. Let us finally note that, at the moment, CAMPO solutions with per-channel granularity are only sporadically adopted. However, as previously motivated in different points of the paper, we claim the suitability and the growing diffusion of ABC systems in the heterogeneous and open wireless integrated networks of the near future, thus increasing the importance and calling for novel solutions to efficiently deal with per-channel continuity management.

5.3.3. Client Visibility

Client visibility may greatly vary from end-to-end continuity management solutions where mobile nodes directly perform the needed management operations with limited or no external help ([Chuanxiong Guo et al. 2004; Snoeren and Balakrishnan 2000; Li Ma et al. 2004]), to proxy-based solutions at different levels of transparency for mobile nodes ([Bellavista et al. 2005a; Bellavista et al. 2005b; Politis et al. 2004; Qi Wang and Ali Abu-Rgheff 2006]), or even to fully transparent systems where infrastructure-side components perform all continuity management actions ([Shenoy and Montalvo 2005; Akyildiz et al. 2005]).

In the end-to-end category, [Chuanxiong Guo et al. 2004] concentrates on how to split end-to-end handovers into two distinct phases: localization of mobile clients and channel continuity maintenance. DNS and peer-to-peer information distribution are suitable for the former phase, while a Subscription/Notification service is adopted for the latter one. Even [Snoeren and Balakrishnan 2000] exploits DNS for mobile node tracking, but proposes modifications to the standard TCP protocol to allow IP address change while ensuring channel continuity. [Li Ma et al. 2004], instead, is primarily based on the adoption of standard protocols, i.e., Stream Control Transmission Protocol (SCTP) [Stewart et al. 2004] and Mobile SCTP (mSCTP) [Riegel and Tuexen 2006]. The primary SCTP feature for continuity management is multi-homing, which enables an SCTP session to be established over multiple interfaces identified by multiple IP addresses; mSCTP provides the additional capability to add, delete, or change IP addresses during active SCTP associations. In particular, [Li Ma et al. 2004] supports two possible end-to-end handover procedures depending on the fact that the addressed deployment environment enables either single-homing or dual-homing. In the first case, [Li Ma et al. 2004] does not provide seamless mobility and the channel is interrupted during handover. On the contrary, in the second case, it provides seamless mobility at the cost of traffic replication. In addition, it permits to deploy proxies with mSCTP capabilities that can perform as gateways for legacy fixed servers without mSCTP capabilities, thus providing a continuity management solution transparent also from the server point of view.

As already mentioned, some CAMPO solutions are neither completely end-to-end nor transparent because they exploit both intermediate proxies deployed on the infrastructure and special-purpose components on mobile nodes. For instance, [Bellavista et al. 2005a] and [Bellavista et al. 2005b] are based on shadow proxies
and client stubs. Mobile agent-based shadow proxies run on the fixed network and dynamically migrate close to the APs currently providing connectivity to their associated mobile clients; client stubs run at mobile nodes and transparently interface with possibly legacy client applications. Both components adaptively resize their buffers depending on handover prediction, with the goal of supporting seamless mobility while minimizing memory and computing overhead.

Other CAMPO solutions exploit well-standardized proxy-based solutions, e.g., Mobile IP and SIP, adapted for seamless continuity management. The Enhanced Mobility Gateway (EMG) uses both Mobile IP and SIP, respectively for non-real-time and real-time services [Politis et al. 2004]. On the one hand, Mobile IP is not appropriate for applications with strict real-time constraints, such as Voice over IP, because of the delay imposed by triangular routing; routing optimization enhancements could solve the problem, but requiring modifications of the standard IP stack over mobile clients. On the other hand, SIP natively supports only UDP because it has been designed mainly for considering streaming applications and is not suitable for highly reliable traffic. EMG components are deployed at the edges between wireless networks and the fixed Internet, by acting as both Mobile IP Foreign Agents and SIP proxies. Also [Qi Wang and Ali Abu-Rgheff 2006] exploits Mobile IP and SIP, by proposing two alternative solutions: i) it decomposes standard Mobile IP and SIP facilities to effectively merge them together in an original integrated support that eliminates redundancies and maximizes efficiency; and ii) it provides a continuity management support fully compliant with standard Mobile IP and SIP, but imposing a greater overhead. In addition, [Cheng Wei Lee et. al 2005] exploits Mobile IPv6, while [Nursimloo and Chan 2005] exploits Fast Mobile IPv6 and SIP to support real-time mobility. [Wi Wu et al. 2005] analyzes the delay due to the usage of SIP for vertical handover among WLAN and UMTS networks. [Sarikaya 2006] delineates five possible architectures to integrate WLANs and cellular networks that differ for the location where Mobile IP home agents are placed.

In the transparent continuity management class, the common goal of [Shenoy and Montalvo 2005] and [Akyildiz et al. 2005] is to provide seamless mobility, the former focusing on traffic re-routing, the latter on interoperability. [Shenoy and Montalvo 2005] supports seamless vertical handover in a transparent manner, by offering signaling capabilities among origin and destination networks. When a cellular-to-WLAN handover is required, infrastructure-side components proactively perform both mobile node authentication and channel allocation; mobile clients have to wait for handover notification messages, to notify the starting of actual handovers, and to perform local channel update. [Akyildiz et al. 2005] specifically aims to support transparent heterogeneity management, by using IP as the gluing protocol: its main components are a Network Interoperating Agent (NIA) running in the fixed Internet and several Interworking Gateways (IGs) residing on the integrated and heterogeneous wireless networks. The centralized NIA provides interoperability capabilities between IGs, thus eliminating the need of direct service level agreements between each pair of involved networks.

By trying to identify a visibility evolution trend, in order to promote CAMPO diffusion, initial solutions have proposed the adoption of intermediary proxies based on standard protocols, e.g., Mobile IP and SIP. However, their limited performance has motivated novel proxy-based solutions specifically designed to support continuity management. About transparent continuity management, this class of solutions usually take advantage only of infrastructure-side components, thus providing also legacy mobile nodes with seamless handovers. Since there is no CAMPO system providing complete transparency, we have included in this category all the contributions that minimize the deployment of newly added components on mobile clients (these CAMPO solutions often rely on a tightly-integrated architecture). End-to-end continuity management has the primary advantage of not requiring any additional CAMPO component running on the infrastructure side, thus being immediately deployable and distributing to interested users the burden/cost of installing and executing required components on mobile nodes.

Currently, neither proxy-based nor transparent nor end-to-end solutions have clearly emerged as the most promising ones. We envision that cellular operators will continue pushing mainly transparent solutions for continuity management, often by exploiting special-purpose supports. However, the spreading of wireless networks based on unlicensed technologies, e.g., IEEE 802.11 WLANs and Bluetooth PANs, should promote the adoption of solutions based on proxies that are not directly managed by communication operators. Finally, at the moment, end-to-end proposals seem the most promising ones for QoS management purposes because of their direct involvement of endpoint nodes.
Table I. The CAMPO literature classified according to the proposed taxonomy (secondary aspects in brackets).

<table>
<thead>
<tr>
<th>CAMPO System</th>
<th>Deployment Scenario</th>
<th>Evaluation Process</th>
<th>Continuity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>interface</td>
<td>mobile node</td>
<td>enviroment</td>
</tr>
<tr>
<td>Stemml and Katz 1998</td>
<td>interface</td>
<td>mainly single-on</td>
<td>eval on client, cm on infra</td>
</tr>
<tr>
<td>Wei Song et al 2005</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on infra</td>
</tr>
<tr>
<td>Minji Nam et al. 2004</td>
<td>interface (infrastructure)</td>
<td>single-on</td>
<td>eval on client, cm on infra</td>
</tr>
<tr>
<td>Hongyang Bing et al. 2003</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Hou and O'Brien 2006</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Cheng Wei Lee et al. 2005</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client, cm on infra</td>
</tr>
<tr>
<td>Chebrolu and Rao 2006</td>
<td>infrastructure</td>
<td>multiple-on</td>
<td>eval on client, cm on both</td>
</tr>
<tr>
<td>Mohanty and Akyildiz 2006</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client, cm on both</td>
</tr>
<tr>
<td>Qian Zhang et al. 2003</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Adamopoulou et al. 2005</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Nasser et al. 2006</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Yang and Venkatsubramanian 2005</td>
<td>infrastructure</td>
<td>multiple-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Gazis et al. 2005</td>
<td>infrastructure</td>
<td>multiple-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Qingsong Song and Jamalipour 2005</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Kibria and Jamalipour 2007</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on client</td>
</tr>
<tr>
<td>Bari and Leung 2007</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on infra</td>
</tr>
<tr>
<td>Balasubramanian and Indukaka 2006</td>
<td>infrastructure</td>
<td>single-on</td>
<td>both on infra</td>
</tr>
<tr>
<td>Luan Huang et al. 2006</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on infra</td>
</tr>
<tr>
<td>Vadale et al. 2005</td>
<td>infrastructure</td>
<td>single-on</td>
<td>eval on both, cm on infra</td>
</tr>
<tr>
<td>Jun-Zhao Sun et al. 2004</td>
<td>infrastructure (path)</td>
<td>multiple-on</td>
<td>both on client</td>
</tr>
<tr>
<td>Yrilalo et al. 2003</td>
<td>infrastructure</td>
<td>multiple-on</td>
<td>eval on client, cm on infra</td>
</tr>
<tr>
<td>Jun-Zhao Sun et al. 2005</td>
<td>infrastructure</td>
<td>multiple-on</td>
<td>both on client</td>
</tr>
</tbody>
</table>
5.4. Overall Considerations and Emerging Trends in CAMPO Literature

In the above overview of the CAMPO literature we have tried to point out the most important aspects of each contribution, by using those primary aspects to position CAMPO systems in our articulated taxonomy. Table I has a twofold goal: on the one hand, it concisely summarizes what already presented for the most relevant CAMPO systems; on the other hand, it additionally indicates how each of these systems relates to the other categories of our classification, even if by providing partial contributions of minor relevance.

Generally speaking, the table shows that many CAMPO systems provide only partial solutions concentrated on a specific subset of CAMPO issues. That is the case, for example, of most papers focused on tight/loose integration [Lera et al. 2005; Buddhikot et al. 2004; Jyh-Cheng Chen and Hong-Wei Lin 2005; Salkintzis et al. 2004], which do not provide any support mechanism for the evaluation process. By delving into finer details, it is possible to observe some other interesting trend. About deployment scenarios, the connector scope is currently the most adopted one, especially based on infrastructure components; peer connectivity is not yet commonly accepted. Moreover, single-on solutions are the most spread, while there are still a few multiple-on proposals, some of them for special-purpose mobile clients. By focusing on the evaluation process, the dynamicity of context input is growing in recent proposals and the considered input increasingly includes different abstraction levels. The objective scope is primarily local despite the degree of flexibility, and the selected entity is usually a connector. Finally, about continuity management, it is possible to observe that most CAMPO contributions that do not adopt a cellular operator perspective exploit a loosely-integrated approach. The most common granularity is per-node, while only few contributions pro-
vide per-channel continuity management. The most usual approach is proxy-based, independently of the adopted visibility sub-category.

6. Conclusive Remarks and Main Open Challenges
The CAMPO area has recently gained relevant interest from both academic and industrial researchers. In fact, the wide availability of several wireless communication technologies, coupled with increased resource availability at mobile clients, asks for novel support solutions to take full advantage of the new network/client capabilities. These research efforts have already provided several interesting contributions, differing not only for the specifically addressed issue, e.g., seamless vertical handover, but also in relation to assumptions made about the targeted execution environment, e.g., mobile node capabilities and available networks. However, common models and frameworks that permit to clearly describe CAMPO contributions and to easily compare them are still missing.

This paper aims to two primary goals. On the one hand, it proposes a unifying model for representing CAMPO solutions and originally identifies three main categories for their classification, i.e., deployment scenario, evaluation process, and continuity management. The proposed model and taxonomy are exploited to clarify the characteristics of the two main families of CAMPO solutions, i.e., 4G and ABC. On the other hand, the paper deeply analyzes the state-of-the-art in the field, not only classifying the existing literature according to the proposed taxonomy, but also pointing out current trends of evolution of the CAMPO research area.

While already proposed contributions demonstrate CAMPO feasibility and potential benefits, there is still the need to face up some open challenges to leverage and accelerate the widespread CAMPO adoption. By analyzing the evolution trends of current CAMPO literature, we claim that future proposals should have the primary goal of integrating several technologies managed by multiple operators. These proposals should provide effective mechanisms to enable interoperability among heterogeneous components in an open and dynamic way. In particular, we claim that CAMPO researchers should mainly focus their current investigation efforts on:

1. context-aware evaluation processes, with an optimal trade-off between evaluation flexibility/effectiveness and expressive power of context representations. Evaluation processes should exploit context awareness to dynamically adapt their behavior to execution environments. Moreover, they should primarily work on mobile nodes to improve scalability and to reduce dependence on external support;
2. hybrid deployment scenarios, which include both infrastructure and peer connectors, the latter with possibly complex coordination capabilities as in MANET. In particular, we envision a growing involvement of mobile nodes to take full advantage of their increasing capabilities, e.g., by adopting multiple-on solutions;
3. open and highly decentralized continuity management solutions. In fact, continuity management is the crucial issue not yet satisfactorily addressed by CAMPO proposals. We claim that next generation continuity management should be as much technology-independent as possible. While cellular/IEEE 802.11 tight integration has represented a valuable first step towards seamless connectivity, continuity management should be performed in a more distributed and open way. Open CAMPO systems should exploit third-party support components instead of ad-hoc ones as in current tightly integrated scenarios. In addition, the distribution of continuity components on both client and infrastructure sides will permit to integrate heterogeneous technologies for wireless connectivity in a more effective and economically-efficient manner.

REFERENCES


