Enabling interoperability as a property of ubiquitous systems: towards the theory of interoperability-of-everything

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Enabling Interoperability as a Property of Ubiquitous Systems: Towards the Theory of Interoperability-of-Everything

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***Abstract*— With the advent of the future Internet-of-Things, and consequent increasing complexity and diversification of the systems landscape, the interoperability becomes a critical requirement for this landscape's scalability and integrated, sustainable development. Can the current considerations of the interoperability paradigm meet these challenges? In this paper, we define the interoperability as a property of ubiquitous systems. In doing so, we use the anthropomorphic perspective to formally define this property's enabling attributes (namely, awareness, perceptivity, intelligence and extroversion), with objective to take the initial steps towards the Theory of Interoperability-of-Everything. The identified concepts and their interrelations are illustrated by the presented I-o-E ontology.**

I. INTRODUCTION

As computer systems become omnipresent, the contemporary paradigm of systems interoperability turns out to be incomplete and insufficient in attempt to address the complex interrelationships of diversified technical environment in which we live and work today. The future Internet-of-Things becomes a reality; hence, the mobile devices, sensors, tags and other identifiable resources with communication and processing capability need to be taken in the picture.

In such technically complex circumstances, the perception of interoperability needs to evolve from the consideration of interoperating pairs of systems to the capability of an autonomous system to sense, interpret, understand and act upon arbitrary messages received from a potentially unknown sender, based on the known relevant or non-relevant, intrinsic and extrinsic properties (facts) of the world in its environment. In this sense, interoperability becomes in fact a property of the system.

Internet of Things (IoT)[1] is defined as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols [2]. In IoT, the "things" will have identities, physical attributes, and virtual personalities. They will be expected to become active participants in business, information and social processes where they are enabled to interact and communicate among themselves and with the environment by exchanging information "sensed" from their near environment, while reacting to the real world events and even affecting it by triggering some actions. Intelligent interfaces will facilitate interactions with these "things" on the Internet, query and change their state and any information associated with them, while also taking into account security and privacy issues.

With the advent of IoT and implementing technologies (it is forecasted that the number of devices connected to Internet will grow to 50 billion, by 2020 [3]), the computing will become ubiquitous – in any device, any location and/or any format. Ubiquitous computing aims to provide more natural interaction of human with information and services, by embedding these information and services into their environment (e.g. everyday artifacts), as unobtrusively as possible [4]. Sometimes, this interaction is not evident, namely, humans may not be aware of the fact that it occurs in the background. It is being carried out in the context, namely, the devices that interact with humans (and with themselves) must be aware of this context.

IoT is expected to evolve from the current research on Wireless Sensor Networks (WSN). WSN usually consists of a set of wireless sensors nodes (from a few tens to a few hundreds, even thousands), which acquire, store, transform and communicate data using wireless technologies [5]. These autonomous nodes are spatially distributed with aim to monitor physical or environmental conditions, such as temperature, sound, pressure, etc., to cooperatively pass their data through the network to a main location, but also to enable a control of a sensor or associated device's activity.

Today, WSN are mostly used in military applications, environmental (indoor and outdoor) monitoring, logistics, healthcare applications and robotics [6].

Some of the most cited application domains of the future IoT are energy efficient homes with self-customizable living environment; smart cities with coexisting industry, retail, residential and green spaces; pervasive healthcare, offering non-intrusive, transparent monitoring of everyday activities; intelligent logistics and transportation, with safety and environmental concerns embedded into the process; retail with customizable shopping experience and full product traceability.

One of the greatest challenges for the IoT is about making different devices exchange the relevant information and consequently, making them interoperate.

ISO/IEC 2382 vocabulary for information technology defines interoperability as

"the capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units".

In a more broad sense, IEEE [7] defines interoperability as:

"the ability of two or more systems or components to exchange information and to use the information that has been exchanged".

In this case, two systems function jointly and give access to their resources in a reciprocal way. The interoperation property in this case is not absolute. Namely, it can be assessed in terms of maturity levels, as proposed by Guédria [8]. Interoperability is sometimes related to the federated approach, which implies that systems must accommodate on the fly in order to interoperate – no pre-determined assets for interoperations are assumed. In fact, this lack of technical pre-conditions is the key argument for distinguishing between integration and interoperability. Interoperability lies in the middle of an "Integration Continuum" between compatibility and full integration [8].

In light of the requirements of the future IoT, we identify two main problems with the current definitions of interoperability. First, they assume necessary awareness and agreement of both actors about their behaviors for a given interaction. This assumption is derived from the predefined motivation to interoperate. Second and even more general, they assume awareness of the coexistence of two systems that interoperate.

Both assumptions cannot, by default hold in future ad-hoc communications and interoperations of the variety of different systems in ubiquitous computing. Even though the current collaboration culture assume sharing and a social context, we consider these as the obstacles for interoperability because they imply the previous agreements between the interoperating systems. Removing these agreements would mean that interoperability will become, in fact, a semantic interoperability. To support that, we can refer to the often used definition of interoperability, by an unknown author:

"Interoperability is a property of a product or system, whose interfaces are completely understood, to work with other products or systems, present or future, without any restricted access or implementation".

In this paper, we discuss on what is needed to develop this property. In specific, the following research question is asked: What is needed for one system to operate based on the message(s) of the arbitrary content, sent by the (an)other (unknown) system(s)? In order to answer this question, first, we define the key principles for the future considerations of interoperability as a property. Then, we discuss about the enabling technologies, based on the identified desirable attributes. Finally, we propose I-o-E (Interoperability-of-Everything) ontology, which illustrates the explanation of the interoperable "thing", in a formal way.

II. INTEROPERABILITY AS A PROPERTY

The cases for the future IoT are typically based on the pre-agreement of the different devices to exchange information and to act upon this information. However, as the number of connected devices and their technological diversity grows, it would become more and more difficult to work on reaching these pre-agreements. More important, a current approach will inevitably lead to application silos, with fragmented architectures, incoherent unifying concepts, and hence, little reuse potential.

Thus, it is highly likely that the "things" of the future IoT will be required to interpret ad-hoc signals and requests from other devices, including the motivation behind these signals and act according to the interpreted motivation.

A. *Interoperability as a property of the systems*

Let us consider a simple future internet of things where there is a surveillance camera which registers undesirable event and urgently needs to send SMS to a property owner (see Fig.1).

However, it seems that the text sending unit failed. Now, the camera broadcast the message (without a knowledge about its receiver, or if there is a receiver at all). In its environment, there are other devices (systems), e.g. thermostat. It appears that thermostat also have text sending unit (to send information about rapid temperature drop or rise). Thermostat registers this message, interprets it and acts (send SMS about surveillance camera event).

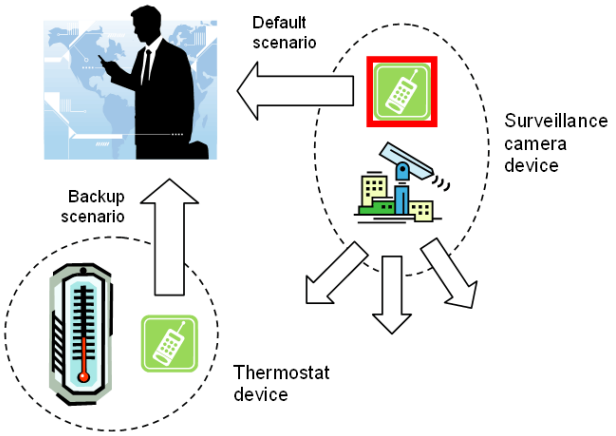

Figure 1. Example IoT scenario

The problem, described in this case can be resolved by the Internet-of-Services. However, the latter implies the functional organization, namely the thermostat's capability to send SMS messages is defined in advance as a service. Such a service is associated with required input requests, by means of format, protocol to deliver, etc. All these requirements are pre-conditions to interoperate, hence, the obstacles. It is important to highlight that, in this case, a communicating entity is not aware of the sole existence of the receiving entity, not to mention the capability to perform the required task by the latter. This is an extension of [D1] definition of interoperability, which assumes no "knowledge of the unique characteristics of the interoperating systems".

Instead of the message in specific format, we can foresee that the communicating entity broadcasts a set of logical statements, namely an ontology, which describes the request to assist in the critical situation.

As explicitly stated in [D3], with the current consideration of the autonomous systems, the perception of interoperability has to be changed to a property of a single system. This property determines the capacity of a system (in a general sense) to adapt, respond, act internally or externally, etc. upon some circumstance. As referred in [D3], this capability depends on the "understanding of the interfaces".

However, interoperability can still be considered as a property of a pair (in a traditional sense of interoperability). Then, it must be taken into account that it is only a specialization of the above defined property. The key consequence of this consideration is that now, interoperability is seen as unidirectional property of a pair.

A social context is important to define the interoperability as it is used to determine the purposeful interoperations. In this context, vaguely defined, interoperability would simply be properly reacting to the utterances of others. What is "properly" may be related to a post-agreement on what a proper reaction is. In other words, the ultimate test to see whether one system have reacted properly may be to see how its environment reacts to its reaction.

The social context of the interoperation may be pre-determined. Namely, sometimes systems expose their capabilities by using services and this is exactly the case for paradigm of Internet-of-Services.

III. ENABLING ATTRIBUTES AND FACTORS

When enabling factors for the above scenarios are considered, we first identify the key attributes of the "things", required for their interoperable behavior. Then, we identify the candidate technologies, methodologies and assets to achieve each of these attributes.

The minimum requirements for an autonomous, intelligent, purposeful, social behavior of a "thing" in the interoperable environment, such as WSN, are: awareness, perceptivity, intelligence and extroversion. Obviously, this consideration of "things" is anthropomorphic.

A short elaboration of the arguments for this choice of attributes is given.

We can distinguish between two aspects of awareness: self-awareness and environmental awareness.

Self-awareness is related to the capability of a "thing" to sense a phenomenon or an event within itself. For example, WSN nodes need to be aware of the available energy levels. Namely, data communication policy of a node may differ from the acquisition policy (different frequency), due to the energy issues. The decisions of adapting these policies to the current energy constraints could be made autonomously by the nodes and the nodes behavior may be adapted in time to optimize their lifetime.

Awareness is related to the capability of a "thing" to sense a phenomenon or an event from its environment. We also extend this consideration by adding the simple capability to receive a message from its environment. The former is a core functionality of a node in WSN and hence, it will not be elaborated in detail. However, it is important to highlight that the awareness of the current nodes is functional in its nature and thus, restricted. Namely, the sensor is aware only of the environmental features of its (pre-determined) interest. The similar point can be made related to the capability of a "thing" to receive a message (of a known format). Hence, we can distinguish between functional and universal environmental awareness.

Perceptivity is a property of a "thing", related to its capability to assign a meaning to the observation from its environment or from within itself. While awareness and self-awareness are properties that have been already achieved by WSN nodes, but only in the restricted, strictly functional scope, perceptivity goes one step further, by facilitating its universal awareness. It enables the "things" to observe based on the arbitrary stimuli and consequently to perceive these observations, namely to transform the physical observation to a meaningful percept. It is important to highlight that these observations are typically multi-modal (e.g. temperature, light, sound, etc.) and diverse in many dimensions (e.g. they are time and location dependent).

Then, based on this percept, a "thing" should be able to decide on the consequent action. This decision is a result of a cognitive process, which consists of identification, analysis and synthesis of the possible actions to perform in response to the "understood" observation, namely a percept. The intelligence, as an attribute of the interoperability property also encompasses assertion, storing and acquisition of the behavior patterns, based on the post-agreements on the purposefulness of the performed actions.

Finally, the last attribute of the "thing" - extroversion is related to the willingness and capability of the "thing" to articulate the above action. It demonstrates the thing's concern about its physical and social environment.

In the reminder of this section, we provide more detailed elaboration including an overview of the existing technologies, methodologies and assets that might be used to enable the above attributes, to facilitate the interoperability property of ubiquitous systems.

A. Enabling awareness

The behavior related to the self-awareness of the nodes can be facilitated by using sensor ontologies.

Several ontologies have been developed to represent sensors and their behavior, since 2004 [11]. Some of the most relevant are MMI ontology of oceanographic devices [12], CSIRO ontology for description of sensors for use in workflows [13], SWAMO ontology [14], A3ME ontology with classification for self-description and discovery of devices and their capabilities [15] and O&M-OWL (SemSOS) ontology for reasoning over sensor data to infer "high-level" concepts from "low-level" phenomena [16].

The above ontologies are highlighted based on the extensive review of the W3C Semantic Sensor Network Incubator Group [17]. Exactly this review was made for the purpose of developing W3C Semantic Sensor Network (SSN) Ontology.

SSN Ontology [18] is a formal OWL DL ontology for modeling sensor devices (and their capabilities), systems and processes. It extends DUL (Dolce Ultra Lite) upper ontology. It is universal in sense that it does not assume a physical implementation of a sensor. Namely, it can be used to describe the process of sensing by the WSN nodes, as well as by the humans.

SSN unfolds around the central pattern that relates what the sensor observes to what it detects. While the latter is determined on basis of its capability, namely accuracy, latency, frequency, resolution, etc. and a stimulus, the former is related to the concepts of features of interest, their properties, observation result and sampling time, etc. The skeleton of SSN ontology is illustrated on Fig.4.

Stimuli are detectable changes in the environment that trigger the sensors (or a decision of a sensor to perform observations). They are related to the observable properties and hence, to the features of interest. The same types of stimulus can trigger different kinds of sensors and can be used to reason about different properties.

Sensors perform observations; they transform incoming stimulus to another representation. They are related to a procedure of sensing – on how a sensor should be realized and deployed to measure a certain observable property. Observations are also seen as parts of an observation procedure.

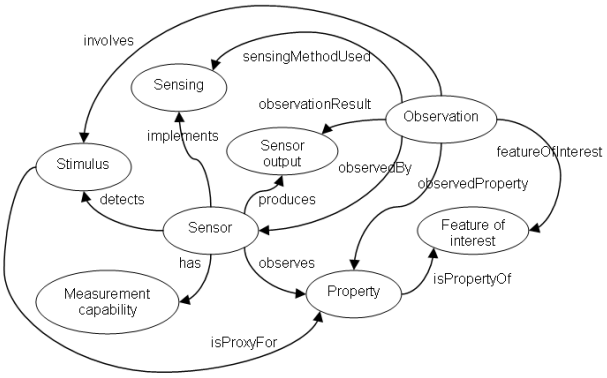

Figure 2. Skeleton of the Semantic Sensor Network ontology

Properties are qualities of the feature of interest (entities of the real world that are target of sensing) that can be observed via stimuli by the sensors.

Obviously, sensor ontology is an useful asset for directly facilitating self-awareness. Furthermore, it can be easily extended to enable processing of the pre-determined, expected observations and making direct conclusions, thus facilitating functional environmental awareness. Some examples are: IoT-enabled business services, collecting and processing sensor data within a rescue environment [19], smart products [20], semantic-based sensor network applications for environmental management [21] and agri-environmental applications [22].

B. Enabling perceptivity

Cognitive psychology considers perception as the organization, identification, and interpretation of sensory information carried out with the objective to represent and understand the environment [23].

Perceptivity is tightly related to the awareness attribute in the sense that constructing the meaning from the observations data is a pre-condition for understanding the context in which some interoperations or communications occur. In other words, the known meaning of the sensor data or data pattern contributes to its communication context awareness, or, in specific, its situational awareness.

When considering the awareness capabilities, mentioned above, we can distinguish between the perceptivity related to perceiving the sensor data and the perceptivity related to assigning a meaning to an incoming message. Consequently, we discuss about the observational and communicative perceptivity. It goes without saying that a "thing" that exhibits both capabilities may process the sensor data and messages in a combined way.

The observational perceptivity is related to computing a percept on basis of a raw sensor data. Here, we refer to the work of Kno.e.sis, USA and the University of Surrey, UK. They developed and implemented a methodology [24] to identify patterns from sensor data, by using Symbolic Aggregate Approximation (SAX). These patterns are then translated into abstractions with an abductive logic framework called Parsimonious Covering Theory (PCT) [25], approximated by the authors by using OWL. The abstractions are directly, or by using reasoning mechanisms, related to an event or a phenomenon. PCT uses domain-specific background knowledge to determine the best explanation for a set of observations, namely to link the patterns to semantic descriptions of different relevant thematic, spatial and temporal features.

In the subsequent effort, with the objective to provide a formal semantics of a machine perception, Henson et al developed IntellegO ontology of perception [26]. IntellegO was made based on the principles of Neisser's Perception Cycle [27], according to which a perception is considered as a cyclic process, in which the observation of the environment, followed by the creation of the initial percepts, is often affected by the process in which we are directing our attention for further exploration, in order to get more stimuli required for constructing the final percept. In this process, humans generate, validate and consequently reduce the hypotheses that explain their observations.

According to IntellegO, based on the observed qualities of the inherent properties of the observed object, a subject creates a number of percepts as parts of the so-called perceptual-theory. Then, in order to clarify which qualities enable the reduction of the perceptual-theory, following types are classified: expected, unknown, extraneous and discriminating qualities. Hence, the specific goal of the perception cycle is to generate a minimum perceptual-theory for a given set of percepts. These percepts may not come only from the features of interest but also from the general environment of a "thing", to which some questions may need to be asked. Hence, perceptivity cannot be addressed independently of extroversion, which is used to articulate these questions.

The trend of service-enablement of "things" pushes us to consider also their capability to perceive interfaces (services), rather than data and/or information. Although this is somewhat out of the scope of the initial research question, it must be taken into account, as the services are credible elements of the "things" environment.

Current work on defining the models in IoT domain is mostly focused on the resources description in management. However, the aspect of accessing and utilizing information, generated in IoT is equally important as enabler of the aforementioned descriptions. Exactly this aspect is addressed by Wang et al, who developed a comprehensive ontology for knowledge

representation in the IoT [28]. This ontology extends the current work on representation of resources in IoT, by introducing service modeling, Quality of Service (QoS) and Quality of Information (QoI) aspects.

Perceiving service interfaces in IoT is tightly related to their discovery. Here, we refer to the work of Guinard et al, who proposed the architecture for dynamically querying, selecting and using services running on physical devices [29]. This architecture can be particularly useful for finding the relevant observation in a specific context. With regard to this, it is important to take into account the work of specification of Sensor Observation Service (SOS) web service [30] by the Open Geospatial Consortium (OGC). Finally, Pschorr et al [31] have shown that publishing sensor data as Open Linked Data, when complementing the use of sensor discovery service can enable the discovery and accessing the sensors positioned near named locations of interest.

When IoT capabilities are considered, we can distinguish between the following types of core, general services of "things": observational, computational, and actuating services.

C. *Enabling intelligence*

In a really broad sense, intelligence as an attribute of the "thing" is related to its processing or computational capability. The processing unit (also associated with small storage unit) is already embedded in the current architecture of nodes in WSNs and its key objective is to reduce energy consumption. This is especially important in multi-hop WSNs.

A unique feature of the sensor networks is the cooperative work of sensor nodes, where multiple and multi-modal observations data is distributed to a central gateway (or another node) which is in charge for their processing. Instead of continuously sending raw data to the nodes responsible for their interpretation and processing, sensor nodes use their own processing capabilities to locally carry out simple computations and transmit only the required and partially processed data.

In a more specific sense and in context of defining the interoperability as a property of a "thing", we consider the intelligence as the capability to perform any and every step of processing, needed for determining the meaningful and purposeful response to the perceived observations. This definition implies that the necessary condition for a cognitive activity is certainly an action. More important, it assumes purposefulness, which is determined socially.

It is important to highlight that this capability has a social context. Namely, when processing requires the computation, which is not possible within a single node, then this computation is requested from its environment. Thus, as it was the case for awareness attribute, intelligence cannot be considered in isolation from the extroversion attribute. Also, it is tightly related to self-awareness, since a particular computation capability is an internal attribute of a 'thing".

When enabling technologies are discussed, a key thing to focus at is a particular kind of logic or logics that could facilitate inference in the context, defined by the above attributes. Although great most of the current efforts in developing sensor, IoT and WSN ontologies are implemented by using OWL, it is our opinion that this poses a serious constraint to the future developments related to enabling "things" with intelligence. Namely, interoperability as a future property must also consider the possibility to "understand" and combine different formalisms and to make meaningful but unambiguous conclusions by using variety of engines.

D. *Enabling extroversion*

Extroversion as a property is considered as a capability of a "thing" to commit to articulating and performing an action, based on a decision.

It reflects its commitment to act socially, namely to actively inform, affect or change its environment, where this engagement is related also to endorsing or denouncing other "things" actions. It also reflects its curiosity, namely the capability to articulate the request for any additional information needed for a complete reasoning during the processes of perception and decision.

IV. INTEROPERABILITY-OF-EVERYTHING (I-O-E) ONTOLOGY

In this section, we summarize the discussion above in a formal way, by synthesizing the identified concepts into I-o-E (Interoperability-of-Everything) ontology. At this point, I-o-E ontology is only considered as an illustration of identified principles for interoperability of ubiquitous systems. Also, I-o-E ontology does not include implementation details; hence, for example, services are not defined.

I-o-E unfolds around two central patterns. Vertical pattern encloses thing-attribute generic relationships, while horizontal pattern defines stimulus-observation-perception-decision-action cycle.

I-o-E extends the SSN ontology to stimulus-observation-perception-decision-action cycle (see Fig.3) in which the value of a stimulus is gradually added with the objective to perform purposefully and socially. The purposefulness and social aspects of the action are realized by the possibility of other "things" to endorse the performed action, thus turning the instance of the cycle to the candidate pattern of behavior. Hence, we distinguish between intrinsic and extrinsic intelligence. Intrinsic intelligence is exhibited if this cycle barely exists; namely, the thing is intrinsically intelligent if it is capable to simply decide on the action. Extrinsic intelligence is exhibit if these actions received the endorsement of other things.

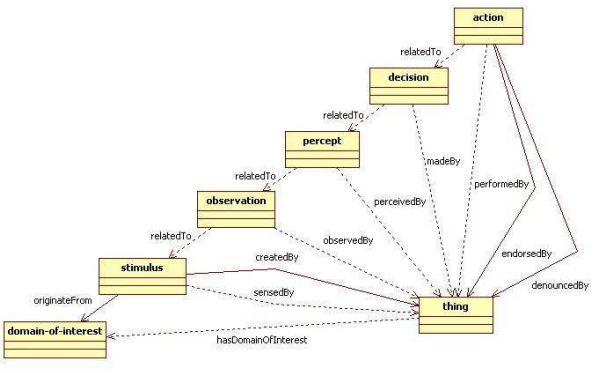

Figure 3. UML representation of the central vertical pattern of I-o-E ontology

These concepts are related to the theory of systems intelligence, proposed by Hämäläinen and Saarinen [32]. The systems intelligence is measured by successful interactions with an environment, and a person's ability to modify their behavior based on feedback from that environment.

On Fig.3, dashed lines illustrate dependency. Namely, they indicate necessary conditions for concepts. Hence, a stimulus exists only if it is sensed – by a thing. However, it may be created by a thing (or it may come from the environment). In another example, a thing has a minimum one domain of interest; however, it may sense a stimulus or stimuli for which we do not know if it comes from any domains of interest, since originateFrom(stimulus, domain-of-interest) is not a necessary condition for a stimulus.

Fig.4 illustrates the central horizontal pattern of I-o-E ontology: thing-attribute. All possible attributes are represented as individuals.

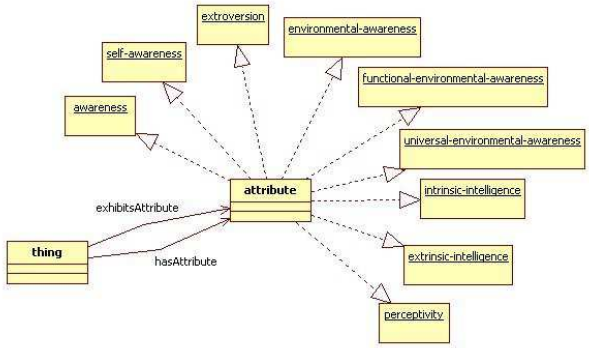

Figure 4. UML representation of the central horizontal pattern of I-o-E ontology

In order to make possible the evaluation of the interoperability property, namely the related attributes, the assertion of things that do not exhibit above attributes by default, is allowed. In other words, association of a thing to an attribute is not a necessary condition for a thing.

Attribution to the things is asserted by the following rules:

[R1](thing(t) ∧ stimulus(s) ∧ observation(o) ∧ exhibitsAttribute(t,'awareness')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(relatedTo(o,s) ∧ observedBy(o,t)))

[R2](thing(t) ∧ stimulus(s) ∧ observation(o) ∧ exhibitsAttribute(t,'self-awareness')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(relatedTo(o,s) ∧ createdBy(s,t) ∧ observedBy(o,t)))

[R3](thing(t) ∧ stimulus(s) ∧ observation(o) ∧ exhibitsAttribute(t,'environmental-awareness')) ⇒ ∀t(∃s(sensedBy(s,t) ∧ ¬createdBy(s,t)) ∧ ∃o(relatedTo(o,s) ∧ observedBy(o,t)))

[R4](thing(t) ∧ stimulus(s) ∧ observation(o) ∧ percept(p)) ∧ exhibitsAttribute(t,'perceptivity')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(observedBy(o,t) ∧ relatedTo(o,s)) ∧ ∃p(perceivedBy(p,t) ∧ relatedTo(p,o)))

[R5](thing(t) ∧ stimulus(s) ∧ observation(o) ∧ percept(p) ∧ decision(d) ∧ action(a)) ∧ exhibitsAttribute(t,'intrinsic-intelligence')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(observedBy(o,t) ∧ relatedTo(o,s)) ∧ ∃p(perceivedBy(p,t) ∧ relatedTo(p,o)) ∧ ∃d(madeBy(d,t) ∧ relatedTo(d,p)) ∧ ∃a(performedBy(a,t) ∧ relatedTo(a,d)))

[R6](thing(t) ∧ thing(t') ∧ stimulus(s) ∧ observation(o) ∧ percept(p) ∧ decision(d) ∧ action(a)) ∧ exhibitsAttribute(t,'extrinsic-intelligence')) ⇒ ∀t(∃s(sensedBy(s,t)) ∧ ∃o(observedBy(o,t) ∧ relatedTo(o,s)) ∧ ∃p(perceivedBy(p,t) ∧ relatedTo(p,o)) ∧ ∃d(madeBy(d,t) ∧ relatedTo(d,p)) ∧ ∃a(performedBy(a,t) ∧ relatedTo(a,d)) ∧ ∃t'(t≠t' ∧ endorsedBy(a,t')))

Note that relatedTo is a transitive symmetric property; hence it is possible to infer relatedTo(p,s) and relatedTo(a,s) in [R4] and [R5][R6], respectively. However, direct assertions of relatedTo(a,s) are also possible in cases when the "thing" needs to make additional observations (and subsequent perceptions) in order to get some missing information from its environment (or from within itself), needed to complete the inference of the decision and, consequently formulated action.

Again, we highlight that the extrinsic intelligence is an attribute which is exhibited by a thing t, only if an action is performed by this thing, based on the set of stimuli it sensed, and only if there exist at least one thing t', different from t, which endorsed this action.

A. Modeling intelligence

The above rules can be used only to validate if there exist stimulus-observation-perception-decision-action cycles where a thing exhibits one or more of the attributes. They are only formal definitions of these attributes. However, substantial intelligence of the "thing", as its attribute can be confirmed if and only if intelligence is exhibited for all these cycles.

The assumption that the "things" act upon every observation they make may sound too optimistic. However, we should take into account that simple storage of the sensation-observation-perception triple can be considered as an action. These asserted triples can later be used for experience-based reasoning.

We discuss about the substantial intelligence in context of the observation sets. An observation set is a set of observations all of which are related to an action. This context is anthropomorphic because it involves consciousness; namely, it does not consider all stimuli sensed by the "thing" but only those that are observed (and in fact, acted upon).

Thus, member-of-observation-set class is defined as equivalent class:

member-of-observation-set ≡ observation(o) ∧ (action(a) ∧ relatedTo(o,a))

All observations are automatically classified to this class if the above conditions are met. All observations that

are related to a single specific action are considered as the members of one observation set.

Also, we discuss about the substantial intelligence in context of the perceptual sets. Similarly to an observation set, a perceptual set is a set of percepts all of which are related to an action.

member-of-perceptual-set ≡ percept(p) ∧ (action(a) ∧ relatedTo(p,a))

The definitions of the above two equivalent classes are introduced to illustrate that we distinguish meaningful observations and percepts from the non-functional ones. In fact, during the process of deciding on the possible action, the "thing" may look up among the relationships between the existing members of these two classes (and resulting actions), similarly to human mind's consideration of knowledge and experience.

While the "occurrences" of intelligent behavior are formalized by exhibitsAttribute relationship, the substantial intrinsic [R7] and extrinsic intelligence [R8] of the "thing" are represented by the inferred hasAttribute(thing(t), 'intrinsic-intelligence') and hasAttribute(thing(t), 'extrinsic-intelligence') relationships. These relationships are inferred, based on the following rules:

[R7](thing(t) ∧ stimulus(s) ∧ observation(o) ∧ percept(p) ∧ decision(d) ∧ action(a)) ∧ hasAttribute(t,'intrinsic-intelligence')) ⇒ ∀t(∀s(sensedBy(s,t)) (∀o(observedBy(o,t) ∧ relatedTo(o,s)) (∀p(perceivedBy(p,t) ∧ relatedTo(p,o)) (∀d(madeBy(d,t) ∧ relatedTo(d,p))))) ∃a(performedBy(a,t) ∧ relatedTo(a,d)))

[R8](thing(t) ∧ stimulus(s) ∧ observation(o) ∧ percept(p) ∧ decision(d) ∧ action(a)) ∧ hasAttribute(t,'extrinsic-intelligence')) ⇒ ∀t(∀s(sensedBy(s,t)) (∀o(observedBy(o,t) ∧ relatedTo(o,s)) (∀p(perceivedBy(p,t) ∧ relatedTo(p,o)) (∀d(madeBy(d,t) ∧ relatedTo(d,p))))) ∃a(performedBy(a,t) ∧ relatedTo(a,d)) ∧ ∃t'(t≠t' ∧ endorsedBy(a,t')))

Note that according to the proposed definition, the substantial extrinsic intelligence is inferred in case of endorsement of only one thing t', different from t. In simple words, if the performed action is useful for at least one another thing, the behavior is characterized by intelligent, independently of the possible denouncements or indifference of the other things in the environment.

V. CONCLUSIONS

In this paper, we argue that the interoperability as a property of ubiquitous systems can be enabled if these systems are empowered with the attributes of awareness, perceptivity, intelligence and extroversion. These attributes then enable the systems to behave and communicate autonomously and openly, without considering the designated features of interest, similarly to humans, in the activities of sensation, perception, cognition and articulation. The anthropomorphic commitment is also kept when social context of the interoperations is considered. Namely, this context is neither predetermined nor pre-agreed. Rather, it is established post-mortem in endorsements or denouncements of the actions, performed as the outcomes of the interoperations.

One of the most obvious and direct effects of such an approach in the future are related to addressing key technological challenge of WSNs: to decrease the energy consumption of "things" and to extend the lifetime of the nodes. First, perceiving raw sensor data in multi-hop WSNs and consequently, transmitting the meaningful percept (or, acting upon this percept) instead of this raw data, can significantly reduce the data volume that needs to be communicated from the sensor nodes to the gateways or processing components. Second, introducing a processing capability of the "things" may, in fact, revoke the need for these components, thus having the similar effect on the traffic.

Furthermore, encoding some kind of "intelligence" into individual things contributes significantly to the possibility of one network of things to scale more effectively and efficiently, even across the boundaries of the other networks. This future benefit is derived from the foreseen capability of "things" to sense, perceive and act independently of the predetermined features of interest.

The amount of the research opportunities in this area is immense, even without considering the technical (hardware) challenges. They are mostly related to the development of top-level theories and strategies which are foreseen neither to replace nor update current approaches, but to reconcile them, by enabling things' proficiency in different standards, languages, even logics.

Even more complex measures of the things' intelligence can be introduced when referring to the notion of social intelligence, defined as the capacity to effectively negotiate complex social relationships and environments. Here, the role of the thing will extend from simply affecting its social environment (systems intelligence) to navigating through the complex social situations and adapting to dynamic conditions.

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