UEF: Ubiquity Evaluation Framework

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Abstract. Ubiquitous computing (UbiComp) systems rely on heterogeneous technologies to enable the anytime-anywhere communication paradigm. Despite the momentum that UbiComp systems have, most new proposals are typically evaluated through varying sets of criteria, making direct comparisons that are far from straightforward. In this paper, we introduce the Ubiquity Evaluation Framework (UEF) aiming to overcome the limitations of hitherto evaluation mechanisms. UEF is unique, as particular protocols of a UbiComp system can be evaluated without requiring a functional system or involving questionnaries to a group of experts in the field. UEF enables the comparison of protocols intended for the same task in the design phase, by employing objective metrics. The generic applicability of UEF is demonstrated in this paper through a case study comparing UbiComp support in two well-established mobility management protocols, namely Mobile IPv6 (MIPv6) and Host Identity Protocol (HIP).

Keywords: Ubiquitous computing, Multihoming, MIPv6, HIP, modeling and performance evaluation.

1 Introduction

Ubiquitous computing (UbiComp) is a model where computers live in the world of people, aware of their location, but in a transparent form to the user [1]. Modern devices and networks to some degree implement this vision for ubiquitous computing as they enable users to access online services 24-hours a day at "any time" and from "any place". In principle, the choice of technologies, system architecture and protocols must be considered in the design phase of UbiComp systems. However, the evaluation approaches taken for UbiComp Systems so far [2, 3] typically consider user-perspective ratings only, or assess a limited set of functionalities. For example, some assessments follow a prototype-based approach and thus have high development costs while not always fully representative of the final system. Others rely on user surveys requiring at least a partially complete and functional system. Moreover, when multiple choices for the software components are available, said approaches do not provide insights for the selection of the best ones during the design phase.

X. Masip-Bruin et al. (Eds.): WWIC 2011, LNCS 6649, pp. 92–103, 2011.

This paper introduces the Ubiquity Evaluation Framework (UEF), which assess the ubiquity support of a protocol by considering its technical features (i.e., those related with the capabilities of UbiComp systems, including security and extensibility), as well as protocol extensions, i.e. features that improve the capabilities of UbiComp systems, but are not mandatory. Both technical features and extensions of UbiComp systems are considered regarding the functionalities of the assessed protocol. To showcase the use of UEF we consider in this paper two mobility management protocols, namely MIPv6 [4] and HIP [5], and study their respective ubiquity support. In doing so, we demonstrate the accuracy and general applicability of UEF.

The contributions of UEF in the evaluation of UbiComp systems are threefold. First, evaluations do not require prototypes or working systems or even experts in the UbiComp area, as UEF does not rely on user interviews. Second, performance can be assessed at any phase of system development, ranging from the design phase to deployment. Third, UEF establishes objective metrics that allow the comparison of protocols intended for the same task in an objective manner. The remainder of this paper starts with Section 2, which reviews related work. Then, Section 3 introduces UEF and Section 4 assesses ubiquity support in MIPv6 and HIP based on our framework. Finally, Section 5 concludes the paper.

2 Related Work

UbiComp systems include different components, namely the computing platform, such as the hardware technologies supported, the software platform, and the users interacting with the system [6]. In this section, we overview the approaches so far taken when evaluating, on the one hand UbiComp systems, and on the other mobility management protocols.

UbiComp systems can be evaluated in terms of quality, which assesses the level of capabilities (i.e., technical characteristics) and the level of extensions [7, 8]. The assignment for each capability/item usually relies on interviews with experts in the field (e.g., with ubiquitous computing experience), giving a classification in the range $\{1, 2, ..., 7\}$. These solutions require the involvement of experts, limiting a general applicability of this type of methodology.

UCAN is a ubiquitous computing application development and evaluation process model [2] that allows the evaluation of ubiquitous applications, such as radio frequency identification (RFID) applications. The evaluation includes different stages and methods, for instance, the original idea can be evaluated using interviews, while the prototype (pilot) is assessed through user acceptance methods. Whilst UCAN requires prototypes and is tailored for applications relying on user satisfaction metrics, in [7] the overall system is evaluated.

Ontonym [3] is a framework that allows the evaluation of pervasive systems. The framework models context based on ontologies. For instance, people are modeled by using classes with different attributes such as Name and ReligiousName. The evaluation considers three aspects: design principles, (e.g., extensibility and documentation); content (e.g., clarity and consistency); and purpose (in which domain the evaluation is performed). Despite using established standards, Ontonym focuses on the context representation problem, and therefore does not provide objective and comparable metrics to evaluate UbiComp systems.

The performance of IP mobility management protocols has been a popular research topic. Due to space considerations, we only review the most salient work in this area in terms of performance metrics support. Usually, metrics include packet delivery cost, handover delay, location update cost, signaling cost, multiple interfaces and simultaneous mobility support. The packet delivery cost metric, for instance, determines the cost (e.g., processing or transmission) of the different packet delivery mechanisms (e.g., tunnel, direct) [9]. The handover delay metric includes movement detection, address configuration, security operations and location registration [10, 11]. The signaling cost is a compound metric that combines the packet delivery cost and the handover cost, commonly designated by location update cost [9]. The location update cost is determined according to the network model (e.g., number of hops, number of domains, wired and wireless links), message rate and respective message length. The difference between the different proposals resides on the fact that some of them include the functions of each involved entity (e.g., home agent, correspondent node), while others only include the mobile node or only the cost of specific operations (e.g., tunneling) [12]. The support of simultaneous mobility metrics is often neglected in evaluations, assuming fixed correspondent nodes [9, 12], although some consider the probability of simultaneous movement as in [13]. Paging efficiency is another metric to consider when evaluating mobility management protocols in a ubiquitous environment, specially due to energy efficiency. Paging support evaluations assess the power consumption cost, the paging delay cost but in a technology-dependent or application-dependent way [14–16].

Based on this survey of previous work in these two areas, we conclude that none of the existing approaches can assess protocol performance regarding its functionality and taking into consideration technical features and extensions of UbiComp systems. As will see later, UEF addresses these limitations, providing a consistent benchmark toolset for a variety of protocols.

3 UEF - Ubiquity Evaluation Framework

UEF defines the ubiquity metric - U_{MH} (see Def. 1) that combines aspects of UbiComp systems with the functionalities of a protocol. Metrics and methods to assess technical features and extensions of UbiComp systems are presented first. The degree of mobility support assesses IP mobility management performance, which is then combined with features of UbiComp systems, expressing the Ubiquity metric.

Definition 1 - ***Ubiquity*** *is the ability to support secure and optimized mobility to enable access to services anywhere and anytime, with acceptable quality levels.*

Table 1. Technical Capabilities of UbiComp systems in UEF for (S) - Software, (U) - User and (H) - Hardware components (with a total of 39)

	Accessibility	Accuracy	Adaptablity	Adjustability	Adoptability	Analyzability	Compatibility	Configurability	Connectivity	Credibility	Customizability	Decomposability	Downloadable	Embeddedness	Effectiveness	Efficiency	Extensibility	Integrability	Interoperability	Interpretability	Invisibility	Learnability	Maintanability	Mobility	Portability	Predictability	Proactiveness	Reconfigurability	Reliability	Reusability	Scalability	Security	Sensibility	Shareability	Stability	Testability	Understandability	Usability	Wearability	
HIP	√	√	√	√	-	√	√	√	√	-	√	0	√	√	√	√	√	√	√	-	-	0	√	√	0	√	0	0	√	√	√	√	√	0	√	√	-	-	-	26
MIP	√	√	√	√	-	√	√	√	√	-	√	0	√	√	√	√	√	√	√	-	-	0	√	√	0	√	0	0	√	√	√	√	√	0	√	√	-	-	-	26
(S)	√	√	√	√	-	√	√	√	√	-	√	√	√	√	√	√	√	√	√	-	-	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	-	-	-	32
(U)	-	√	-	√	√	√	√	-	-	√	-	-	-	-	-	-	-	-	-	√	-	-	-	√	-	-	-	-	-	-	-	-	√	-	-	-	√	√	-	11
(H)	√	√	√	√	-	√	√	√	√	-	√	√	-	√	√	√	√	√	√	-	√	-	√	√	√	√	-	√	√	√	√	√	√	√	√	-	-	-	√	30

Table 2. Extensions of UbiComp systems in UEF for (S) - Software, (U) - User and (H) - Hardware components (total of 22)

	Authentication	Authorization	Automation	Autonomy	Context Reusability	Durability	Entity Tracking	Identity Tracking	Inferred Context	Location Tracking	Negotiation	Response Time	Seamlessness	Self-Control	Service Coverage	Standardization	Trust	User Context	User preference	User profile	User Satisfaction	Utility	
HIP	√	√	√	√	-	-	√	√	-	√	-	√	0	-	0	√	-	-	-	-	-	-	9
MIP	-	-	√	√	-	-	-	-	-	-	-	√	√	-	√	√	-	-	-	-	-	-	6
(S)	√	√	√	√	√	-	√	√	√	√	√	√	√	-	√	√	-	√	√	√	-	-	17
(U)	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	√	-	-	-	√	√	4
(H)	-	-	√	√		√	-	-	-	-	-	√	√	-	√	√	-	-	-	-	-	-	7

3.1 Formulation

The first contribution of UEF is the ubiquity metric that combines technical capabilities, lC, and extensions, lU, of UbiComp systems, according to the degree of mobility, Ψ,supported by a protocol. Eq.1 formulates Ubiquity - U_{MH}, where W_{lC} and W_{lU} are the weights for technical characteristics and extensions aspects, respectively. Weights are assigned as follows: $W_{lC} + W_{lU} \leq 1$. A simple rule to assign weights relates the number of technical or extensions items and the overall number of items (technical + extensions), having $W_{lC} = nLC/(nLC + nLU) = 0.65$ and $W_{lU} = nLU/(nLC + nLU) = 0.35$.

$$U_{MH} = (W_{lC} * lC + W_{lU} * lU) \cdot \Psi \tag{1}$$

Technical capabilities and extensions are determined for each component of a UbiComp system, namely user (U), software (S) and hardware or computing platform (H), as shown in Table 1 and Table 2. MIPv6 and HIP fall in the software component category (S). Thus, capabilities and extensions of the protocols are evaluated by considering only the capabilities and extensions of the software component. A "$\surd$" in the Table entries means that the respective capability is supported; "0" means that it is not supported; and "$-$" means that the capability is not applicable.

UEF should be usable without full expertise in UbiComp systems and at any stage of system development (from design to deployment phases). As such, capabilities and extensions are evaluated using a Boolean scale (0-not supported and 1-fully/partially supported). Moreover, to avoid ambiguity in the evaluation, UEF employs the meaning of each capability/extension according to standard dictionaries [17]. Finally, UEF considers non-overlapping capabilities and extensions as opposed to [7, 8] that evaluates an item twice, namely as a capability and as extension. Each capability/extension is determined according to Eq. 2 specified in [7], where n is the number of supported capacities/extensions, C_i is the value of the capacity (0 or 1) with $MaxScale = 1$, and n_ξ is the number of capacities/extensions that apply to the component.

$$C_\xi = \frac{\sum_{i=1}^{n} C_i}{n_\xi \cdot MaxScale}, with\ \xi \in \{u, s, h\} \tag{2}$$

UEF assesses mobility support through the degree of mobility Ψ, which is a compound metric of performance and cost aspects of the mobility management process, as per Eq. 3. Common approaches, such as [9, 12] consider cost aspects only. Performance aspects include the level of energy efficiency Ef and handover procedure preparation rate λ_{prep}. Cost aspects include handover Hc and signaling Sc costs as well as the handover procedure finalization rate λ_{fina}. The term $N \cdot maxS$ corresponds to the number of cost aspects and the maximum cost value, respectively, with $maxS = 1$, and $N = 3$. The weight W_m is used to distinguish performance and cost aspects.

$$\Psi = N \cdot maxS + W_m(Ef + \lambda_{prep}) - (1 - W_m) \cdot (Hc + Sc + \lambda_{fina}) \tag{3}$$

In IP mobility management evaluation, UEF includes metrics for energy efficiency and the procedure preparation rate, a significant improvement over previous work that only evaluates mobility management performance by assessing costs [9, 12, 13]. UEF explores the end-host mobility approach, when all procedures are triggered by the mobile node, and includes support for simultaneous mobility events. In the latter case, the correspondent node plays a dual role as it is also a mobile node. The procedure rates include the procedure preparation rate before the handover, λ_{prep}, and the procedure finalization rate, λ_{fina}, after the handover. Considering a total of n_{proc} procedures and $n_{proc} = n_{prep} + n_{fina}$, the rates are $\lambda_{prep} = n_{prep}/n_{proc}$ and $\lambda_{fina} = n_{fina}/n_{proc}$.

The handover cost, Hc, quantifies cost in terms of handover delay, d, measuring the sum of procedure delays in the n_e entities. Handover delay, d, is determined as follows: $d = \sum_{e=1}^{n_e} \sum_{j=0}^{n_{je}} \Delta t_{proc_{j,e}}$, with n_{je} procedures executed at entity e with Δt_{proc} processing time. The handover cost, Eq. 4, includes the cost of procedures invoked after handover only. A sigmoid function normalizes delay values that have increased granularity by a factor of d_g (=1000 by default).

Handover cost could consider other metrics, such as handover delay at Layer 2 [11], but this would tie UEF to a specific radio access technology and prevent us from apportioning the performance of the assessed protocol.

$$Hc = 1/(1 + e^{-\frac{\sqrt{d+1}}{d_g}}) \tag{4}$$

The signaling cost, Sc, Eq.5, determines the procedure overhead (Gp set) of the protocol, as in [9].

$$Sc = \left[\ 1 + e^{-\sqrt{\sum C_p / max(C_p)}}\ \right]^{-1} \ \forall_p \in Gp \tag{5}$$

The relation between the sum of all procedures $\sum C_p$ and the maximum cost $max(C_p)$ of all the procedures is the base for the signaling cost formulation. In UEF, the cost of a procedure C_p is formulated according to the message size, the message transmission frequency or the number of transmissions, and the processing cost Φ of each entity. Common approaches rely mainly on the message size only [9]. Eq. 6 determines the cost of a procedure invoked nI times, with message size L_i and transmitted nTx times or at a frequency Q_i.

$$C_p = \textstyle\sum_{n=0}^{nI} \left[\sum_{t=1}^{nTx} \sum_{i=1}^{nM} \left(L_{n,t,i} \cdot Q_{n,t,i} \cdot \sum_{e \in \{\dots\}} \Phi_{n,t,i,e}\right)\right] \tag{6}$$

For the number nTx and frequency Q_i of transmissions we make the following assumptions:

- $Q_i = 1$, if $nTx > 1$, i.e. when there are retransmissions;
- $nTx = 1$, if $Q_i > 1$, for instance, messages that do not require any reliability but are sent frequently (e.g., router advertisements).

The processing cost, Pc, of an entity Φ_e is the relation between the processing cost of a procedure and the number of interfaces of entity e, $\Phi_e = Nif_e \cdot Pc_e$. UEF considers multihomed nodes and does not rely on upper-layer parameters (e.g., session rate) to determine the processing cost. Instead, Pc corresponds to the relation between the processing delay $pDelay$ and the operation complexity, as given in Eq. 7. Complexity is modeled by the number of operations $nOper$, and the size of data structures $sizeData$. Whilst the size of the data structures can be dynamic, UEF only considers the size of a single record, for simplicity. When procedures do not involve data structures, $sizeData = 0$. $sizeData$ differs from message length, since it accounts for the size of structures necessary to perform the operations in procedures (e.g., record in a routing table).

$$Pc = [nOper \cdot (1 + sizeData)] \cdot pDelay \tag{7}$$

Energy efficiency, Ef, considers the rates of reducing the active area $\lambda_{rdActArea}$ and the paging cost λ_{rdPagC}, as per Eq. 8. N is the number of cost aspects and $maxS$ the maximum value of these costs, with $N = 1$ and $maxS = 1$. Power saving mechanisms at the physical layer are not included in order to meet the technology independence requirement.

$$Ef = N \cdot maxS + W_e \cdot \lambda_{rdPagC} - (1 - W_e) \cdot \lambda_{rdActArea} \tag{8}$$

The rate of active area reduction, $\lambda_{rdActArea}$, is the relation between the domain $dArea$ and the paging area $pArea$: $\lambda_{rdActArea} = \frac{dArea-pArea}{dArea}$. The paging area is determined by considering the node that initiates paging till the endpoint (e.g., mobile node). Additionally, the area can consider the radius coverage (in meters), or simply the number of hops between the paging initiator and the endpoint as discussed in [14]. The domain area is limited by the prefix management entity, for instance an IPv6 router, and the endpoints. Values close to 1 indicate that the paging area is too small, with reduced costs, but with few optimizations. The paging cost, $PagC$ is given in Eq. 9, where L represents the message size, transmitted nTx times. Each entity e participating in the paging group Ga has Nif interfaces in idle state during Δt interval, and for each paging message the processing cost is Pc. The paging group Ga includes all entities involved in paging signaling.

$$PagC = \sum_{t=1}^{nTx} L_t \cdot \sum_{\forall_e \in Ga} \left(Nif_{e,t} \cdot Pc_{e,t} \cdot \Delta t_{e,t}\right) \tag{9}$$

The processing cost, Pc, is determined according to Eq. 7 with $sizeData = 0$. The ratio of paging cost reduction, λ_{rdPagC}, is the relation between paging cost at effective idle intervals, Δt_idle, and theoretical intervals, Δt_Tidle, during which the MN could remain in idle state (e.g., no data transfer and no mobility management signaling exchanges), $\lambda_{rdPagC} = \frac{PagC_{\Delta t\_idle}}{PagC_{\Delta t\_Tidle}}$.

4 UEF Use Case: Ubiquity in MIPv6 and HIP

After detailing the UEF specification, we now proceed with the evaluation of MIPv6 [4] and HIP [5] with respect to the effectiveness of their ubiquity support.

4.1 Ubiquity Derivation for MIPv6 and HIP

HIP supports mobility management with the RendezVous extension. The ubiquitous support is determined according to its technical capabilities and extensions. Using Tables 1 and 2 we see that MIPv6 and HIP have similar technical capabilities, that is, $lC_{MIP} = lC_{HIP} = 26/32 = 0.81$. MIPv6 does not gain any from its extensions support, $lU_{MIP} = 6/17 = 0.35$, but HIP does, $lU_{HIP} = 9/17 = 0.53$.

The formulation of the degree of mobility for the registration (RG), security (AA), address configuration (AD) and movement detection (MD) procedures are based on Eq. 2. Mobility management in MIPv6 includes Mobile Node (MN), Home Agent (HA) and Correspondent Node (CN) entities. In HIP, the HIP Initiator (HI), the RendezVous Server (RVS) and the HIP Responder (HR) manage mobility. As some procedures rely on IPv6 mechanisms, we employ $E1$ as MN or HI, $E2$ as HA or RVS and $E3$ as CN or HR.

MIPv6 registration is based on binding messages. MN sends Binding Update (BU) to the HA and CN when new addresses are available. BUs are retransmitted till the reception of a Binding Acknowledgment (BA). Moreover, binding can be refreshed using Binding Refresh Request (BRR), or the CN can inform the MN about errors using Binding Error (BE) message. The cost is determined similarly to HIP.

HIP registration is performed in three steps (*s1*, *s2*, *s3*) according to the handover phase. In *s1*, HI and HR register with RVS using *I1, R1, I2* and *R2* messages. The cost of this step is determined by Eq. 10. The base exchange (step *s2*) corresponds to a four-way handshake between HI and HR and only involves the RVS to forward I1 messages.

$$\begin{aligned} C_{RG-HIP_{s1,s2}} &= \sum_{t=1}^{nTx} L_{I1,t} \cdot \sum_{e\in\{HI,RVS,HR\}} (Nif_{e,t} \cdot Pc_{e,t}) + L_{R1} \cdot \sum_{e\in\{HI,RVS,HR\}} (Nif_e \cdot Pc_e) \\ &+ L_{I2} \cdot \sum_{e\in\{HI,RVS,HR\}} (Nif_e \cdot Pc_e) + L_{R2} \cdot \sum_{e\in\{HI,RVS,HR\}} (Nif_e \cdot Pc_e) \end{aligned} \tag{10}$$

After the handover (step *s3*), HI needs to update the locator information on *dest* nodes, which include RVS and HR. For such purpose, it employs the update message with locator information, and issues an *echo_request*, which status of update is reported in the *echo_response* message. The registration cost of the update is determined according to Eq. 11.

$$\begin{aligned} C_{RG-HIP_{s3}} &= \sum_{t=1}^{nTx} L_{UPD(locator),t} \cdot \sum_{e\in\{HI,dest\}} (Nif_{e,t} \cdot Pc_{e,t}) \qquad (11) \\ &+ L_{UPD(echo\_req)} \cdot \sum_{e\in\{dest,HI\}} (Nif_e \cdot Pc_e) + L_{UPD(echo\_resp)} \cdot \sum_{e\in\{HI,dest\}} (Nif_e \cdot Pc_e) \end{aligned}$$

MIPv6 can rely on external mechanisms, such as IPsec, to enable security. Nevertheless, our study focuses on the return routability, since it is an internal procedure of MIPv6 that allows the verification of addresses when the MN is at foreign networks. Eq. 12 formulates the cost of this procedure relying on the Home Test init (HoTI), Care-of Test init (CoTI) and respective reply messages. Integrity protection and encryption is performed in HIP by employing the Encapsulating Security Payload (ESP). The registration cost already includes the security cost C_{AA-HIP}, as ESP security association is part of the base exchange.

$$\begin{aligned} C_{AA-MIP} &= \sum_{t=1}^{nTx} L_{HoTi,t} \cdot \sum_{e\in\{MN,HA,CN\}} (Nif_{e,t} \cdot Pc_{e,t}) \qquad (12) \\ &+ \sum_{t=1}^{nTx} L_{CoTi,t} \cdot (Nif_{MN,t} Pc_{MN,t} + Nif_{CN,t} Pc_{CN,t}) \\ &+ L_{HoT} \cdot \sum_{e\in\{MN,HA,CN\}} (Nif_e \cdot Pc_e) + L_{CoT} \cdot (Nif_{MN} \cdot Pc_{MN} + Nif_{CN} \cdot Pc_{CN}) \end{aligned}$$

Address configuration in MIPv6 and HIP nodes relies on IPv6 schemes that include Router Solicitation (RS), Router Advertisements (RA) and the messages in the Duplicate Address Detection (DAD) mechanism. Neighbor Solicitation (NS) messages are sent to multicast addresses with the reply of Neighbor Acknowledgement (NA) messages. In addition, IPv6 routers (at home and foreign networks, Rtr_h and Rtr_f, respectively) advertise prefixes via Router Advertisements (RA) frequently, while Router Solicitation messages are retransmitted on error events. Eq. 13 defines the cost of address configuration.

$$\begin{aligned} C_{AD} = &\sum_{t=1}^{nTx} L_{NS,t} \cdot \sum_{e\in\{E1,E2,E3\}} (Nif_{e,t} \cdot Pc_{e,t}) + L_{NA} \cdot \sum_{e\in\{E1,E2,E3\}} (Nif_e \cdot Pc_e) \\ &+ \sum_{t=1}^{nTx} L_{RS,t} \cdot \sum_{e\in\{E1,E2,E3\}} (Nif_{e,t} \cdot Pc_{e,t}) + Q_{RA_{home}} \cdot L_{RA_{home}} \cdot \sum_{e\in\{E1,Rtr_h,E2,E3\}} (Nif_e \cdot Pc_e) \\ &+ Q_{RA_{foreign}} \cdot L_{RA_{foreign}} \cdot \sum_{e\in\{E1,Rtr_f,E2,E3\}} (Nif_e \cdot Pc_e) \end{aligned} \tag{13}$$

Movement detection also relies in IPv6 schemes, namely the Neighbor Unreachability Detection (NUD) mechanism. NUD uses solicited NS and NA messages and the respective cost is formulated according to Eq. 14.

$$C_{MD} = \sum_{t=1}^{nTx} L_{NS,t} \cdot \sum_{e\in\{E1,E2,E3\}} (Nif_{e,t} \cdot Pc_{e,t}) + L_{NA} \cdot \sum_{e\in\{E1,E2,E3\}} (Nif_e \cdot Pc_e) \tag{14}$$

Finally, MIPv6 includes the tunnel cost, since packets can be forwarded to MNs at foreign networks via tunnels. The cost of tunnel establishment is determined in an application independent fashion, as tunneling relies on IPv6 encapsulation mechanisms. The tunnel establishment cost, as per Eq. 15, considers only the size of message headers and respective processing cost in MN, HA and CN.

$$\begin{aligned} C_{TU} = &\sum_{t=1}^{nTx} HdrT_{MN,t} \cdot (Nif_{MN,t} \cdot Pc_{MN,t}) \qquad (15) \\ &+ \sum_{t=1}^{nTx} HdrT_{HA,t} \cdot (Nif_{HA,t} \cdot Pc_{HA,t}) + \sum_{t=1}^{nTx} HdrT_{CN,t} \cdot (Nif_{CN,t} \cdot Pc_{CN,t}) \end{aligned}$$

4.2 Evaluation Methodology

In this UEF study case we consider the problem of choosing a protocol for a UbiComp system at the design phase. Hence, the evaluation does not target a particular scenario with specific technologies, but examines ubiquity support in generic UbiComp systems. Thus, MIPv6 and HIP protocols are assumed to be operating with the maximum message length (e.g., with all options filled). In addition, only the mandatory messages are considered; optional messages, such as *HIP - NOTIFY*, are not included.

The nodes (e.g., MN, HI, CN, HR) are configured with three interfaces, $nif = \{1, 2, 3\}$, a common configuration in mobile terminals. Moreover, MN/HI can communicate simultaneously with several correspondent nodes, $ncns = \{1, 5, 10\}$, within which different types of applications can be used. In addition,

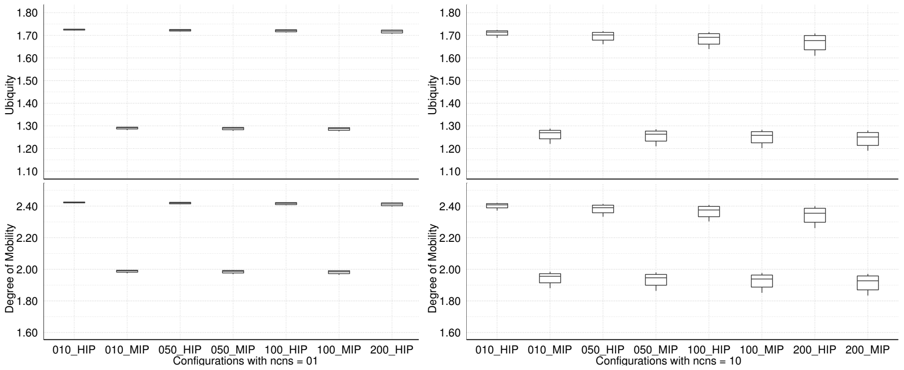

Fig. 1. Single (left) and 10 nodes (right) Ubiquity and degree of Mobility boxplots using UEF

nodes move with different speeds, thus having to handle a number of handovers $nho = \{10, 50, 100, 200\}$. All sessions last 300s. Assuming we are in the design phase of a UbiComp system, values of processing delay cannot be measured (as no prototype is available). Thus for this study case, we take all processing times to follow normal and exponential distributions, with different means $\{1s, 10s\}$. Different distributions are used to accommodate different modeling mechanisms for processing times. The analytical evaluation has been performed using the R framework [18] and considering that both MIPv6 and HIP do not include energy efficiency mechanisms $Ef = 0$, as no paging schemes are incorporated.

We use ubiquity weights $W_{lC} = 0.65$ and $W_{lU} = 0.35$ according to number of items in technical and extensions categories. The degree of mobility weight is equal to $W_m = 0.5$, as no energy efficiency mechanisms are considered and thus the degree of mobility relies mainly on the cost. Values higher then 0.5 tend to neglect the impact of cost in mobility support.

4.3 Results

Figs. 1 and 2 present our evaluation results ordered by the number of handovers and type of protocol under study. For instance, 200_HIP is an HIP study case with 200 handovers. Statistical significance is based on 100 runs for each case.

UEF can assess ubiquity taking into consideration protocol functionalities in different conditions that UbiComp systems can face. Under mobile scenarios, the number of handovers impacts the performance of mobile management protocols. All procedures required to handle mobility are triggered often, introducing degradation in the performance, (Fig. 1), as signaling overhead increases, (Fig. 2). The number of handovers also impacts handover performance; observe the difference between single and 10 simultaneous nodes on left and right sides of Fig. 1, respectively. Location updates, due to mobile events, need to be forwarded to more nodes.

Results also put in evidence the particularity of UEF that considers protocol functionalities in the assessment of ubiquity and degree of mobility. In the UEF

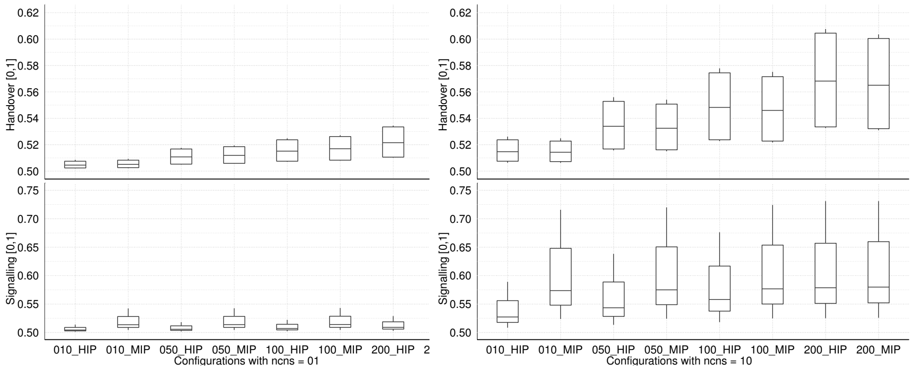

Fig. 2. Single (left) and 10 nodes (right) Handover and signalling costs boxplots using UEF

study case, HIP supports mobility better (~ 2.4) than MIP (~ 1.9 for 10 handovers with 10 simultaneous nodes) since some procedures are triggered before handover, as opposed to MIP, where procedures run after the handover.

5 Conclusion

We introduced UEF, a framework that assesses the ubiquity support of a protocol in an objective manner by considering multiple aspects of UbiComp systems regarding protocol functionalities. Evaluations carried out with UEF do not require any working system or prototype, as UEF metrics can be used at any phase in the development of a UbiComp System, ranging from system design to deployment. In addition, surveys involving users or field experts are not necessary. We used UEF in a study case to objectively evaluate MIPv6 and HIP concerning mobility management support. The study case showed that HIP supports ubiquity more efficiently than MIPv6, and for that reason HIP is a potential candidate to be deployed on UbiComp systems where mobility management and security are a concern.

To sum up, UbiComp systems integrate network protocols for diverse tasks. As multiple protocols can seemingly perform the same task, the choice of the most suitable and best-performing protocol is not always straightforward. UEF enables researchers and practitioners alike to objectively quantify the value of different technical features and extensions for mobility management in UbiComp systems.

Acknowledgment

The first author acknowledges the support of the PhD grant SFRH/BD/61256/2009 from Ministério da Ciência, Tecnologia e Ensino Superior, FCT, Portugal. This work is supported by CoFIMOM project PTDC/EIA-EIA/116173/2009.

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