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Enhancing heterogeneous mobile network management based on a well-founded reference ontology

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ABSTRACT

The fulfillment of the Always Best Connected & Served concept in future mobile wireless networks depends on their ability to maintain a seamless association between the user's equipment and the network. As a result, many researchers and developers have proposed several decision-support mechanisms to cope with this challenge. One of the promising mechanisms to aid mobile wireless networks in achieving ubiquitous coverage with a seamless connection is semantic reasoning. However, once it relies on ontologies, proper representation of Link and Connection – entities that bind the communication nodes – is paramount. Unfortunately, although several network-related ontologies present these concepts, they are unclear on which entities they bind, nor do they present them simultaneously. Also, the same ambiguity can be perceived in vocabulary recommendations of several telecommunication standard bodies. Our main contribution is the ontological analysis that clarifies the definition of Link and Connection in telecommunication domain. Besides, we analyze their dependencies while refining other concepts such as Medium, Server, and Neighbor. Thus, we provide the foundations for a new network-related ontology to support mobility management in wireless networks.

1. Introduction

One of the main challenges of future mobile networks is to provide continuous wireless communication services anywhere, at any time. Unfortunately, this ideal scenario has defied researchers and developers over the years, being first described by Gustafsson and Jonsson [1] as the Always Best Connected (ABC) scenario. Later, other works expanded this concept [2–5], adding other requirements such as quality of service (QoS) and quality of experience (QoE). Thus, it has evolved to be the Always Best Connected and Served (ABCS) scenario, representing the current research efforts to provide ubiquitous mobile coverage with a seamless connection.

One of the paths chosen by researchers and developers to provide a ABCS scenario in future mobile wireless networks relies on heterogeneous radio access sub-networks (RAN) [6–8]. They allow users' equipment (`Ue`) to access the wireless network through communication nodes known as access points (`APs`) which have different radio access technologies (RAT), e.g., 3G, 4G, 5G, P25, TETRA, WiFi, WiMAX, Satellite, among others. This approach enhances RAN's coverage and capacity, bringing the best features of each RAT, and providing the ubiquitous coverage of the ABCS concept. However, on the other hand, it defies the mobility management processes that allow the seamless connection since it depends on complex procedures' agreements between different telecommunication standard bodies (hereafter called standard bodies for short).

The recommendation TS 21.905 from the 3rd Generation Partnership Project (3GPP) standard body [9] defines mobility management in wireless networks as the set of procedures that maintains a given `Ue` attached to a serving network. One is the handover process, a mobility management procedure that handles the `Ue` movement between `APs`, while a communication service, such as a conversation or a data transfer, remains intact. The standard bodies specify this process mainly by using network attributes and measurements such as `Ue's` received power strength or quality [10]. Besides, in most cases, they use simple 'if–then' rules to decide whether it is appropriate to move between available `APs`.

Many researchers have proposed different decision-support approaches to improve the handover process over the years. For example, they have suggested new triggers to initiate the handover process, such as battery life and security level. Also,

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different decision support approaches have been proposed based on the multi-attribute decision-making process(MADM), Fuzzy Logic, Game Theory, Graph Theory, Utility Functions, and Machine Learning (ML) methods [11–15]. In many cases, they were combined to get the best of their capabilities and provide better decision options.

Recently, semantic technologies have been added to the group of tools capable of improving decision-making [16–19]. According to Rospocher and Serafini [19], the reasons to use semantic technologies go beyond to their reasoning capacity. It also acts as an integrator of structured knowledge and data available on the web, as a decision-support system (DSS) web service, and as a storage of a semantically rich track of the entire decision process. Nevertheless, to use semantic reasoning as part of a decision support system for mobility management, an ontology has to be able to describe not only its entities but also their relationships and the rules that must be followed.

As a good practice in ontology engineering [20], we searched for available network-related ontologies to cope with the task by reusing its concepts and models. Although many of the concepts are reusable, such as `Communication Devices` and `Interfaces`, others used to describe the relationship between communication nodes need to be more accurate. For example, ontologies such as the NDL [21–23], the OpenMobileNetwork [24], and ToCo [25] refer to them as `Links`, while ontologies such as SAREF [26] refer to them as `Connections`. Furthermore, the vocabulary recommendations of the standards bodies provide no clear definition of `Link` and `Connection`. Thus, the ontology engineer struggles to comprehend whether these terms are synonyms. Moreover, if they are not synonyms, are there any dependencies on each other? Again, the standard bodies are not clear on this matter. Hence, we need to better understand the nature of relationships between the communication nodes before creating an ontology that can support decision-making in mobile wireless networks, especially in the handover process. In this sense, a deeper analysis of the nature of the relationships between communication nodes was made, especially between `Ue` and `APs` in a wireless environment, using a conceptual data modeling tool called OntoUML [27].

Our contribution is threefold. First, we clarify the concepts of `Link` and `Connection`, clearly comprehending what they are, which entities they bind, and how they are related. Then, we propose a novel concept to enhance the ontological description of a mobile wireless environment – the `Medium`, which is missing in the available network ontologies. Finally, we propose enhancements to describing some concepts, such as `Server` and `Neighbor`, poorly described in a few network-related ontologies. All these concepts are fundamental to supporting decision-making in mobile network management, especially in the handover process.

This paper is organized as follows. Section 2 presents basic concepts of mobile management on wireless networks and conceptual data modeling using OntoUML. Section 3 reviews the network-related ontologies proposed by the academia and by standard bodies and discusses the gaps that prevent their immediate use for semantic reasoning in mobile management. Section 4 evaluates the nature of the relationship between communication nodes and reviews and clarifies essential concepts. Section 5 discusses the proposed conceptual model, comparing the researched ones and highlighting the improvements. Finally, Section 6 presents our conclusions and gives direction for future works.

2. Background

2.1. Information exchange in communication networks

Provide information exchange between users is one of the main goals of a communication network. The ITU Recommendation V.662-3 [28] defines two methods for information exchange: simplex and duplex. In simplex communication, information can be transmitted between two entities, in both directions, but not simultaneously. On the other hand, in duplex communication, information can be transmitted in both directions simultaneously. The same vocabulary recommendation defines the terms unidirectional and bidirectional to characterize what it defines as links. A link *where the transfer of users' information is possible in one preassigned direction only* is called unidirectional. In contrast, a bidirectional link is one *where the transfer of users' information is possible simultaneously in both directions between two points*.

We can describe several communication systems using these previous definitions. The Global Positioning System (GPS) can be described as a simplex communication system that uses unidirectional links. Trunking Radio Systems, like TETRA and P25, can be described as simplex communication systems that use a pair of unidirectional links, employing a technique known as the Frequency Division Duplexing (FDD) [29]. Modern cellular systems such as the 3GPP's 4G and 5G systems employ various techniques to deliver information. They allow duplex communication systems using multiple unidirectional links employing the FDD technique, as well as simplex communication using bidirectional links, employing a technique called Time Division Duplexing (TDD) [29]. This last technique is also employed in WiFi systems. Future mobile communications systems will rely on modern approaches such as the In-Band Full-Duplex [29], which allows duplex communications using bidirectional links.

2.2. Network functions in communication networks

In mobile communication networks, each node executes a function to provide information exchange between users ultimately. Each standard body specifies its network entities, although some nomenclature may be shared between them. Fig. 1 shows an example with some of these nodes in a 3GPP 4G wireless network, whose functions are defined in [9]. Nodes `ue1` and `ue2` are user equipment (`Ue`), and they are responsible for the communication between users represented by the association in orange in Fig. 1. However, in networks like 3GPP 4G, this communication depends on the communication between other network nodes. Network nodes such as `ap1` and `ap2` play the role of access points (`AP`) of the network. They are responsible for forwarding user information over the communication system. For instance, to enable the communication between `ue1` and `ue2`, `ue1` communicates with `ap1` that communicates with other nodes in the network, which via some node path reaches `ap3` that communicates with `ue2`. Conversely, other network nodes are responsible for other functions. For instance, the `mme` node is an inner node of the network, and one of its responsibilities is to provide mobile management when `ue1` moves between the coverage area of `ap1` and `ap2`.

Traditionally, these nodes were built considering their roles in the network. However, due to the technological advances of software-defined networks, software-defined radio, and network functions virtualization, the role of each communication node can change over time [6]. In modern mobile networks such as the 3GPP 5G network, many of the functions that were played by nodes defined by hardware can now be defined by software. For instance, the function of the `mme`, a node with a role defined by hardware in the 3GPP 4G network, can now be played by any network node with the mobility management function loaded in a 3GPP 5G network.

Another ordinary example illustrates how network nodes can play different roles at the same time. Let us consider a mobile phone with one cellular interface and one WiFi interface. In their ordinary operations, they both play the role of `Ue`, each interacting with its wireless network. However, there are times

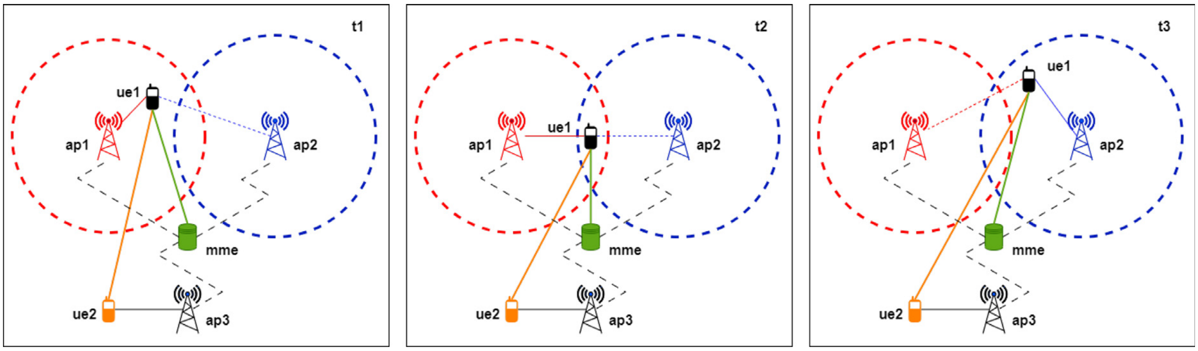


Fig. 1. A Simple Handover Scenario in 3GPP's 4th Generation Mobile Network.

when the WiFi interface is set to work as an AP for users close to the mobile phone. Besides, it also needs to play the role of an Ue while interacting with the cellular interface playing the role of an AP. In this scenario, the WiFi interface plays the role of AP, providing network access to surrounding users. At the same time, it plays the role of Ue towards the cellular interface.

2.3. Mobility management in wireless networks

Mobility management in wireless networks can be defined as the set of procedures that maintains a Ue attached to a serving wireless network. These mechanisms allow users to be still served while moving within the coverage area. As described in [30], two distinct operation modes characterize the relationships between the Ue and the wireless network: the idle and the connected mode. In the former case, the Ue does not exchange user data with the network, while the latter does with other communication entities. Although both modes have the same relational nature, they rely on different decision-making approaches to keep the Ue bound with the network. In this work, our focus is on managing these relationships while in the connected mode. It represents the most challenging decision-making process, depending on interactions between the Ue and the wireless network, while the idle mode depends only on the Ue. In this sense, analyzing the connected mode brings more richness to our analysis.

Each standard body gave different names for this basic mobility management process while the Ue is in connected mode: handover, handoff, or association control [12]. To normalize the term, we choose handover (HO) as a reference for all of them. Fig. 1 shows a basic HO process performed in a 4G network specified by the 3GPP standard body [10]. Although specific to it, the process shows a general procedure found in other mobile systems since they share the same basic principles.

At t_1, the ue1 is being served by ap1, and it is moving towards the region covered by (ap2). Both access points belong to the same network in which the ue1 is attached. This attachment allows the communication between ue1 and . Also, it provides communication between ue1 and the 4G's mobile management entity(mme), responsible for monitoring Ue's location and its requests for handover.

Then, at t_2, the HO process is initiated. Different rules and scenarios can trigger the initiation phase: received signal power degradation, traffic offloading, interference, etc. In this case, we assume an ordinary and common trigger: the degradation of received signal power from the serving AP (ap1). At this moment, ue1 starts the measuring report process, collecting information such as signal strength, frequency, and RAT about the nearby APs such as the ap2. These APs are also known as the Ue's **neighborhood** and represents an important concept in mobile management. Without this network awareness, a HO cannot be executed. Moving forward, it sends these information to the network's mobile management entity (mme) to decide which AP should be selected to keep ue1 attached to the network, maintaining their current associations to other nodes, such as the one between ue1 and ue2 (orange line). This step starts the decision-making phase of the handover process. This phase of the HO process is a field of research of its own. Many authors proposed different strategies in different scenarios to handle the decision process [11–15], based on different methods from different fields like Operational Research and Artificial Intelligence.

Once defined which AP is the most suitable to handle an association with the Ue, the HO execution phase starts. Then, at t_3, all the necessary procedures to create a new association between the ue1 and the new server are done at the same time it terminates the old association with the old server. In order to accomplish it, the information exchange between ue1 and ue2 and between ue1 and mme are halted, while the association between ue1 and ap1 and the association between ue1 and ap2 change their roles (server *or* neighbor). In our example in Fig. 1, ue1 is associated with ap2 while maintaining the attachment with ue2 and mme. From the user's point of view, nothing happened, and he/she can keep using their applications without interruption.

Even though the previous case shows a simple HO case, other scenarios involve more complex procedures. There are two special concerns in mobile management for heterogeneous wireless networks: the HO between two APs with different radio access technologies (RATs), the HO between two APs that belong to different operators.

As pointed out by Tayyab et al. [30], when a handover occurs between access points with the same radio access technology (RAT), the process is known as a intra-RAT HO or horizontal HO. Similarly, when they have different RATs, the process is called a inter-RAT or IRAT HO or vertical HO. These handover processes can be found on modern cellular networks based on 3GPP standards, when the Ue moves from 5G to 4G, 2G to 3G, among others. The same behavior can be seen on wireless networks based on IEEE standards, when a Ue moves from a Wifi network to a WiMax network. However, there are more complex IRAT HO cases. They are the ones that specify a HO when a Ue moves from an AP with a RAT specified by one standard to another AP with a RAT specified by another standard. The 3GPP recommendation TS 23.402 [31] is an example of a standard procedure description that handles handovers between different RATs that are specified by different standard bodies. In the same sense, also as described in [30], different operators can provide many types of systems and technologies to handle a network attachment. An intra-operator HO happens when the access points, regardless of their RATs, are operated by the same organizational entity. In contrast, when it happens between access points of different operators, it is called an inter-operator HO. The roaming procedure is an example of an inter-operator HO, as it allows the user to attach to a different network outside the range of his/her home network.

2.4. Conceptual data modeling using OntoUML

OntoUML was initially conceived as a fragment of the UML 2.0 based on a foundational ontology – the Unified Foundational Ontology (UFO) [27]. The idea was to design a language for structural conceptual modeling having the same ontological distinctions presented in UFO's Endurant fragment. Also, it has the same formal syntactic constraints that grammatically bound its set of valid models. Due to its continuous development, the current OntoUML version has absorbed some concepts from UFO's Perdurant fragment while maintaining its consistency regarding its foundational ontology isomorphism and constraints. In this sense, OntoUML is a modeling language with formal and real-world semantics explicitly defined.

OntoUML has been adopted by many research, industrial, and government institutions worldwide over the years. These different discourse universes have provided recurrent modeling patterns that helped the developers review and extend the language. As a consequence of this effort, a body of language patterns and anti-patterns [32] was created. Also, since the OntoUML language is a UML profile, it enables its use in various existing UML tools. Currently, it can be used as a plugin[1] in Visual Paradigm, allowing UML class modeling stereotyped with UFO's meta-classes.

This foundational ontology is usually presented in three main fragments: UFO-A, the ontology of Endurants; UFO-B, the ontology of Perdurants; and UFO-C, the ontology of Intentional and Social Entities. Considering the scope of this work, we focus on briefly describing the concepts of UFO-A and UFO-B.

2.4.1. Theory of Endurants

Although many conceptual modeling languages have artifacts that aim to model types whose instances are object-like entities, also known as Endurants, ontology-driven languages, such as OntoUML, enhance the distinction between types. Unlike traditional conceptual modeling languages, such as ER or UML, ontology-driven languages provide a better understanding of the nature of object-like entities. The meta-categories described by UFO's Theory of Endurants (also known as UFO-A) have among their foundations two outstanding principles: Existential Dependency and Identity.

Fig. 2(a) shows the taxonomy based on the Principle of Existential Dependency. As described in Fonseca et al. [33], this taxonomy presents two types of Endurants: **Substantials** and **Moments**. While Substantials are existentially independent objects, Moments are specific aspects of individuals, dependent on them to exist. Hence, there is a special relation between Substantials and Moments called **inherence**. For instance, while an Apple is a Substantial, its color and weight are Moments. In other words, the Apple's color and weight inhere the Apple.

Moments are specialized into two types: **Intrinsic** and **Extrinsic** Moments. While Intrinsic Moments are aspects that depend only on the individual that bears them to exist, Extrinsic Moments on another individual to subsist.

Intrinsic Moments are also specialized in **Quality** and **Intrinsic Modes**. According to [35], "Modes are intrinsic moments that are not directly related to quality structures", which means it cannot be expressed in terms of a single scale. Differently, Qualities are aspects of an individual mapping into a specific quality space. For instance, weight and color are Qualities since they are mapped into a quality space, such as a non-negative decimal scale or an RGB scale, respectively. On the other hand, a headache or an ability to speak a foreign language are Intrinsic Modes as they cannot be expressed in terms of a measurement unit. In addition, other Moments can describe them, such intensity in the case of a headache. In this sense, there is a special inherence relation between Substantials and Intrinsic Moments and it is called **characterization**.

Like Intrinsic Moments, there are two types of Extrinsic Moments: **Externally Dependent Modes (EDM)** and **Relators**. The former classifies aspects inherent to one individual but dependent on another to be perceived, while the latter aggregates aspects that are the mereological sum of EDMs. To illustrate such concepts, let us consider two instances of a Person named John and Mary. Whenever John is in love with Mary, this aspect of John inherently depends on him, but it also needs Mary to exist. In this case, the aspect of John being in love with Mary is as an EDM. However, this is not enough to say that John has a girlfriend; it could be a platonic love. Therefore, we have a one-sided relationship. Only when Mary is also in love with John (another EDM) can we state that John dates Mary in the same manner that Mary dates John. In this case, the relation `John dates Mary` holds since it has a Relator called `Date`, as a consequence of John being in love with Mary and Mary being in love with John. Then, the moment Relator mediates the involved Substantials, and it is the truthmaker of the relationship (relation stereotyped as ≪**mediation**≫ in Fig. 2(a)).

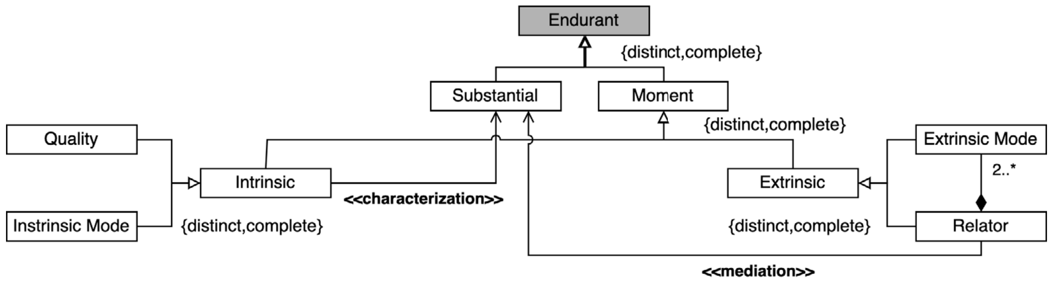
From another point of view, Endurants are specialized based on the principle of Identity, as portrayed in Fig. 2(b). It distinguishes types that specify a single principle of identity to judge if an instance is the same of another instance or not, and those that provide distinct identity principles. Moreover, it states that *while changes can undergo over an individual, hisher identity remains the same*[33]. So, **Sortals** are types of Endurants that holds a single identity principle while **Non-Sortal** types do not.

Sortals can be **Rigid** and **Anti-Rigid**. Instances of the Rigid type cannot cease to be an instance of it without ceasing to exist, while instances of Anti-Rigid types can subsist while moving in and out of their extension. Sortal Rigid types are then classified as **Kinds** and **Subkinds**. Although both carry the principle of Identity, a Kind provides it uniquely, while Subkinds carry the same principle of Identity that a Kind provides. On the other hand, Sortal Anti-Rigid types are further classified as **Phases** and **Roles**. Phases are relationally independent types defined by contingent but intrinsic instantiation conditions. On the other hand, Roles are relationally dependent types.

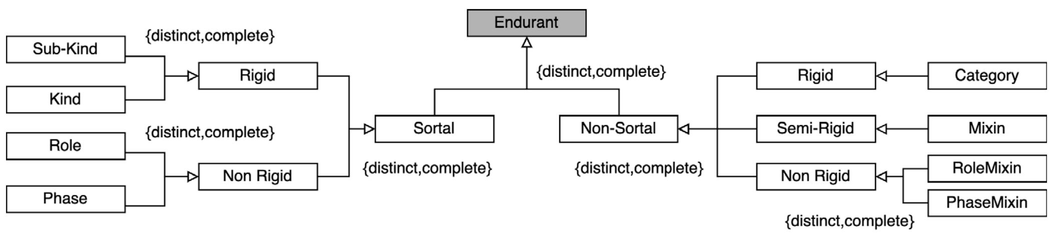
To clarify the above definitions, let us assume Person is a Kind, and that an instance of Person can be, biologically, a Man or a Woman. Thus Man and Woman may be Subkinds of Person. Also, Child and Adult are Phases that an instance of Person can assume depending only on their intrinsic properties such as age. On the other hand, an instance of Person can be a Student or an Employee, Roles that instances of Person can assume depending not only on intrinsic properties but also on their relationship with instances of another entity, such as a school or a company.

Unlike Sortals, **Non-Sortals** ultimately classify entities of different Kinds but have common properties. For instance, a Work of Art, as an instance of a Non-Sortal, can be a painting, a piece of music, or a statue, instances of different Kinds. In the same way that Sortals, Non-Sortals are distinguished by their rigidity. Hence, Non-Sortals are classified as **Rigid**, **Anti-Rigid**, and **Semi-Rigid**. A **Category** is a Rigid Non-Sortal aggregating essential properties common to different rigid sortals. A **PhaseMixin** categorizes an Anti-Rigid relationally independent non-sortals, aggregating properties common to different Phases. Mirroring the PhaseMixin, a **RoleMixin** is also an Anti-Rigid Non-Sortal, but has a relational dependency, like the Role type. The **MixIn** type is Semi-Rigid, representing properties shared by different Kinds that are essential to some but are accidental to others.

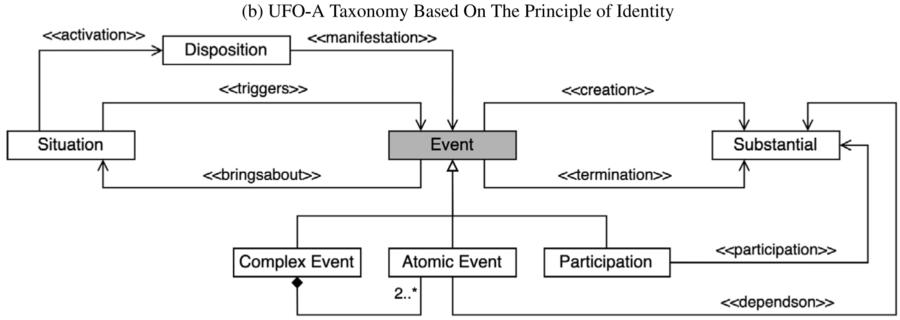
[1] Available at https://github.com/OntoUML/ontouml-vp-plugin



(a) UFO-A Taxonomy Based On The Principle of Existential Dependency



(b) UFO-A Taxonomy Based On The Principle of Identity



(c) Fragment of the UFO-B Taxonomy

Fig. 2. An Extract of The Unified Foundational Ontology (UFO), focused on the A and B fragments, inspired by [33,34].

2.4.2. Theory of Perdurants

As described in the previous section, UFO distinguishes between **Endurants** and **Perdurants** (or **Events**). While Endurants' remain fully present over time, even if their essential or contingent properties may change simultaneously, Perdurants' may be partially present in time, i.e., some of its parts are not necessarily present at a certain instant.[2] Fig. 2(c) presents the main Perdurant concepts along with main relationships between them as well as with the Endurants concepts.

The theory of Perdurants or the UFO-B fragment conceived by Guizzardi et al. [34] orbits around three main concepts: **Dispositions**, **Events**, and **Situations**. Situation is a particular configuration of a portion of reality. Dispositions are particular types of Moments that are only manifested in particular Situations, if manifested at all. Hence, Situations may **activate** Dispositions and their **manifestations** are Events themselves. Also, when an Event occurs, it brings about a new Situation. In other words, *events change reality by changing the state of affairs from one situation to another [34]* .

Two possible relations exist between Events and Situations. One is when a Situation **triggers** an Event at a determined time-point (Event starting point). In this case, an Event occurs because a Situation just began to exist. Alternatively, an Event **brings about** a Situation whenever it starts to exist because an Event has just occurred. In this case, a Situation becomes a fact at a determined time-point (Event ending point).

Events share some underlying characteristics with Endurants, although they cannot be confused with them since they have different grounding natures regarding their identities through time. Like Endurants, Perdurants have a part-whole or mereological structure in an ontological sense. Hence, Events may be composed of other Events. Using the classical example presented by Guizzardi in [34], we can have an Event **e** described as the murder of Caesar. However, this Event can also be seen as a composition of two distinct and sequential events: **e1** – the attack on Caesar and **e2** – Caesar's Death. So, Events can be either **Atomic** or **Complex**, depending on their mereological structure. While Complex Events are aggregations of at least two disjoint Events, Atomic Events have no other events as their parts.

Like Moments, Events are also existential-dependent entities. In particular, Atomic Events are said to **depend on** an object directly (stereotyped as ≪**dependson**≫ in Fig. 2(c)). On the other hand, Complex Events can be decomposed, separating each part regarding its dependent object or participant. Also, a portion of an Event exclusively dependent on a single object is called **Participation**. Moreover, Endurant's creation and destruction are special kinds of participation. When associations decorated with ≪**creation**≫ and ≪**termination**≫ stereotypes bind Endurants and Events, it means that the creation or the destruction of such Endurant happened on that Event.

Finally, in the same manner that objects define the spatial properties of Events they depend on, Events' temporal properties define the temporal properties of objects. These temporal properties are like Qualities described in UFO-A. Hence, they can be mapped in a suitable quality structure or property value space,

[2] https://plato.stanford.edu/entries/events/#EveVsObj

Table 1
A non-exhaustive list of high-level competence questions for handover initiation.

Question	HO Trigger
Is the received signal power below the configured threshold?	degraded received signal power
Is the received signal quality below the configured signal-to-noise ratio threshold?	degraded received signal quality
Is the battery power below the configured threshold?	battery power lifetime
Does the Ue's RAT provide the inherent security level for the applications being used?	security level evaluation
Does the current Ue's RAT provide the quality of experience (QoE) the user expects?	degraded QoE

allowing several alternative quality spaces to be associated with them. For instance, it allows modeling time in many ways: continuous or non-continuous intervals, with beginning and ending points, or instants with a single time point.

3. Evaluation of ontologies for mobility management

Any system development should start by gathering requirements. An ontology-based system development relies on natural language questions, also known as **competence questions (CQ)**, to gather its functional requirements that later are transformed into concepts and relationships. It is an interactive phase of system development where questions, possible dependencies, concepts, and relationships are refined over time.

In systems that support the HO process, we may divide the competence questions into two groups to clarify their purposes. While one aims to evaluate whether a HO process should initiate, the other aims to evaluate the success of its execution whenever it occurs. Hence, each group includes different types of competence questions with different degrees of complexity.

Table 1 shows a non-exhaustive list of CQs devoted to the HO initiation phase. Each one is related to a different HO trigger described in Section 2.1 (degraded received power, degraded signal-to-noise ratio, battery lifetime, and security level, among others). Being used alone or combined with others, these CQs may be presented as high-level questions, collapsing many concepts and relationships. To clarify them, a top-down approach can be used, as presented in Table 2, using the degraded received power trigger as an example. To improve communication between developers, each CQ is numbered, as well as its dependencies to other CQs (CQD).

Differently from the first group, each CQs devoted to the HO execution phase evaluates its success, regardless of what has triggered it. Hence, they need to check if an HO has occurred, and if positive, they must check if the associations between communication nodes remain intact. Table 3 shows an example of possible questions to evaluate the HO execution.

Thus, an ontology that supports mobility management must adequately describe the fundamental entities that appear in the CQs: the communication nodes and their possible associations. Section 3.1 presents the research works that focus on network ontologies and how they describe such fundamental entities, while Section 3.2 discusses significant gaps in these ontologies that prevent their direct use in a decision support system responsible for mobility management.

3.1. State of the art

Evaluating existing ontologies is an essential phase of an ontology-building process [20]. It means that concepts and modeling decisions that have already been studied and discussed can be reused to speed up the development of a new ontology. In this sense, we extensively researched network-related ontologies, whether proposed by the academic community or by the telecommunication standard bodies. Our research also shows how academic research and standard bodies' recommendations inspired each other.

Table 2
Clarification of competence questions for HO initiated by received signal power degradation.

CQ	Question	CQD
01	Is the received signal power below the configured threshold?	
02	What is the received signal threshold for handover initiation?	
03	What is the current received signal transmitted by the serving AP?	
04	What are the current received signals transmitted by the neighbor APs?	
05	Are there any received signals transmitted by the neighbor APs greater than the received signal transmitted by the serving AP?	03, 04
06	Which AP does deliver the strongest received signal among the ones that are greater than the current received signal transmitted by the serving AP?	05
07	Which AP has the strongest **predicted** received signal that is greater than the current received signal transmitted by the serving AP and was not scanned by the Ue?	

Table 3
Competence questions for HO execution evaluation.

CQ	Question	CQD
01	Has a handover occurred?	
02	Did the association between the Ue and the mobility management entity remain intact?	01
03	Did the association between Ues remain intact?	01

One of the most influential research efforts on ontologies for network description is the Network Description Language (NDL) [21–23]. Conducted by many researchers since its beginning in 2006, it was initially inspired by standard bodies' recommendations such as the ITU-T G.805 Generic Functional Architecture of Transport Networks [40] and the IETF Generalized Multiprotocol Label Switching (GMPLS) [41]. Later, after improvements over the years, it became a standard adopted by the Open Grid Forum and was renamed as Network Markup Language (NML)[3]. According to them, the schema can describe not only a high-level domain network topology but also technical details and all technological capabilities of a network.

The NDL research inspired other efforts to provide a proper network ontology. In [42], researchers evaluated the ITU-T G.805 recommendation using the UFO concepts and OntoUML constructs. Although their aim was not to produce a network ontology, it was fundamental to show the ambiguities of the recommendation's terms and definitions and how useful it is to describe them using a foundational ontology. On the other hand, the ToCo ontology [25] is an effort to extend the NDL schema, targeted to describe transport networks, stating its capability to describe any network infrastructure. Similarly, other works such as FuzzOnto [36] and OpenMobileNetwork [24] also propose alternatives to it.

[3] Available at http://www.ogf.org/documents/GFD.206.pdf

Table 4
Comparison between available network ontologies and the main concepts for mobility management in wireless networks.

Network ontology	Purpose	Concepts					
		Link	Connection	Interface	Neighbor	Ue	AP
NDL [21–23]	Infrastructure Description	x		x			
ToCo [25]	Infrastructure Description	x		x	x	x	x
FuzzOnto [36]	Infrastructure Description					x	x
OpenMobileNW [24]	Infrastructure Description				x	x	x
OneM2M [37]	M2M Interoperability		x			x	
SAREF [26]	IoT Interoperability		x			x	
PingER [38]	Performance Measurement	x		x			
PingER-MOPL [39]	Performance Measurement	x		x			
Our proposal	Mobility Management	x	x	x	x	x	x

In the same direction, the standard bodies have proposed their ontologies to represent network functions. The OneM2M ontology [37] was proposed by the International Telecommunication Union (ITU) and detailed by the European Telecommunications Standards Institute (ETSI) [43], presenting a base ontology to describe machine-to-machine communication. Along with them, ETSI presented the SAREF core ontology [26] in order to enable interoperability between solutions from different providers and among various activity sectors in the Internet of Things (IoT). Hence, the primary concern of these standard bodies seems to be the management of IoT operations rather than a general ontology to describe communication networks.

Finally, to the best of the authors' knowledge, only a few proposed ontologies handle network performance measurement. The MOMENT ontology project [44] is a core ontology that handles the domain of network performance measurement. It inspired works such as the PingER [38], developed to serve as a reference vocabulary and structure for round trip time (RTT) tests. Nunes et al. [39] proposed an improvement of PingER ontology using the Measurement Open Pattern Language [45], an ontology pattern language based on UFO's theory .

3.2. Gaps on network ontologies for mobility management

Evaluating all the previous recommendations and ontologies proposed by the academic community and the standard bodies (Section 3.1), none seems to be adequate to deal with mobility management. To the best of the authors' knowledge, no network ontology properly represents one of the main mobility notion, the relationships between communication nodes, especially between the `Ue` and the mobile network's `AP`s. Also, an essential concept for mobile management – the `AP's` neighborhood – briefly appears in only two ontologies and needs to be better explored.

Therefore, there are issues that need to be addressed to allow the mobility management in wireless networks, such as (i) the description of the neighborhood concept, since the reasoning entity needs to know what are the available `AP`s that can maintain the relationship between the `Ue` and the mobile network; (ii) the proper use of terms such as `Link` and `Connection` to represent the relationship between communication nodes ; (iii) the existential dependency between `Link` and `Connection`. Table 4 presents the researched ontologies and their coverage of these concepts, which are discussed as follows.

The concept of neighborhood emerges from the handover process, showing the need to represent the roles an `AP` can play as seen by the `Ue`: server or neighbor. Although crucial for mobile management, this concept barely appears in the researched network ontologies. The NDL [21–23] ontology deals with fixed networks, an communication infrastructure that does not need such concept. The FuzzOnto ontology [36] states that it was created to support heterogeneous mobile networks, but the neighborhood concept does not appear. It only appears in ToCo [25] and OpenMobileNetwork [24] ontologies. However, while the former has properties to bind `Ue's` and `AP`s (`hasAssociatedStations` and `ApsInRange`), the latter just describe the `AP`'s neighborhood list, avoiding the description of the `Ue`'s association.

Unlike neighborhood, the concept of `Link` and `Connection` appears abundantly in the researched ontologies, although not simultaneously in the same ontology. Therefore, sources such as dictionaries and the vocabulary recommendations of the standard bodies recommendations were reviewed to understand these concepts correctly. However, while the former presents them as synonyms,[4,5] the latter presents them as different things.

`Link` is defined by the International Electrotechnical Commission (IEC) recommendation 60050.701 [46] and by the ITU-R V.662-3 [28] recommendation as a means of telecommunication with specified characteristics between two points. In contrast, `Connection` is defined in the same recommendations as a *temporary association of transmission channels or telecommunication circuits, switching and other functional units set up to provide for the transfer of information between two or more points in a telecommunication network*. Besides being difficult to understand, they do not allow us to infer if `Link` and `Connection` depend on each other or which entities they bind. The 3GPP recommendation TR 21.905 [9] defines a radio link as a logical association between a single `Ue` and a single UTRAN `AP`. Moreover, the recommendation categorizes links as downlink and uplink, providing direction to the information exchange between the `Ue` and the UTRAN `AP`. Finally, in the same recommendation, a `Connection` is defined as a communication channel between two or more endpoints.

These definitions commonly show that `Link` and `Connection` are logical relations between points (entities) representing information exchange. On the other hand, while `Link` is defined as a relationship built between two entities, `Connection` is defined as a relationship that is created between *two or more* entities. Although we can differentiate these logical relationships using this criterion, other questions appear since it is unclear whether they refer to the same points or if these relationships can exist without each other.

Finally, it is worth to say that the researched ontologies are hard to reuse as they do not simultaneously deal with `Link` and `Connection`. Moreover, while some describe the relationship between communication nodes as `Links`, others use the term `Connection`. Even reusing more than one ontology to describe `Links` and `Connections`, it is not clear how to describe their dependency. In this sense, the following section aims to clarify the use of these concepts in order to construct an ontology or mobile network management.

4. The relationship nature between communication nodes

The vocabulary recommendations [28,46,47] converge to define communication as the process of transferring information

4 https://www.merriam-webster.com/thesaurus/link
5 https://www.collinsdictionary.com/dictionary/english-thesaurus/link

according to agreed conventions. However, this definition does not contribute to a good domain characterization of how information is transferred between communication entities or what conventions must be followed before communication occurs. Inspired by previous analysis [42,48], we use OntoUML constructs as our conceptual modeling tool to improve our understanding of which entities, relationships, and processes are involved in a communication scenario.

4.1. Interfaces roles

Recommendations from several standard bodies suggest how communication entities transfer information between them. As defined in recommendations ITU-R V.662-3 and IEC 60050.701 [28,46], a `Signal` *is a physical phenomenon one or more of whose characteristics may vary to represent information*. On the other hand, the ITU-T recommendation Z.100 [49] states that *the primary means of communication are by signals that are output by the sending agent and input by the receiving agent*. Finally, the TIA Glossary of Telecommunication Terms [47] provides several definitions for `Signal`, one of them as *a detectable transmitted energy that can be used to carry `Information`*. Hence, we may say that communication between two entities occurs when a `Signal`, which may represent information, is generated and transmitted by an entity called `Sender` and is detected by another entity called `Receiver`.

Considering the mobile wireless network domain, we hereafter call the communication entity as `Interface`, an electronic device able to transmit and/or receive electromagnetic waves (`EMWave`) which play the role of `Signals`. Also, there are several electronic appliances that can be composed of more than one `Interface`. We refer to them as `Communication Devices`. As our first modeling approach, we could model `Sender` and `Receiver` as subkinds of `Interface`, a kind by itself, which is part of a `CommunicationDevice`, another kind.

However, the description in Section 2.1 suggests that `Sender` and `Receiver` may have a non-rigid behavior rather than a rigid one since `Interfaces` can transmit and receive at the same time. In other words, an `Interface` can be either a `Sender` or a `Receiver`, sometimes simultaneously. So, rather than being subkinds of an `Interface`, `Sender` and `Receiver` are roles it can play while sending or receiving a `Signal`. This modeling approach is shown at the top of Fig. 3.

Another insight that comes from the same section is that there is a need for an agreement to properly allow different types of communication between `Interfaces`. The TIA Glossary of Telecommunication Terms [47] defines `Protocol` as the formal set of conventions governing the format and control of interaction among communicating functional units. In other words, the `Protocol` establishes the process and the characteristics an `Interface` may have. Thus, we consider `Protocol` as a mode that characterizes an `Interface`.

Finally, `Interfaces` in a mobile communication system also have functions that needs to be fulfilled, as described in Section 2.2. So, we account such functions as roles the `Interface` can play as a consequence of the advances in modern communications. This modeling approach is shown at the bottom of Fig. 3.

4.2. The basic bonding between interfaces

Let us consider a simple wireless communication scenario where there are only two `Interfaces`: one playing only the `Sender` role and another playing only the `Receiver` role. Fig. 4 shows the beginning of the bonding process between these two entities.

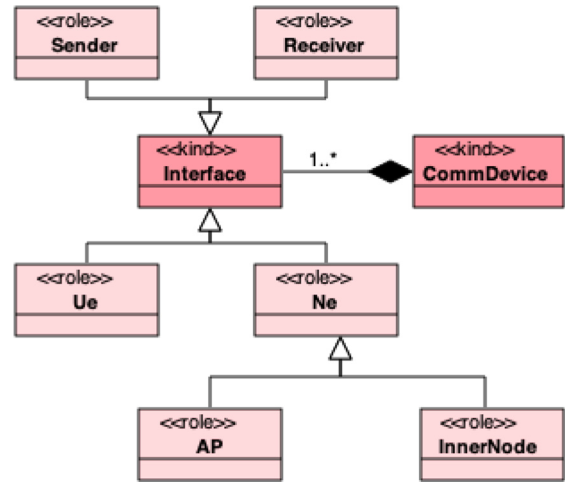


Fig. 3. The Roles of an `Interface`.

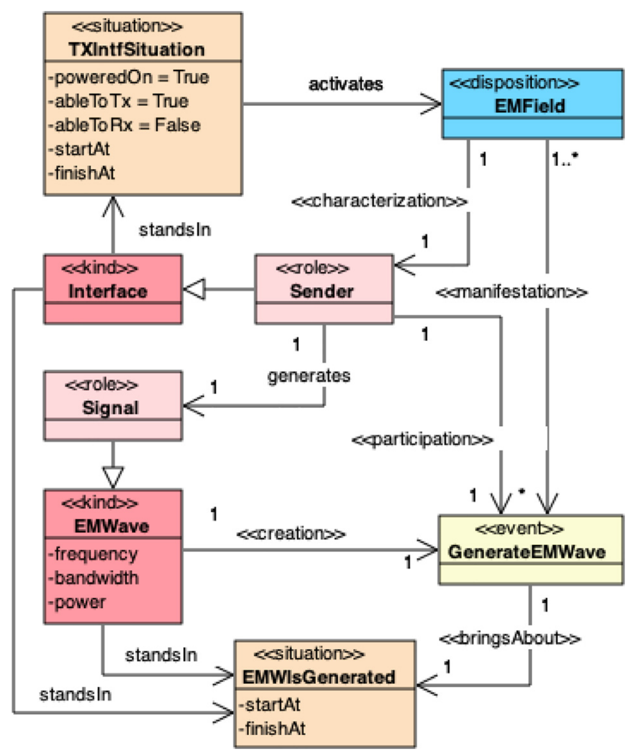


Fig. 4. Bonding Creation Process – Phase 01 – `Signal Generation`.

It starts right after the event of powering up the `Interface`, which will play the role of a `Sender`. It brings about a new `Interface` situation (`TxIntfSituation`). Once established, this situation may activate the `Interface`'s disposition to create oscillating electromagnetic fields (`EMField`) while playing the role of a `Sender`. Whenever the disposition is activated, these oscillations produce electromagnetic waves (`EMWave`), which are created in the `GenerateEMW` event as the manifestation of the `EMField` disposition. This new event brings about a new situation called `EMWIsGenerated` where `EMWave` and the `Interface` stands in. The `EMWave` is characterized by some electromagnetic properties such as frequency, bandwidth, and power, and plays the role of `Signal` as described in Section 4.1.

Moving forward in our scenario, the fact that an `EMWave` is generated (as a `Signal`) is not enough for it to be detected by an

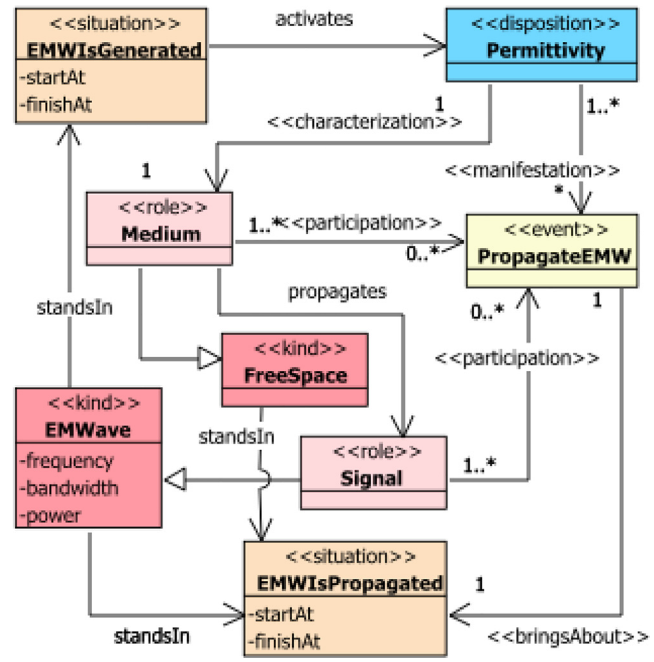


Fig. 5. Bonding Creation Process – Phase 02 – Signal Propagation.

Interface playing the role of a Receiver. It first needs to propagate through or over a Medium until it reaches its detector. A Medium is defined as *a natural medium or manufactured structure through or over which a Signal is conveyed*[46]. Many entities can play the role of a Medium: coaxial or fiber optic cables, the air, among others. In wireless communications, the air is also called FreeSpace, which plays the role of a Medium.

As described in Fig. 5, the EMWIsGenerated situation may activate the capacity of the FreeSpace to propagate the EMWave, also known as the free space magnetic permittivity (Permittivity). As soon as it is activated, this disposition is manifested by an event (PropagateEMW), which brings about the EMWIsPropagated situation, where the EMWave and Free Space stand in. Thereby, the FreeSpace, playing the role of a Medium propagates the EMWave while playing the role of a Signal.

Fig. 6 presents the final phase of bonding the process. Like the first phase, this one starts right after the Interface, playing only the role of a Receiver, is powered up, bringing about a new situation (RxInterfaceSituation). Once established, the new situation may activate the Receiver's disposition (Sensitivity) capable to detect the EMWave playing the role of Signal. However, this RxInterfaceSituation is not enough to activate the Receiver's disposition. The disposition may be activated only when the EMWIsPropagated situation is also present in a given space–time frame. And when activated, that disposition is manifested by the DetectSignal event, where the Signal, Medium, and the Receiver have participation. Also, it brings about a new situation called EMWIsDetected. At this point, an Interface playing the role of a Receiver detects a Signal, a role played by the EMWave.

The last interaction reveals the expected result of our description: the relation *detectsSignal* binding a Receiver to a Signal generated by a Sender, as portrayed in Fig. 6. However, the analysis of this material relation raises a question: What is the nature of the truthmaker that supports it?

To detect a EMWave playing the role of Signal in our scenario, it is necessary that a minimal subset of EM properties of the

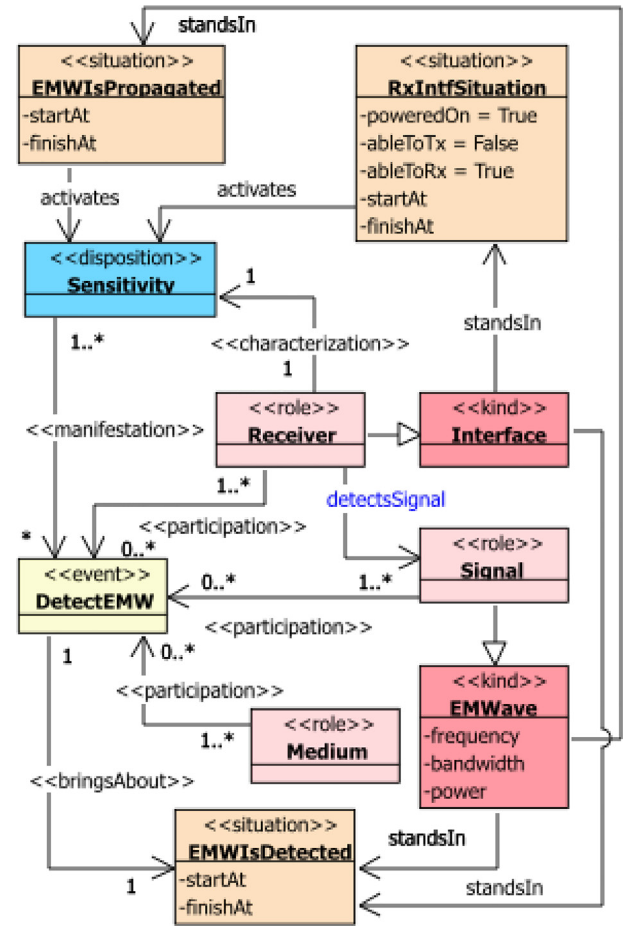


Fig. 6. Bonding Creation Process – Phase 03 – Signal Detection.

Interface playing the role of Receiver matches the EM properties of the EMWave. Thus, the Receiver is committed towards the Signal. However, this is not reciprocal. To illustrate it, let us consider the selection of a broadcast radio station. Selecting a radio station means that we are selecting an EM property of the Interface (e.g. frequency or channel) playing the role of Receiver that allows the reception of the EMWave generated by the radio station playing the role of Sender. The Signal coming from the radio station does not commit to adjusting itself to allow its reception. In other words, there are commitments of the Receiver towards the Signal but not the other way around.

This relation asymmetry is also found when we consider that a Signal has to travel through the Medium to reach the Receiver. In our scenario, the EM properties of both EMWave (the Signal role) and Interface (the Receiver role) have to match, at least, a subset of the FreeSpace's EM properties (the Medium role). However, FreeSpace's EM properties do not change to allow the EMWave to propagate, and neither do they change to match the EM properties of the Interface.

Therefore, a new relationship called DetectBond binds Signal, Medium and Receiver and supports the relation *detectsSignal* in Figs. 6 and 7. It is a composition of the asymmetrical commitments between Receiver-Signal, Signal-Medium, and Receiver-Medium, all of them representing external dependent modes (EDMs). Considering such asymmetries, we propose that the DetectBond is also an EDM.

Finally, to accommodate a common representation used in the domain, we also propose a derived relation (*detects*) between Receiver and Sender supported by the same truthmaker.

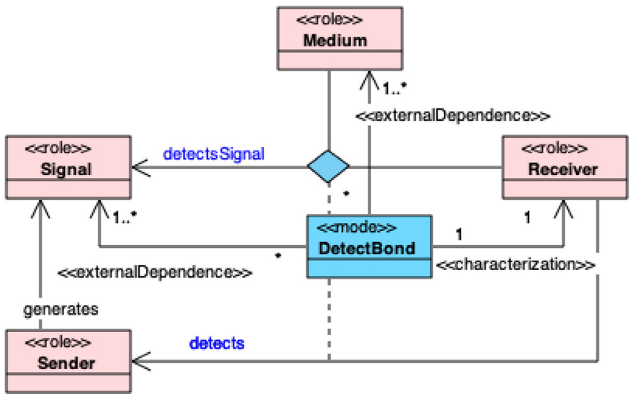


Fig. 7. Bonding Creation Between Signal, Medium and Receiver Entities.

4.3. The decoded bond

The communication scenario becomes more realistic than the previous one as soon as more Signals generated by several Senders and propagated by a Medium reach the Receiver and match its properties. In this case, some will bring valuable Information, while others will not, interfering with the proper understanding of the first group.

The definition of interference given by [28] states that it is *a disturbance of the reception of a wanted signal caused by interfering signals, noise or electromagnetic disturbance*. It also defines noise as *any variable physical phenomenon apparently not conveying information and which may be superimposed on, or combined with, a wanted signal*. Both definitions mention the term *wanted signal*. Hence, we infer that a WantedSignal is a Signal conveying information that is not only detected but also understood or decoded by the Receiver. Moreover, since the Signal is decoded, we can infer that Receiver and Sender share the same communication technology, another commitment between these two entities. Additionally, this new Signal's role is extended to its generator, the Sender. Therefore, as we have a WantedSignal, we also have a WantedSender. Also, a new relation (*detectsSignal*) is created between the Receiver and the WantedSignal, having a new truthmaker – a DecodedBond. We also propose a derived relation (*decodes*) between Receiver and WantedSender supported by the same truthmaker. Fig. 8(a) shows these new entities.

In contrast with WantedSignals, interference and noise are types of UnwantedSignals, as they are detected but not decoded by the Receiver. They also extend this condition to their bearers, becoming UnwantedSenders, a role many Senders can play. First, we can consider natural and artificial Senders that share the same electromagnetic properties with the Receiver, like the Sun and power lines. However, they do not provide any valuable information. Another scenario of an UnwantedSignal is when a Sender is designed to exchange information and shares the same electromagnetic properties but not the same communication technology. In this case, the Receiver detects the Signal but cannot decode it, although it may carry Information. Finally, there is a scenario where the Signal carries Information, and the Receiver and the Sender share the same electromagnetic properties and communication technology, but still cannot decode it. In this case, the Medium deteriorates the Signal so that the Receiver cannot correctly decode it. In any of these cases, there is no new relationship between Sender and Receiver besides the one created by the detection event, as shown by Fig. 8(a).

In many communication systems, the Receiver has to deal with only one WantedSender. However, there are other systems, like the mobile networks, that the Receiver has to deal with several WantedSenders simultaneously. Although only a subset may be chosen to transfer information, the other ones have to be monitored as they can be selected later. At the same time, the Receiver moves around a mobile coverage area, enabling the handover process described in Section 2.3. In this sense, a WantedSender can play two roles: as a SelectedSender, when it is selected as the one responsible for transferring information, or as a MonitoredSender, when it is only monitored by the Receiver, becoming a SelectedSender whenever necessary.[6] As a result, it creates new specialized relationships of the DecodedBond pictured in Fig. 8(b).

Now, a relator called SelectedBond supports the material relation between a SelectedSender and a Receiver. Moreover, another relator called MonitoredBond supports the material relation between a MonitoredSender and a Receiver. It is worth pointing out that the collection of all MonitoredSenders represents the neighborhood concept, as described in Section 2.3. For instance, the HO process in a 3GPP's mobile network can only be executed if a Ue reports all its neighbors (MonitoredSenders) to the network, allowing the selection of the most suitable AP to maintain seamless communication.

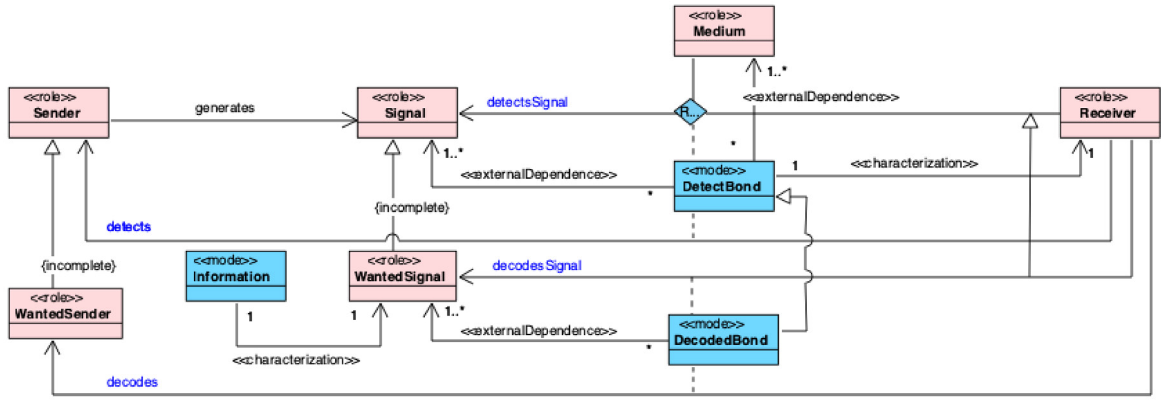
4.4. The HandShake bond

An agreement that needs to be fulfilled while Interfaces communicate with each other is whether the transferred information has guaranteed delivery. Again, The TIA Glossary of Telecommunication Terms [47] calls this agreement handshaking, *defining it as a sequence of events governed by hardware or software, requiring mutual agreement of the state of the operational modes prior to information exchange*. To allow the representation of such agreement in our model, we borrow the concepts of Source and Sink from ITU-T Recommendation G.805 [40]. In this recommendation, Source represents the Interface that starts the communication, while Sink represents the targeted Interface. Like Sender (and their roles, such as the SelectedSender) and Receiver, Source and Sink are roles that an Interface can play simultaneously.

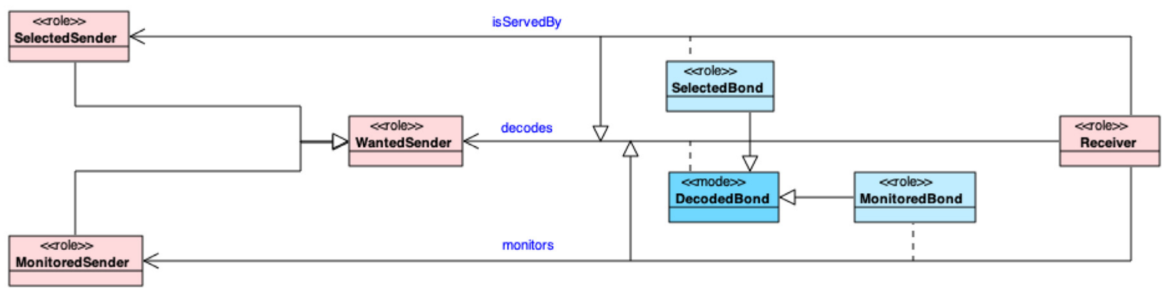
Fig. 9 shows the agreement that guarantees information delivery. First, a SelectedBond has to be created between the Interface playing the role of Source and SelectedSender, and the other one playing the role of Sink and Receiver. Then, as the counterpart of the agreement, another SelectedBond has to be created between the Interface playing the role of Sink and SelectedSender, and the other one playing the role of Source and Receiver. This process results in a new relationship, supported by a **relator** we call HandshakeBond. This new bond highlights two interesting concepts: first, if an agreement has to occur before transferring the information, it is necessary that SelectedBonds between Interfaces playing simultaneously the roles of SelectedSender and Receiver exist. Thus, a HandShakeBond depends on SelectedBonds.

Also, SelectedBonds and HandShakeBond bind different roles of the same entity – the Interface. While SelectedBonds represent relationships between Interfaces while playing the role of SelectedSenders and Receivers, HandShakeBonds represent the relationships between Interfaces while playing the role of Source and Sink. Fig. 9 presents the new relationship that bonds both Interfaces and the relationships between SelectedSender and Receiver that support it.

[6] In mobile networks based on 3GPP's recommendations, SelectedSender and MonitoredSender are known as **Server** and **Neighbor** respectively.



(a) Creation of the DecodedBond



(b) SelectedBond And MonitoredBond As Roles Of The DecodedBond

Fig. 8. Multiple Bonds Created Between Sender and Receiver Entities.

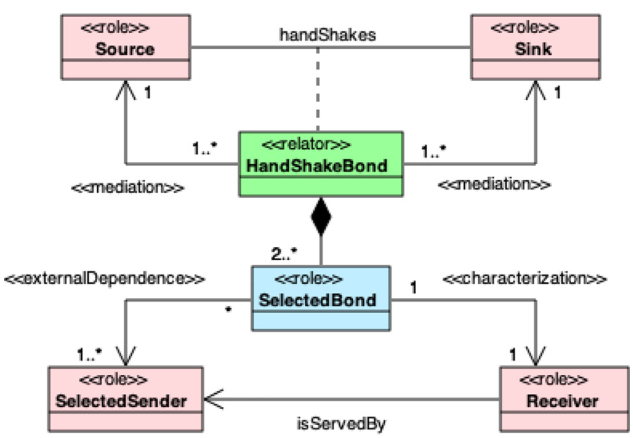


Fig. 9. Communication Agreement Between Interfaces.

4.5. Link and connection

As presented in Section 3.2, the definitions of Link and Connection are unclear, and some aspects are not well described: what entities do these relationships bind? Is there a dependency between them? Can a Connection exist without a Link? To answer these questions, we use the communication scenario described in Fig. 1 to elaborate a UML sequence diagram (Fig. 10) representing a simplified version of the mobile phone registration and connection process in a 4G mobile network [50]. While describing the process, we employ the conceptual models presented so far to support our analysis.

Let us assume a moment before t_1 in Fig. 1. All communication entities are on except for ue1. Also, according to the concepts described in Section 2.3, let us assume that these entities are actually Interfaces rather than Communication Devices. Hence, in Fig. 1, interfaces ap1 (ap1:Interface) and ap2 (ap2:Interface) are playing the role of APs (ap1:AP, ap2:AP), while interface ue1 (ue1:Interface) is playing the role of Ue (ue1:Ue). Since ap1 and ap2 are active, they transmit their Signals, playing the role of Senders (ap1: Sender and ap2:Sender), as shown at the top of the sequence diagram in Fig. 10.[7]

Once ue1 is active, it also starts playing the role of a Receiver (ue1:Receiver), detecting and decoding the Signals coming from ap1 and ap2 while playing the roles of Senders. As soon as ue1 decodes such Signals they start to play the roles of WantedSignals and, consequently, ap1 and ap2 become WantedSenders. The interactions of ue1:Receiver with ap1:WantedSender and with ap2:WantedSender create relationships supported by the truthmakers ap1_ue1_DBnd and ap2_ue1_DBnd as instances of DecodedBond in Fig. 10. Moreover, new roles are set since the decodification is successful. While ue1 begins to play the role of Sink (ue1:Sink) since it is the Information's destiny, ap1 and ap2 begin to play the role of Source (ap1:Source and ap2:Source, respectively).

Right after, ue1:Receiver starts the network and cell acquisition processes to select the appropriate access point, which allows its information exchange with other Interfaces playing the same role as an Ue, like ue2 (ue2:Interface) in Fig. 1. In our example, ue1 selects ap1 to be its access point to the mobile network after the cell acquisition process. However, just selecting an access point is not enough to allow information exchange. An agreement between these two entities has to be established first. According to the 3GPP recommendation TS 36.300 [50], this

[7] The par stereotype encloses actions that happen at the same time.

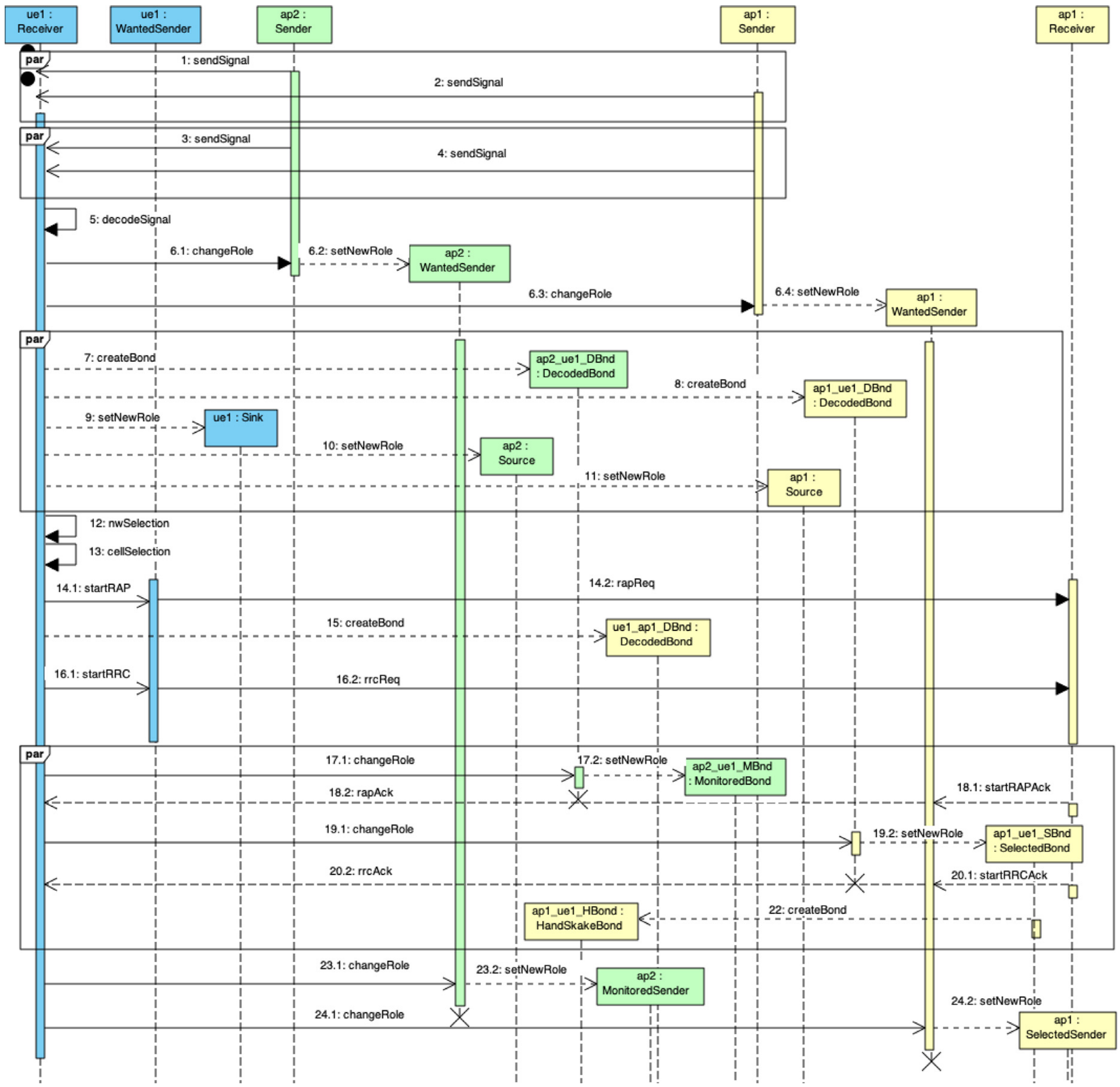


Fig. 10. The UML Sequence Diagram Representing The Interactions Between Entities In a Simplified 4G Registration and Connection Process.

agreement is accomplished only when the result of two processes initiated by ue1:Receiver, the Random Access Process (RAP) and the Radio Resource Control (RRC), are successful. If one of the processes fails, the HandShakeBond will not be created, even though instances of DecodedBonds continue to exist.

The bottom part of Fig. 10 shows the creation and termination of instances after successfully executing the RAP and RCC processes. First, right after the reception of RAP acknowledgment, another bond between ue1, now playing the role of WantedSender (ue1:WantedSender), and ap1, playing the role of Receiver (ap1:Receiver), is set. This bond is supported by the relator ue1_ap1_DBnd (ue1_ap1_DBnd: DecodedBond) and is the counterpart of the relator ap1_ue1_DBnd. Then, after the success of the RAP and RCC processes, some roles cease to exist, replaced by new ones. By the time ap1 is selected as the access point for ue1, the role ap1: WantedSender ceases to exist as soon it starts to play the role of SelectedSender (ap1:SelectedSender). Also, the relator ap1_ue1_DBnd ceases to exist as soon it starts to play the role of SelectedBond (ap1_ue1_SBnd:SelectedBond). On the other hand, as ap2 is not the selected access point, but it is correctly detected and decoded, the role ap2:WantedSender ceases to exist as soon it starts to play the role of MonitoredSender (ap2: MonitoredSender). Moreover, the relator ap2_ue1_DBnd ceases to exist as soon as it starts to play the role of MonitoredBond (ap2_ue1_MBnd: MonitoredBond). Finally, as the result of the successful RAP and RRC processes, a new bond between ue1:Sink and ap2:Source is created, supported by a new relator (ue1_ap1_HBnd: HandShakeBond).

The conceptual model applied in this simple example of registration and connection in a 4G mobile network clears out the relationships created between the communications entities and allows us to improve our understanding of what really Link and Connection are. Remembering the definition of Link in Section 3.2, vocabulary recommendations such as ITU V.662-3 and IEC 60050.701 define Link as a *means of telecommunication with specified characteristics between two points*. Hence, as it is a means of telecommunication between two points, the Signal, which carries Information that is transmitted by one point and received by the other point, needs not only to be detected but also decoded.

Looking at our model presented in Fig. 8(a), the Link entity does not correspond to the DecodedBond entity at first glance. The DecodedBond represents the bond between Interfaces playing the role of WantedSender and Receiver along with the FreeSpace playing the role ofMedium. On the other hand, although the Link definition also describes the bonding between two communication entities (Interfaces), it apparently ignores the third one (FreeSpace). Hence, Link and DecodedBond look as if they are not the same entity. However, a note in the same Link definition provided by ITU V.662-3 says that *the type of the transmission path or the capacity is normally indicated, e.g. radio link, coaxial link, broadband link*. It suggests that the recommendation is specializing Link by using entities that would play the role Medium (e.g. radio, coaxial) or Signal properties (e.g. broadband). Hence, we infer that the recommendation chose to use entities playing the role of Medium as a form of Link specialization rather than recognizing it entities necessary to its existence. To reuse the term and avoid bringing a new one to the domain, we assume that Link and DecodedBond represent the same Interface binding, but the former is a collapsed form of the latter.

Similar to the Link definition, the vocabulary recommendations are unclear when describing the Connection concept. They can be easily confused as they are *logical relationships that bind communication entities*. In this case, other definitions can help us understand the nature of the Connection concept and how it matches our conceptual model.

Some of them can be found in ITU-T Recommendation E.417 [51]. This recommendation defines a *connectionless* information transfer as *a type of information transfer between two entities that do not need any prior path or connection being established.* On the other hand, a *connection-oriented* information transfer refers to the same transfer of information between two entities, but a path or connection needs to be first established. Hence, for some information transfer services, a new relationship between the related communication entities must occur before any data transfer. In this sense, the Connection concept suggested in this recommendation matches the HandShakeBond concept presented in our model. Furthermore, like the HandShakeBond that depends on SelectedBonds (a specialization of DecodedBonds) in our conceptual model, a Connection depends on Links to occur whenever a communication Protocol demands it.

Assuming that Link is a collapsed form of the DecodedBond and that Connection matches our HandShakeBond concept, we infer that Link and Connection bind different roles of the same entity – the Interface. While Link binds the roles of WantedSender and Receiver, the Connection binds the roles of Source and Sink.

5. Discussion

The main goal of developing a network ontology for mobile management support is to provide the means for applying semantic reasoning to select the proper association between the Ues and APs. The handover process described in Section 2.3 is one of the mobile management processes that depend on such selection to maintain the Ue exchanging data with other communication nodes.

The central gap addressed by this work is the adequate representation of Link and Connection concepts and their dependencies. Although many ontologies describe these concepts, to the best of the authors' knowledge, none describe them simultaneously or how they relate to each other. To highlight the improvement that our conceptual model brings (hereafter called **hint** ontology), we compare it against ToCo ontology. After analyzing all the researched network ontologies, only ToCo can represent most of the relationships between communication entities in a HO scenario, a capacity already demonstrated in [52]. We compare both ontologies using the scenario described in Section 2.3, trying to answer the competence questions (CQ) presented in Tables 2 and 3.

Tables 5 and 6 show the scenario described in Section 2.3 at timestamps t_2 and t_3, respectively, using the Turtle format of the Resource Description Framework (RDF) modeling approach. On the left side, we used the concepts from ToCo to describe the scenario, while on the right side, we used the concepts presented in this work. Looking at both Tables, competence questions CQ01 to CQ06 from Table 2 can be answered by both ontologies. A SPARQL query can filter the toco:hasTxPower property on the left side and get the strongest receiver power at each timestamp. Also, a query can filter the toco: has AssociatedStations property between two consecutive timestamps, such as t_2 and t_3, and check if the objects are different. The same approach can be made on the right side, using the hint:power property to get the strongest receiver power and the :linkID property to evaluate if their values are different.

However, competence questions described in Table 3 can only be answered on the right side of Tables 5 and 6, using our conceptual model. Remembering the description of the HO process in Section 2.3, a successful exchange between Links must keep Connections, whenever established, unaltered. We can use the same approach used to evaluate if Link has changed by adding an extra evaluation of :connID properties and comparing its values. The necessary concepts for that are highlighted in red in both tables. The reason why ToCo ontology cannot do the same evaluation is simple: it does not have the Connection concept. On the left side, associations changes between Ue and APs can happen without HO success awareness.

The Connection concept not only allows us to evaluate the success of the HO process but also allows us to evaluate other issues. Since the Link between Ue and AP allows multiple Connections, we can evaluate them in case of interruption or failure. For instance, considering the same scenario of the previous example, a failure in the Connection between Ue and the mme represent a HO failure. However, if there was a failure in the Connection between ue1 and ue2 and the Connection between ue1 and mme remains the same, we can evaluate that the issue was not necessarily motivated by the HO process.

The proper representation of concepts such as Link and Connection is not the only improvement brought by our conceptual model. If, on the one hand, we reused many concepts established by available network ontologies, on the other hand, some new concepts appeared during our research, not being mentioned by other ontologies nor by the standard bodies' vocabulary recommendations. That is the case with the Medium concept. For instance, in the ITU-R V.662-3 recommendation [28], the Link definition states that *the type of the transmission path or the capacity is usually indicated, e.g., radio link, coaxial link, broadband link*. In this case, the recommendation is assigning properties belonging to the Signal itself (broadband as a synonym for bandwidth) or the Medium (radio, coaxial) as part of the Link properties.

Although some network representations can overlook the Medium concept, it must not be forgotten. For instance, to answer CQ07 from Table 2, the decision process need to evaluate the predicted strength of the received signal power of the available APs located where the Ue is heading. Therefore, it is necessary to evaluate the path loss between the Ue and the available APs. And the path loss calculation needs the characteristics of the propagation Medium. In our conceptual modeling, the Medium concept is explicitly represented because of its real interaction with Senders and Receivers, which allows bonding between them. Hence, ontology engineers can deal with Medium's representation whenever necessary as long they reuse an ontology based on our conceptual model.

Table 5
Comparison between ToCo and hint ontology to represent the mobility management of Fig. 1 at timestamp t_2.

RDF fragment using ToCo ontology	RDF fragment using hint ontology
@prefix toco: <http://purl.org/toco/> . @prefix om: <http://purl.oclc.org/.../sensordata.owl/> . @base <http://www.example.com/ex> . :ap1 a toco:BaseStation ; toco:hasAssociatedStations :ue1 ; toco:hasWLAN :ap1-wlan1 ; toco:stationsInRange :ue1 . :ap2 a toco:BaseStation ; toco:hasWLAN :ap2-wlan1 ; toco:stationsInRange :ue1 . :ue1 a toco:CellularUserEquipment ; toco:apsInRange :ap1 ,:ap2 ; toco:hasWLAN :ue1-wlan0 . :ap1-wlan1 a toco:WLAN . :ap2-wlan1 a toco:WLAN . :ue1-wlan0 a toco:WLAN . :ap1_ue1 a toco:LTEAssociation ; toco:from :ap1 ; toco:hasTxpower :ap1_ue1_TXPwr ; toco:to :ue1 . :ap2_ue1 a toco:LTEAssociation ; toco:from :ap2 ; toco:hasTxpower :ap2_ue1_TXPwr ; toco:to :ue1 . :ap1_ue1_TXPwr a om:hasValue -72 ^^xsd:integer. :ap2_ue1_TXPwr a om:hasValue -65 ^^xsd:integer.	@prefix gufo: <http://purl.org/gufo/> . @prefix hint: <http://myontology.com/hint#> . @base <http://www.example.com/ex> . :LTE a hint:Protocol . :ap1 a hint:AP ; hint:isServedBy :ue1 ; gufo:inheresIn :LTE ,:ap1Signal . :ap1Signal a hint:WantedSignal ; hint:power -72 . :ap1_ue1 a hint:DecodedBond ; gufo:mediates :ap1 ; :ue1 ; :linkID 32541 ; :startedAt "t1"^^xsd:string . :ap2 a hint:AP ; gufo:inheresIn :LTE ,:ap2Signal . :ap2Signal a hint:WantedSignal ; hint:power -65 . :ue1 a hint:Ue ; hint:handshakes :ap1 ; hint:isServedBy :ap1 ; hint:monitors :ap2 ; gufo:inheresIn :LTE . :ue1_ap1 a hint:DecodedBond ; ufo:mediates :ap1, :ue1 ; :linkID 89567; :startedAt "t1"^^xsd:string . :ue1_ap1_conn a hint:HandSkakeBond ; hint:handSkakeBondHasSelectedBond :ap1_ue1 , :ue1_ap1 ; gufo:mediates :ap1 , :ue1 ; :connID 77889 ; :startedAt "t1"^^xsd:string . :ue1_ap2 a hint:DecodedBond ; gufo:mediates :ap2 , :ue1 ; :linkID 25654 ; :startedAt "t1"^^xsd:string . :ue1_ue2_conn a hint:HandSkakeBond ; hint:handSkakeBondHasSelectedBond :ap1_ue1 ,:ue1_ap1 ; gufo:mediates :ue1 ,:ue2 ; :connID 12345 ; :startedAt "t1"^^xsd:string .

Table 6
Comparison between ToCo and hint ontology to represent the mobility management of Fig. 1 at timestamp t_3.

RDF fragment using ToCo ontology	RDF fragment using hint ontology
@prefix toco: <http://purl.org/toco/> . @prefix om: <http://purl.oclc.org/.../sensordata.owl/> . @base <http://www.example.com/ex> . :ap1 a toco:BaseStation ; toco:hasWLAN :ap1-wlan1 ; toco:stationsInRange :ue1 . :ap2 a toco:BaseStation ; toco:hasAssociatedStations :ue1 ; toco:hasWLAN :ap2-wlan1 ; toco:stationsInRange :ue1 . :ue1 a toco:CellularUserEquipment ; toco:apsInRange :ap1 ,:ap2 ; toco:hasWLAN :ue1-wlan0 . :ap1-wlan1 a toco:WLAN . :ap2-wlan1 a toco:WLAN . :ue1-wlan0 a toco:WLAN . :ap1_ue1 a toco:LTEAssociation ; toco:from :ap1 ; toco:hasTxpower :ap1_ue1_TXPwr ; toco:to :ue1 . :ap2_ue1 a toco:LTEAssociation ; toco:from :ap2 ; toco:hasTxpower :ap2_ue1_TXPwr ; toco:to :ue1 . :ap1_ue1_TXPwr a om:hasValue -81 ^^xsd:integer. :ap2_ue1_TXPwr a om:hasValue -60 ^^xsd:integer.	@prefix gufo: <http://purl.org/gufo/> . @prefix hint: <http://myontology.com/hint#> . @base <http://www.example.com/ex> . :LTE a hint:Protocol . :ap2 a hint:AP ; hint:isServedBy :ue1 ; gufo:inheresIn :LTE ,:ap2Signal . :ap2Signal a hint:WantedSignal ; hint:power -60 . :ap2_ue1 a hint:DecodedBond ; gufo:mediates :ap2 , :ue1 ; :linkID 85465 ; :startedAt "t3"^^xsd:string . :ap1 a hint:AP ; gufo:inheresIn :LTE ,:ap1Signal . :ap1Signal a hint:WantedSignal ; hint:power -81 . :ue1 a hint:Ue ; hint:handshakes :ap2 ; hint:isServedBy :ap2 ; hint:monitors :ap1 ; gufo:inheresIn :LTE . :ue1_ap2 a hint:DecodedBond ; gufo:mediates :ap2, :ue1 ; :linkID 14758; :startedAt "t3"^^xsd:string . :ue1_ap2_conn a hint:HandSkakeBond ; hint:handSkakeBondHasSelectedBond :ap1_ue1 , :ue1_ap2 ; gufo:mediates :ap2 , :ue1 ; :connID 96357 ; :startedAt "t3"^^xsd:string . :ue1_ap1 a hint:DecodedBond ; gufo:mediates :ap1 , :ue1 ; :linkID 95142 ; :startedAt "t3"^^xsd:string . :ue1_ue2_conn a hint:HandSkakeBond ; hint:handSkakeBondHasSelectedBond :ap1_ue1 ,:ue1_ap1 ; gufo:mediates :ue1 ,:ue2 ; :connID 12345 ; :startedAt "t1"^^xsd:string .

6. Conclusion and future works

The main contribution of the presented work is clarifying the terms Link and Connection in the telecommunication domain using an ontological analysis. We also show their dependencies while refining concepts like Server and Neighbor and proposing new ones like Medium. They represent a novel effort to provide a network-related ontology that supports mobility management in wireless networks.

As demonstrated, available network-based ontologies describe these possible relationships sometimes as Links, sometimes as Connections. Moreover, none of the researched network ontologies describe them simultaneously. Hence, this situation raises two fundamental questions:

(i) do Links and Connections describe the same thing?
(ii) If not, are they dependent on each other?

To help us solve these questions, we looked for Link and Connection definitions in English dictionaries and vocabulary recommendations of several standard bodies. We discovered that their definitions are not the same in those recommendations, although English dictionaries consider them synonyms. Even the recommendations are unclear on which entities Link and Connection bind nor if there is any dependency between them.

We show, using OntoUML, that there are many relationships between communication nodes, whether they are playing the roles of Sender or Receiver. One of them is the Link, a relation that can be defined as the logical one created between Senders and Receivers whenever the Signal of the latter is detected and decoded by the former. We also show that Links can be specialized in mobile networks. They can play different roles due to the roles that Senders and Receivers can also play as SelectedSenders (or Servers) or MonitoredSenders (or Neighbors).

We also present that Connections are logical relationships created due to an established agreement between communication nodes whenever it demands it. And, if this demand exists, there is a message exchange process that needs to be handled by Interfaces playing the roles of Senders and Receivers simultaneously. Hence, a pair of Links needs to exist between them, making us conclude that a Connection needs Links to exist. Besides, while Links are relationships between Senders and Receivers, Connections are relationships between Sources and Sinks, all of them as roles of the same entity – the Interface.

We are currently testing the proposed conceptual model in Protegé [53], an open-source ontology editor. Although the OntoUML plug-in in Visual Paradigm allows us to export the proposed conceptual model in OWL format, some mismatches are challenging and are being solved manually. Also, we are working on a solution to load a network ontology based on the proposed conceptual model into a wireless network emulator called Mininet-Wifi [54]. We aim to use such ontology to evaluate the emulator's HO process while using semantic reasoning.

Finally, we foresee the possibility of generalizing and extending the presented conceptual model by enriching the network protocol stack representation. Tanenbaum and Wetherall propose that the communication between two entities using the same protocol can be represented by several "virtual" communications. Therefore, a VirtualInterface handles the communication on a particular protocol layer with the same features and behavior as expected in our concept of Interface.

CRediT authorship contribution statement

Julio Cesar Cardoso Tesolin: Conceptualization, Methodology, Formal analysis, Writing – original draft. **André M. Demori:** Conceptual data modeling review. **David Fernandes Cruz Moura:** Conceptualization, Telecommunications concepts review, Writing review, Supervision. **Maria Cláudia Cavalcanti:** Conceptualization, Conceptual data modeling review, Writing review, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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