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TOWARDS A MOBILE WIRELESS NETWORK ONTOLOGY FOR RADIO ACCESS POINTS SELECTION SUPPORTED BY SEMANTIC REASONING

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Orientador(es): Maria Claudia dos Reis Cavalcanti, D.Sc.
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“Far better it is to dare mighty things, to win glorious triumphs,
even though checkered by failure,
than to take rank with those poor spirits who neither enjoy much nor suffer much,
because they live in the gray twilight that knows neither victory nor defeat.“
(Theodore Roosevelt)

RESUMO

As redes de comunicação críticas são ativos valiosos que os órgãos de segurança pública e defesa civil, como as Forças Armadas, têm para prevenir e gerenciar eventos como desastres naturais, conflitos armados e acidentes de trânsito, entre outros. No entanto, independentemente das escolhas de cada país para implementar essas redes, os órgãos de segurança pública e defesa civil buscam fornecer a cobertura sem fio mais abrangente possível. Em um cenário ideal, o agente de segurança poderia se comunicar por meio de qualquer rede sem fio, independentemente da operadora ou da tecnologia de acesso. Para isso, uma solução proposta é usar redes de acesso heterogêneas para oferecer cobertura onipresente com uma conexão ininterrupta. Entretanto, um dos desafios na implementação dessa solução é o gerenciamento da mobilidade. Este trabalho tem como objetivo demonstrar que o uso do raciocínio semântico no suporte à decisão é eficaz no gerenciamento da mobilidade em redes de comunicação móvel heterogêneas. Para isso, desenvolvemos ontologias de referência e operacional para representar os principais elementos de uma rede de comunicação no contexto do gerenciamento de mobilidade em uma rede de comunicação móvel sem fio. Uma vez desenvolvidas, implementamos um caso de uso usando um emulador de rede WiFi em conjunto com a ontologia operacional para demonstrar a capacidade de tomada de decisão apoiada pelo raciocínio semântico.

Palavras-chave: redes móveis heterogêneas; ontologias; raciocínio semântico.

ABSTRACT

Critical communication networks are valuable assets that public safety and civil defense agencies, such as the Armed Forces, have to prevent and manage events such as natural disasters, armed conflicts, and traffic accidents, among others. However, regardless of each country's choices to implement such networks, public safety and civil defense agencies seek to provide the most comprehensive wireless coverage possible. In an ideal scenario, the security agent could communicate via any wireless network, regardless of operator or access technology. To this end, one proposed solution is to use heterogeneous access networks to provide ubiquitous coverage with an uninterrupted connection. However, one of the challenges in implementing this solution is mobility management. This work aims to demonstrate that the use of semantic reasoning in decision support is effective in managing mobility in mobile communication networks. To this end, we developed reference and operational ontologies to represent the main elements of a communication network in the context of mobility management in a wireless mobile communication network. Once these elements were in place, we implemented a use case using a WiFi network emulator to demonstrate the decision-making capacity supported by semantic reasoning.

Keywords: heterogeneous mobile networks; ontologies; semantic reasoning.

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LIST OF ABBREVIATIONS AND ACRONYMS

3GPP	3rd Generation Partnership Project
ABCS	Always Best Connected & Served
ANSI	American National Standards Institute
AP	Access Point
ARIB	Association of Radio Industries and Businesses
C2	Command and Control
CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
CCSA	China Communications Standards Association
CQ	Competence Question
CQD	Competence Question Dependency
EB	Brazilian Army (Exército Brasileiro)
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplexing
HetNet	Heterogeneous Wireless Networks
HO	Handover
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electronic Commission
IP	Internet Protocol
ISO	International Organization for Standardization
ITU	International Telecommunication Union
KR&R	Knowledge Representation and Reasoning
NFV	Network Function Virtualization
ODCM	Ontology-Driven Conceptual Modeling

OGC	Open Geospatial Consortium
OWL	Web Ontology Language
OSI	Open Systems Interconnection
PS	Public Safety
PSTN	Public Switched Telephone Network
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RDF	Resource Description Framework
RF	Radio Frequency
SDN	Software Defined Network
SDR	Software Defined Radio
SWRL	Semantic Web Rule Language
TIA	Telecommunications Industry Association
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TDSI	Telecommunications Standards Development Society, India
TTA	Telecommunications Technology Association
TTC	Telecommunication Technology Committee
Ue	User Equipment
UFO	Unified Foundational Ontology
W3C	World Wide Web Consortium

CONTENTS

1 INTRODUCTION

The news reminds us daily that we live in a world where risks are always present, created by natural disasters or human activities (armed conflicts, traffic accidents, among others). A society that wishes to survive these threats must identify each type of risk and evaluate the necessary assets to prevent and, in the worst case, manage such situations. One of these assets is the critical communication network.

Camara and Nikaein [CAMARA; NIKAEIN, 2015] describe a critical radio communication network, also known as Public Safety (PS) Network or Public Protection Disaster Relief (PPDR) Network, as a radio communication system used by rescue and law enforcement services, such as the armed forces, police, fire department, and emergency medical services, to prevent and respond to incidents that endanger people and/or properties. Originally designed to provide only trunked voice services (*walkie-talkies*), they had to evolve to handle increasing data demands. The International Telecommunication Union (ITU) recognizes the importance of such wireless networks by recommending the use of the 3rd Generation Partnership Project (3GPP) fourth-generation wireless communication networks as a solution for providing broadband PS networks [ITU Radiocommunication Sector (ITU-R), 2021]. Although several countries have been using different deployment strategies to bring their PS networks to life, they aim to provide nationwide wireless coverage for their field agents (a.k.a. first responders). Like PS agencies, researchers and developers of mobile wireless networks aim to provide communication anywhere, anytime - a scenario also known as Always Best Connected & Served (ABCS)[SAAD; KASSAR; SETHOM, 2016].

One of the paths chosen by researchers and developers to provide the ABCS scenario in future mobile wireless networks relies on heterogeneous wireless networks (HetNet) [DARWISH et al., 2021; STAMOU et al., 2019; ZHANG et al., 2019]. 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 the coverage and capacity of the radio access network, combining the best features of each radio access technology (RAT). Nevertheless, it defies the mobility management processes that allow seamless connection since it depends on complex procedures and agreements between different telecommunication standard bodies.

This research proposes using semantic reasoning as part of decision-making strategies for handling HetNets mobility management in complex situations where context knowledge is essential.

1.1 Motivation

Public Safety networks aim to enhance coordination between first responders, facilitating coordinated responses to emergencies, improving situational awareness, leading to better decision-making and resource allocation, increasing public safety, saving lives, and reducing property damage by allowing faster response times and improved coordination. The ITU recognized the importance of the PS networks by publishing a dedicated recommendation [ITU Radiocommunication Sector (ITU-R), 2021] that describes the PS operations and the wireless communication technologies able to bring stable broadband communication for first responders. In the same sense, PS authorities recognize and agree that having a broadband public safety wireless network with nationwide coverage is necessary. However, how to deploy these networks is not a consensus.

One alternative is to build a public safety wireless network. In this case, governments maintain complete control over the network infrastructure and the security protocols. Also, these networks can be specific to public safety needs, including features like priority calls and panic buttons. However, building and maintaining a national network can be financially demanding, limiting themselves to specific technologies and hindering future advancements. For instance, Brazil, China [RCR WIRELESS NEWS, 2019], and South Korea[Samsung Newsroom, 2019] were some of the countries that chose to build their public safety network. For instance, the Brazilian government, represented by its Army, designed a two-layer public safety network to provide wireless coverage in cities with over 20,000 inhabitants [DEPARTAMENTO DE CIÊNCIA E TECNOLOGIA - EXÉRCITO BRASILEIRO, 2015]. While the first layer is based on a reliable, well-known trunking solution (P-25 trunking radio technology), the second layer is based on the 3GPP 4G wireless network operating at the 700 MHz band.

Another viable choice is to hire services from public mobile networks. It is a cost-effective solution that leverages existing infrastructure and allows rapid implementation. However, in this case, governments have less control over network security and prioritization during emergencies, and it may compete with commercial network traffic during peak usage periods. The United Kingdom and Australia chose this deployment alternative by exploring existing commercial mobile networks through agreements with service providers [UNITED KINGDOM GOVERNMENT, 2019]. To support this strategy, the Australian government led a study in 2016 to evaluate the advantages and disadvantages of each deployment type. They concluded that hiring services from public mobile networks was the best choice for their context [AUSTRALIAN GOVERNMENT - PRODUCTIVITY COMISSION, 2016].

Lastly, the United States has conducted a hybrid deployment to bring the best of both worlds. They are building a dedicated network for core public safety communication (the FirstNet) and partnering with AT&T to supplement coverage in remote areas [FIRSTNET, 2020]. Although it combines the benefits of a dedicated network for critical situations with cost-effective commercial network access, it reports on challenges to manage and integrate two separate systems.

Despite the deployment strategies, PS agencies aim to provide the broadest wireless coverage possible. In an ideal scenario, the first responder could communicate using any wireless network available, regardless of its network operator or radio access technology. Providing ubiquitous coverage with seamless connection is an effort that has been defying researchers and developers over the years as Fragkiadakis *et. al* [FRAGKIADAKIS et al., 2011] and by Marabissi and Fantacci [MARABISSI; FANTACCI, 2017] exemplify.

1.2 Challenges

Modern and future mobile communication relies on ubiquitous connectivity, a vision embodied by the *Always Best Connected & Served - ABCS* paradigm [SAAD; KASSAR; SETHOM, 2016], seeking to seamlessly connect users to the optimal network regardless of operator, ensuring the best possible service quality and experience. Thus, multi-operator heterogeneous wireless networks are emerging as a combination of various mobile operators integrating different radio access technologies (RATs) like cellular (e.g., 4G, 5G) and Wi-Fi, creating a complex yet adaptable network ecosystem. Although implementing heterogeneous wireless networks (HetNet) aims to solve network coverage and capacity issues, researchers and developers must face challenges such as network sharing, device capabilities, RAT interoperability, and mobility management.

Network sharing encompasses various approaches like roaming, where a user accesses another network operator, and radio access network (RAN) sharing, where infrastructure is co-located. However, implementing efficient network sharing requires overcoming billing, security, and spectrum management challenges across different operators. Network slicing, where the network is virtually divided to cater to diverse service needs (e.g., high bandwidth, low latency), adds another layer of complexity regarding resource allocation and orchestration. Furthermore, network **device capabilities**, especially the user's handset, are crucial in navigating a HetNet. Heterogeneous networks need handsets that seamlessly switch between RATs based on signal strength and service type. Technologies such as network function virtualization (NFV) and software-defined radios (SDRs) have the power to enable it. NFV allows for flexible network management by decoupling software functions from hardware, while SDRs provide software-based control over radio functionalities. However, ensuring compatibility between different vendors' equipment and enabling smooth network switching within a single device poses significant challenges.

Interoperability between diverse RATs is another hurdle. Standardization bodies like 3GPP (3rd Generation Partnership Project) and IEEE (Institute of Electrical and Electronics Engineers) are vital in defining the specifications of the handover procedures for cellular and Wi-Fi technologies. These specifications ensure smooth transitions without call drops or data loss. However, achieving seamless interoperability across many vendors and RATs remains an open challenge since few makers and operators have implemented it. Finally, **mobility management** within a multi-RAT HetNet presents a complex optimization problem. Traditionally, choosing the optimal network to connect requires real-time signal strength analysis, user mobility, and network congestion. However, the decision process can use other inputs to derive an optimal connection. In a PS scenario, non-network-related inputs, such as responding to PS events (e.g., flooding, thunderstorms, social breakout, and New Year's celebration). Each challenge previously described suggests research opportunities. **This work focused on mobility management in HetNets**.

1.3 Problem Statement and Research Goal

Mobility management in mobile wireless networks, especially the handover process, has been a research topic over the years to provide ubiquitous coverage with seamless connections to users. Several research contributions [CHANDAVARKAR; REDDY, 2012; ZEKRI; JOUABER; ZEGHLACHE, 2012; AHMED; BOULAHIA; GAïTI, 2014; OBAYIUWANA; FALOWO, 2016; MALATHY; MUTHUSWAMY, 2018] have been proposed to enhance the decision-making process to select the appropriate HetNet to deliver the best user's quality of service (QoS) and experience (QoE). These approaches rely on different strategies from operational research and machine learning areas, which are hardly dependent on data gathered from several network elements.

However, there are situations where a network element should decide the association between the user equipment (Ue) and the access point (AP) based on complex situations with incomplete or uncertain information. For instance, how a decision engine should answer a statement such as *The city is under a thunderstorm, and all first-responders handsets must be associated with APs using frequencies under 1 GHz as they are less sensitive to raindrop degradation?* . Or *There is flooding in certain regions of the city. The handsets of the first responders must be associated with APs installed at rooftops.* Hence, **our research problem is how to enrich the decision support for mobility management in HetNets to decide based on context understanding.**

An approach to handle this situation is to utilize semantic reasoning, a field of artificial intelligence (AI) that unlocks the potential for machines to reason, infer new knowledge, and solve problems based on their understanding of the context. Several works have already demonstrated the semantic reasoning capabilities to enhance decision support systems (DSS) [ROSPOCHER; SERAFINI, 2012; APAJALAHTI et al., 2016; RäISäNEN; BELL; APAJALAHTI, 2018; MAARALA; SU; RIEKKI, 2017; DISSANAYAKE;

COLICCHIO; CIMINO, 2019]. However, none has already been used to support mobile management decision-making processes. But before describing and reasoning about public safety situations, it is necessary to describe and reason about the elements of a heterogeneous mobile wireless network. Thus, **our research aims to show that using semantic reasoning effectively allows decision-making in HetNets mobility management**. Our specific goals(SG) are:

SG01 create a reference ontology representing the necessary mobile networks concepts and relations for mobility management support;

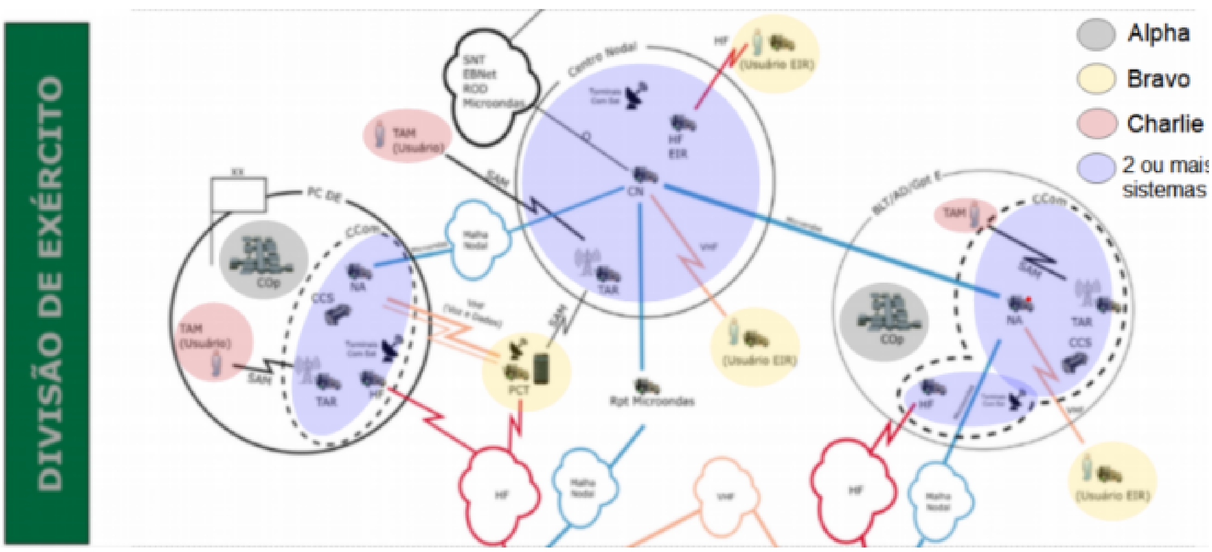
SG02 develop an operational ontology based on the reference ontology that allows reasoning capabilities for mobility management support using semantic reasoners and

SG03 show the semantic reasoning potential to support mobility management decision-making in a simulated wireless network.

1.4 Research Relevance For The Brazilian Army

The deployment and management of Heterogeneous Networks (HetNets) pose significant challenges in both civilian and military domains. In the military context, seamless communication between distinct defense systems, each relying on many hardware and software-defined communication nodes, is critical. This research addresses this challenge by developing ontologies that enable interoperability and semantic reasoning. Two strategic Brazilian Armed Forces projects exemplify this need: the System of Command and Control Systems (S2C2) and the RDS-Defesa project.

Figure 1 – Fac2Ter representation in an army division



Source: Fac2Ter S2C2 project report.

Sponsored by the Brazilian Army through the FINEP and FAPEB funding agencies[1], and developed by various institutions such as CDS, IME, PUC-Rio, UFRGS and UnB, the S2C2 project aims to provide interoperability solutions to deal with the challenges of integrating the Army Command and Control (C2) Applications Family (FAC2FTer), as presented in Figure 1. These C2 systems must communicate and share information through communications systems, where wireless nodes such as access points (AP) and user equipment (Ue) play a key role. It reinforces the need for interoperability between FAC2FTer systems, where the Ue receives information from the C2 systems, helping its decision-making processes, and the C2 system receives information from the communications systems about communications capabilities and opportunities.

The RDS-Defesa project is a Brazilian Defense Ministry initiative to provide seamless communication between all Brazilian Armed Forces branches. Conducted by the Brazilian Army at Centro de Tecnologia do Exercito (CTex), this project aims to promote interoperability by developing a family of multi-band software-defined radio equipment operating in the HF, VHF, and UHF bands, capable of operating on various waveforms. Moreover, it aims to provide cognition capacity for these radios, allowing them to make decisions based not only on the measurement of the radio environment but also on the information coming from different military systems.

Hence, this research contributes to both projects by providing a robust ontology that supports semantic reasoning for network management and decision-making in dynamic military environments. The proposed ontology also facilitates the interoperability between legacy and modern communication systems by using an adequate hardware and software-defined network representation.

1.5 Methodology

This work was conducted within the Design Science Research (DSR) paradigm. This problem-solving approach aims to expand human knowledge by creating innovative artifacts that address challenges and enhance their environments [BROCKE; HEVNER; MAEDCHE, 2020]. Beyond delivering new solutions, DSR also develops a deeper understanding of why these artifacts are effective (or ineffective) in specific contexts, known as design knowledge (DK). The DSR process involves six core stages: problem identification, objective definition, design and development, demonstration, evaluation, and communication. The process can begin at different steps depending on the research focus and goals. Figure 2 illustrates the DSR process and potential entry points.

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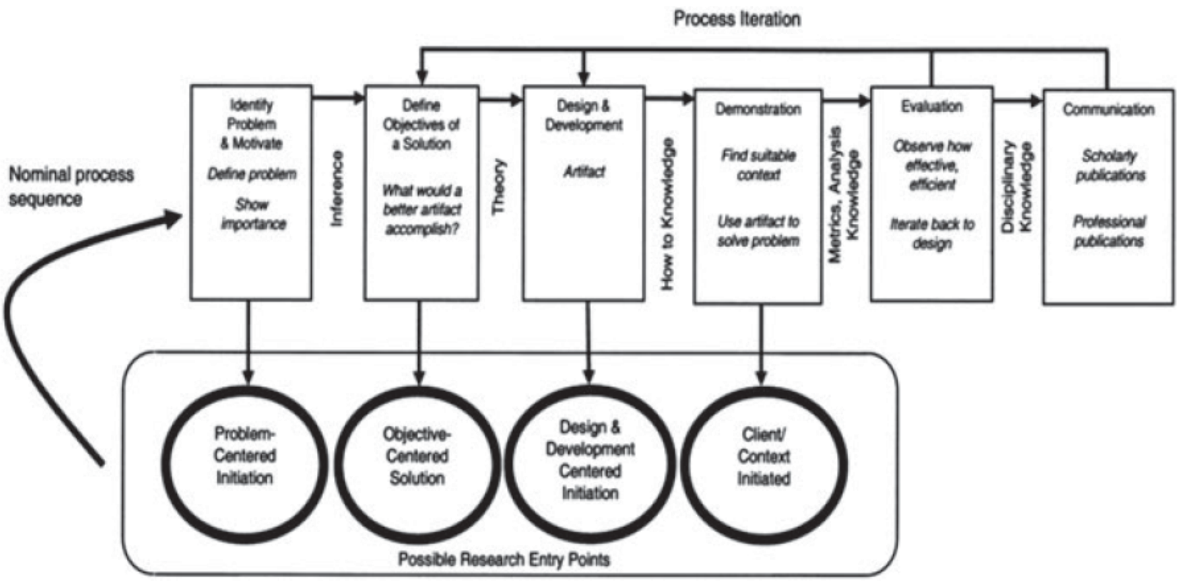
Figure 2 – DSR methodology process model



Source: [BROCKE; HEVNER; MAEDCHE, 2020].

This research was initiated by examining challenges associated with deploying Heterogeneous Networks (HetNets). Mobility management emerged as a critical issue. A literature review assessed existing decision-making approaches for mobility management in wireless networks, revealing a need for improved handling of complex and uncertain conditions, such as those encountered in public safety scenarios. Semantic reasoning was identified as a potential solution to enhance decision-making in these situations.

The research objective was to show the capability of semantic reasoning to enrich mobility management decisions in HetNets. To achieve this, specific goals included developing appropriate ontologies to represent mobile network elements. Aligned with the DSR paradigm of artifact creation, two artifacts were designed and developed: a conceptual model representing essential mobile network elements (reference ontology) for mobility management and a machine-processable OWL artifact (operational ontology) based on the conceptual model. A ubiquitous coverage scenario was used to demonstrate and evaluate the artifacts' ability to handle mobility management. Finally, the research findings were disseminated through this dissertation and academic publications.

1.6 Outline

The remainder of this thesis is organized as follows. Chapter 2 presents the fundamental concepts for fully comprehending our research effort, reviewing selected telecommunication networks and ontology-driven conceptual modeling topics. Chapter 3 presents the related work analysis, where similarities and gaps were identified. Next, in Chapter

4, a conceptual model (or reference ontology) is proposed using well-known ontology engineering methodologies and approaches. Its goal is to properly represent the necessary concepts and relationships to support mobility management through semantic reasoning, supported by well-known ontology engineering methodologies and approaches. Chapter 5 shows how a machine-readable artifact (or operational ontology) was derived based on the reference model proposed in the previous chapter, presenting implementation choices for bringing an OWL-based ontology. Chapter 6 describes a use case based on a handover scenario using a wireless network simulator. Lastly, Chapter 7 presents final considerations, contributions, and directions for future work.

2 BACKGROUND

This section briefly reviews some main concepts about telecommunications networks, knowledge representation & reasoning, and ontology-driven conceptual modeling used in our research.

2.1 Telecommunication Networks

A telecommunication network is a system that enables communication between multiple devices or locations through the transmission of signals. In other words, it is a composition of nodes interconnected by links that facilitate the exchange of information. Nodes are individual points within the network where data is generated, received, or processed. These nodes can be anything from a smartphone or computer (terminal nodes) to a router or a satellite (intermediate nodes). Links, however, represent the physical or virtual attachments between nodes, allowing data to be transmitted from one node to another. They can be wired, like fiber optic cables or copper wires, or wireless, like radio waves or microwaves. Together, nodes and links form the backbone of telecommunication networks.

The following sections do not attempt to provide an exhaustive description of modern telecommunication networks. Instead, they briefly review some of their main concepts to ground our discussion about mobility management in mobile wireless infrastructure networks.

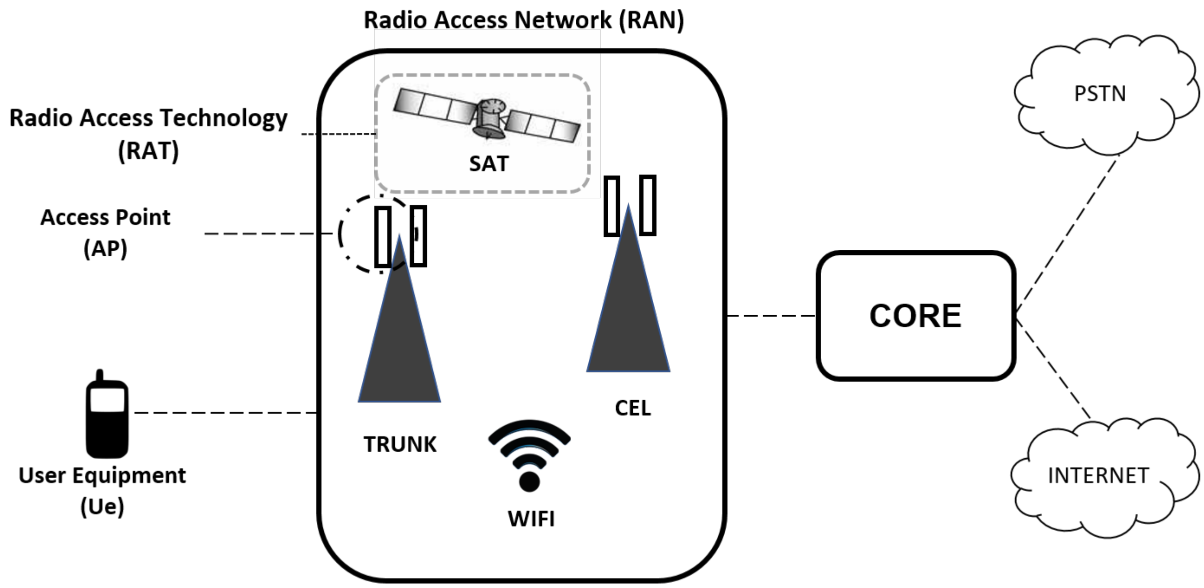
2.1.1 Ad-Hoc and Infra-structured Networks

Telecommunication nodes can be arranged in two main architectures: infra-structured and ad-hoc network architectures. Sohraby *et al.* [SOHRABY; MINOLI; ZNATI, 2007] describe an infra-structured network as a telecommunication architecture that relies on a central access point (AP) to manage communication between terminal nodes. The AP acts as a bridge, allowing terminal nodes such as laptops or smartphones to access the network's resources, like the Internet. In contrast, ad-hoc networks work without a central AP. The nodes communicate directly with each other, forming a peer-to-peer (P2P) connection. Choosing a proper architecture depends on the requirements and goals interconnected nodes must achieve to exchange information. While the infra-structured architecture offers a centralized, scalable, and secure approach for permanent deployments, an ad-hoc architecture offers a flexible and easy-to-deploy solution for temporary connections or situations lacking infrastructure.

Intermediate nodes in infra-structured networks ultimately play specific functions to deliver information between terminal nodes. Some intermediate nodes provide network access to terminal nodes, while others take the payload delivered to these access nodes and route it until the destination is reached. These networks can be categorized based on the medium that the technology access nodes employ. They can be wired when the access technology is based on wired links, such as the Ethernet, or wireless when it is based on wireless links, such as IEEE 802.11 and 3GPP cellular technologies. [BEARD; STALLINGS; TAHILIANI, 2015].

Although intermediate nodes in infra-structured wireless generally provide process and forward functions to allow information exchange between terminal nodes, telecommunication standard bodies do not commit themselves to specifying the same processing and routing functions or even nominating the intermediate nodes in the same manner. For instance, the 3GPP TR 21.905 vocabulary recommendation [Technical Specification Group Services and System Aspects, 2021b] nominates terminal nodes as user equipment `Ue` and the intermediate node responsible for providing network access to terminal nodes as either `BTS`, or `nodeB`, or `enodeB` or `gnodeB`, depending on the radio access technology (RAT) being used (2G-GSM, 3G-UMTS, 4G-LTE or 5G-NR). In contrast, IEEE 802.11 recommendations nominate terminal nodes as stations and the intermediate node providing network access as access points. Since the core of this research is to provide support for mobility management for mobile wireless networks, we chose to name the terminal node as user equipment (`Ue`) and the network access node as an access point (`AP`), regardless of the RAT being used by both node types, as portrayed in Figure 3.

Figure 3 – A heterogeneous wireless network



Source: Prepared by author.

Lastly, infra-structured wireless networks can also be classified considering the RAT homogeneity provided to the terminal nodes. A homogeneous infra-structured wireless network provides user access with a single RAT. In contrast, as described by Bosch *et al.* [BOSCH et al., 2020], a heterogeneous infra-structured wireless network relies on distinct RATs provided by multiple telecommunication standard bodies specifications.

2.1.2 Information Exchange in Teleommunication Networks

Providing information exchange between users is one of the main goals of a communication network. The ITU Recommendation V.662-3 [ITU Radiocommunication Sector (ITU-R), 2005] 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) [KOLODZIEJ, 2021]. 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) [KOLODZIEJ, 2021]. 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 [KOLODZIEJ, 2021], which allows duplex communications using bidirectional links.

2.1.3 Telecommunication Standard Bodies

Network standards are necessary to coordinate the information exchange between different network vendors and suppliers. According to Tanenbaum and Wetherall [TANENBAUM; WETHERALL, 2011], standards increase the market for products adhering to them, leading to mass production, economies of scale in manufacturing, better implementations, and other benefits that decrease price and further increase acceptance. In this sense, standards define what is needed for interoperability. They fall into two categories: *de facto* and *de jure*. *De facto* (Latin for “from the fact”) standards have just happened without any formal plan. On the other hand, *De jure* (Latin for "by law") standards are adopted through the rules of some formal standardization body. International standardization authorities are generally divided into two classes: those established by treaty among national governments and those comprising voluntary, non-treaty organizations. Several organizations of each type exist in the Information and Communication Technologies (ICT) standards, notably ITU, 3GPP, ISO, IEEE, and TIA.

The International Telecommunication Union (ITU)[1] is a specialized agency of the United Nations (UN) that focuses on Information and Communication Technologies (ICTs), acting as the technical arm of the UN for telecommunication, ensuring smooth international communication and technology development. The ITU is structured into three main sectors. The radiocommunication sector (ITU-R) manages the radio frequency spectrum and satellite orbits globally and develops standards for radiocommunication systems. The telecommunication standardization sector (ITU-T) focuses on developing technical standards for telecommunications. These standards ensure that various communication technologies and devices of different manufacturers work together seamlessly. Lastly, the telecommunication development sector (ITU-D) bridges the digital divide by promoting access to ICTs in developing countries, working on projects to improve infrastructure, train personnel, and bridge the gap between those with and without access to communication technologies. Study groups (SG) are responsible for delving deeper into specific technical areas within each sector. These groups bring together experts from member countries and industries to discuss, research, and develop the technical recommendations and standards that the ITU is known for.

The 3rd Generation Partnership Project (3GPP)[2] unites seven telecommunications standard development organizations: ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC, also known as organizational partners. It provides its members a stable environment to produce the reports and specifications defining 3GPP technologies. 3GPP specifications cover cellular telecommunications technologies while providing hooks for non-radio access to the core network and interworking with non-3GPP networks. The primary function of 3GPP is to develop and maintain technical specifications and recommendations for mobile telecommunications technologies. These specifications define the operation of cellular networks, ensuring seamless global communication across devices and service providers. The standards cover the Radio Access Networks (RAN), describing the communication protocols between mobile devices and base stations, the Core Network and Terminals, defining how data is routed and switched within the network and how devices connect to it, and Service Capabilities, specifying what services, like voice calls, texting, or data transfer, are available and how they function. Developing 3GPP standards and recommendations relies

[1] available at https://www.itu.int/en/about/Pages/default.aspx
[2] available at https://www.3gpp.org/about-us

on the Working Groups (WG). They are dedicated teams composed of technical experts from member organizations, including network operators, equipment manufacturers, and research institutions. Each working group focuses on a specific aspect of mobile technology, and through collaboration and discussion, WGs propose, refine, and ultimately approve technical specifications that become the foundation of 3GPP standards.

The Institute of Electrical and Electronics Engineers (IEEE)[3] is a global professional organization for engineers, scientists, and other professionals working in various areas of technology focusing on electrical engineering, electronics engineering, computer engineering, and related fields. Highly influential and followed by manufacturers, developers, and governments worldwide, the IEEE standards define how things should be designed, built, and operated to ensure compatibility, safety, and efficiency. The IEEE technical societies are specialized groups within the organization that focus on specific areas of technology, such as the Communications Society (ComSoc) for telecommunications or the Computer Society (CS) for computer science. Each of the 39 technical societies has its group of experts, publications, conferences, and activities. They advance knowledge in their respective fields while developing standards through working groups, providing professional development opportunities for members, and hosting conferences and workshops to share research and innovation.

The International Organization for Standardization (ISO)[4] is an independent, non-governmental international organization. It comprises representatives from national standards bodies of member countries, focusing on developing and publishing international standards for a wide range of products, services, and processes. It is a global platform where experts from different countries come together to create voluntary international standards. These standards ensure quality, safety, efficiency, and interoperability across various industries and sectors. The backbone of ISO's standard development process lies in its technical committees (TCs). Each TC focuses on an industry or technical area, like healthcare, agriculture, or information technology. Within TCs, working groups (WGs) delve deeper into specific topics or standards. These WGs include volunteer experts from member countries, industry, and academia. Through a consensus-based approach, WG members discuss, research, and draft the technical specifications that become ISO standards. On issues of telecommunication standards, ISO and ITU-T often cooperate (ISO is a member of ITU-T) to avoid two official and mutually incompatible international standards.

Accredited by the American National Standards Institute (ANSI) as a Standard Developing Organization (SDO), the Telecommunication Industry Association (TIA)[5] is an association that represents global information and communication technologies (ICT).

[3] available at https://www.ieee.org/about/index.html
[4] available at https://www.iso.org/about-us.html
[5] available at https://tiaonline.org/about/

As an essential organization, creating technical standards and specifications for a wide range of ICT products and services ensures its standards' compatibility, interoperability, safety, and performance. The standard development process relies on the participation of member companies, including equipment manufacturers, service providers, government entities, and end-users. It works through various engineering committees (ECs), focusing on cellular towers, voice-over IP (VoIP) equipment, structured cabling, satellites, and mobile device communication. TIA's standards contribute to the smooth functioning of global communication networks, promoting innovation by providing a common ground for developing new technologies compatible with existing infrastructure.

Telecommunication standard bodies play a crucial role in developing and standardizing terms and vocabulary recommendations within mobile networks and telecommunications. These bodies provide a structured framework for conceptual modeling, ensuring consistency and interoperability in the rapidly evolving field. Noteworthy standards such as ITU-R V.662-3 [ITU Radiocommunication Sector (ITU-R), 2005], IEC 60050.701 [Technical Committee 1, 2019], and the TIA Telecom Glossary [Telecommunications Industry Association, 2022] are instrumental in shaping the language used in the industry.

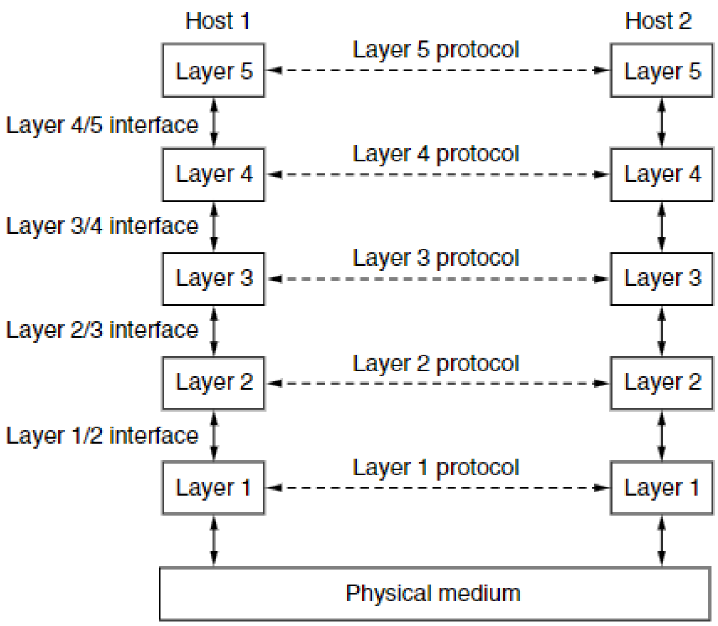
2.1.4 Layered Network Design

Communication between devices, such as computers and mobile phones, has come a long way since its beginnings, where only the exchange of information, transmitting and receiving bits over a medium, was the only task required. Modern communications require more challenging tasks to properly deliver information between the participating entities. Tasks such as error correction, flow control, switching, routing, and cryptography, among others, are now indispensable. As a consequence, designing a communication network became more complex and challenging. Many authors [TANENBAUM; WETHERALL, 2011; KUROSE; ROSS, 2016; COMER, 2006] propose a layered network architecture design approach as an alternative to overcome the ever-increasing complexity. This abstract approach simplifies network development by dividing complex tasks into several simple ones, favoring modularity, modification, and testing.

2.1.4.1 Concepts

As the name suggests, a layered network architecture comprises a set of layers, as Figure 4 portrays. A **layer** is an abstraction representing a functionality within the network architecture offered to a higher layer. In other words, a rank N layer offers functions or **services** to a rank N+1 layer. The information to be exchanged flows from the highest to the lowest layer, where it is exchanged with another communication entity. The number, the name, the contents, and the functions of each layer may differ from one network architecture to another.

Figure 4 – Layered network architecture design approach



Source: [TANENBAUM; WETHERALL, 2011].

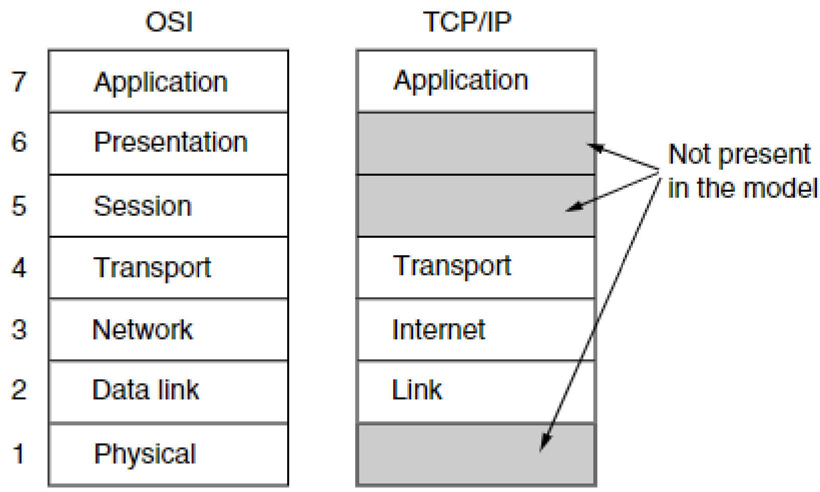
Figure 4 exemplifies a simple communication between two communication devices or **host**s. It occurs vertically, with information coming from higher to lower layers through **service**s and **interface**s. However, the layered design approach provides an abstraction that helps the network architecture design. Because of its layering functionality, it looks like entities in the same layer exchange information directly between them, according to a set of rules of **protocols**. In this situation, these entities are called **peers**. Therefore, while the lowest layer physically exchanges information with its peers, there are virtual communications between peers in higher layers. According to Tanenbaum and Wetherall [TANENBAUM; WETHERALL, 2011], a network architecture is a set of layers and protocols, while a list of protocols, one per layer, is known as a protocol stack.

2.1.4.2 Reference Models

Many reference models proposed by the literature or standard bodies recognize the strength of using a layered network design.The most well-known reference models are the ISO-OSI reference model and the TCP/IP model. According to Tanenbaum and Wetherall [TANENBAUM; WETHERALL, 2011], while the former provides a general model, discussing layer features that are still relevant nowadays, the latter provides protocols that are still widely used.

The ISO/OSI reference model has seven layers: Physical, Data Link, Network, Transport, Session, Presentation, and Application. The **Physical** layer transmits and receives raw bits over a communication channel. It deals with mechanical, electrical, and

Figure 5 – Comparison between ISO/OSI and TCP/IP models



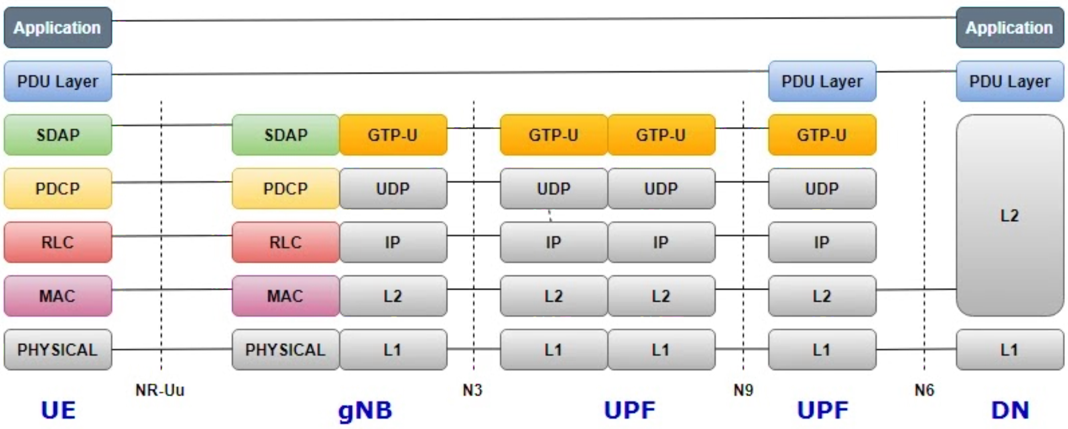
Source: [TANENBAUM; WETHERALL, 2011].

timing interfaces, along with the propagation medium, where the signals are propagated. Moving up, the **Data Link** layer is concerned with transforming the raw transmission/reception into a stream of bits that looks free of errors by masking them in a way that the network layer is not aware of. Moreover, to deal with the issue of accessing shared channels in broadcast networks, there is a Data Link sub-layer called **Medium Access Control (MAC)** that is specially designed to solve this issue. Next, the **Network** layer is responsible for determining whether packets are routed from source to destination. Since routing paths can be static or dynamic, the network layer has to be able to deal with both behaviors. One of the disadvantages of dynamic routing is the possibility of creating congestion, an issue that has to be handled along with other higher layers. Moving up, the **Transport** layer accepts data from its adjacent higher layer and passes it to the network layer unless data is first split into smaller units. Lastly, it must ensure all pieces arrive correctly at the other end. These tasks must be done efficiently to isolate higher layers from changes in the hardware technology over time. The **Session** layer allows users on different machines to establish sessions between them, offering various services such as dialog control, token management, and synchronization. Next, the **Presentation** layer deals with the syntax and semantics of the transmitted information rather than moving bits around. It manages abstract data structures and allows higher-level data structures to be defined and exchanged. Finally, the **Application** layer comprises a set of protocols commonly needed by users, like the HTTP protocol, the basis for the World Wide Web.

On the other hand, the TCP/IP reference model proposes a four-layer network architecture, where many of them overlap the layer definitions of the ISO/OSI reference model. In the TCP/IP reference model, the **Link** layer is the lowest layer and describes what links must do to meet the needs of this connectionless internet layer. According to Tanenbaum and Wetherall [TANENBAUM; WETHERALL, 2011], this layer is not properly a layer, as defined in the layered architecture design. It resembles more of an interface between hosts and transmission links. Moving up, the **Internet** layer is considered the backbone of this reference model. It allows host packet injection into any network, having them traveling regardless of their destination. They may arrive in a different order, and it is the duty of the higher layers to rearrange them. Next, the **Transport** layer is designed to allow peer entities to carry on a conversation, just as in the ISO/OSI transport layer. Finally, like the ISO/OSI reference model, the **Application** layer comprises all entities able to exchange user information directly. Figure 5 shows the layer comparison between the ISO/OSI and TCP/IP models.

However, standardization bodies do not have to fully commit with the OSI or TCP/IP reference models. These models serve as inspirational insights and a means of communication between network developers. For example, Figure 6 shows the layered architecture of the 3GPP 5G user plane sub-network. Although some layers may have the same network function described by the reference models, others were engineered in way that new network functions could be developed.

Figure 6 – 3GPP 5G layered architecture - user plane



Source: <https://www.lteprotocol.com/2020/02/5g-protocol-stack.html>.

2.1.5 Mobile Wireless Networks

Mobile wireless networks are a specialized subset of wireless networks specifically designed to cater to users on the move [ALSHARIF et al., 2020]. For instance, cellular networks employ a network of access points (a.k.a base stations) that communicate with mobile devices within their designated coverage areas. As a mobile user moves from one base station to another, the network seamlessly hands over the connection, ensuring uninterrupted communication. This inherent mobility has revolutionized communication, enabling constant connectivity and real-time applications.

One of the main challenges of future mobile networks is providing continuous wireless communication services anywhere, anytime. Unfortunately, this ideal scenario has defied researchers and developers over the years, being first described by Gustafsson and Jonsson [GUSTAFSSON; JONSSON, 2003] as the Always Best Connected (ABC) scenario. Later, other works expanded this concept [PASSAS et al., 2006; KELLOKOSKI; KOSKINEN; HäMäLäINEN, 2013; RAO; BOJKOVIC; BAKMAZ, 2013; SAAD; KASSAR; SETHOM, 2016], adding other requirements such as quality of service (QoS) and quality of experience (QoE). Thus, it has evolved into the Always Best Connected and Served (ABCS) scenario, representing the current research efforts to provide ubiquitous mobile coverage with a seamless connection.

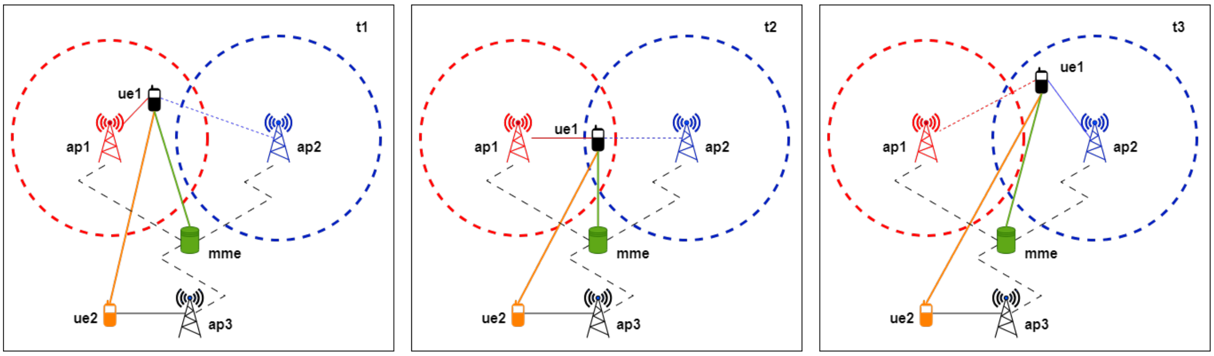
Among possible evolutionary paths to provide the ABCS scenario in future mobile wireless networks, researchers and developers have been relying on heterogeneous radio access sub-networks (RAN) [DARWISH et al., 2021; STAMOU et al., 2019; ZHANG et al., 2019]. They allow users' equipment (`Ue`) to access 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 the coverage and capacity of the RAN, bringing together the best features of each RAT and providing ubiquitous coverage of the ABCS concept. On the other hand, it defies the mobility management processes that allow the seamless connection since it depends on the agreements of complex procedures between different telecommunication standard bodies (hereafter called standard bodies for short).

2.1.6 Mobility Management In Mobile Wireless Networks

Mobility management in wireless networks can be defined as procedures maintaining a `Ue` attached to a serving wireless network. These mechanisms allow users to remain served while moving within the coverage area. Tayaab *et al.* [TAYYAB; GELABERT; JANTTI, 2019] describe two distinct operation modes that 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 [MALATHY; MUTHUSWAMY, 2018]. To normalize the term, we choose handover (HO) as a reference for all of them. Figure 7 shows a basic HO process performed in a 4G network specified by the 3GPP standard body[Technical Specification Group Core Network and Terminals, 2022]. Although specific to it, the process shows a general procedure found in other mobile systems since they share the same basic principles.

Figure 7 – Handover scenario



Source: Prepared by author.

At t_1, the user equipment `ue1` is being served by an access point `ap1`, and it is moving towards the region covered by another access point (`ap2`). Both access points belong to the same network in which the `ue1` is attached. This attachment allows the communication between `ue1` and other user equipment `ue2`. 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, such as 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 represent an important concept in mobile management. Without this network awareness, a HO can not be executed. Moving forward, it sends this 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 with 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 its own field of research. Many authors proposed different strategies in different scenarios to handle the decision process [AHMED; BOULAHIA; GAïTI, 2014; MALATHY; MUTHUSWAMY, 2018; MáRQUEZ-BARJA et al., 2011; OBAYIUWANA; FALOWO, 2016; ZEKRI; JOUABER; ZEGHLACHE, 2012], based on different methods from different fields like Operational Research and Artificial Intelligence. Recently, semantic technologies have been added to the group of tools capable of improving decision-making, as described in [ROSPOCHER; SERAFINI, 2012; APAJALAHTI et al., 2016; RäISäNEN; BELL; APAJALAHTI, 2018; MAARALA; SU; RIEKKI, 2017; DISSANAYAKE; COLICCHIO; CIMINO, 2019]. The reasons to use semantic technologies go beyond their reasoning capacity. As stated by Rospocher and Serafini [ROSPOCHER; SERAFINI, 2012], the benefits of using it are threefold: it acts as an integrator of structured knowledge and data available on the web, as a DSS web service, and as a storage of a semantically rich track of the entire decision process.

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 simultaneously when it terminates the old association with the old server. 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 Figure 7, `ue1` is associated with `ap2` while maintaining the attachment with `ue2` and `mme`. From the user's point of view, nothing happens, 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. In the scope of mobile management in heterogeneous wireless networks, there are two of special concern: 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 Tayab *et al.*[TAYYAB; GELABERT; JANTTI, 2019], when a handover occurs between access points with the same radio access technology (RAT), the process is known as an intra-RAT HO or horizontal HO. Similarly, when they have different RATs, the process is called an inter-RAT 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 [Technical Specification Group Services and System Aspects, 2021a] is an example of a standard procedure description that handles handovers between different RATs specified by different standard bodies. In the same sense, 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.

2.2 Knowledge Representation and Reasoning

Since the dawn of artificial intelligence, researchers have been trying to create systems capable of performing tasks that allegedly require human intelligence. To achieve this, they would need knowledge about the function they are intended to accomplish. Two main approaches to making systems knowledgeable are teaching and learning from experience. Machine learning has been a far more prominent approach to learning from experience, demonstrating great value across various classification and prediction tasks. Unlike machine learning, which focuses on identifying patterns from data, the teaching approach emphasizes clear and understandable explanations of concepts, relationships, and rules within a specific knowledge area. Brachman and Levesque [BRACHMAN; LEVESQUE, 2004] define this last approach as Knowledge Representation and Reasoning (KR&R), which deals with two fundamental questions: how to represent knowledge about the world in a way that is both understandable and usable by machines, and how to reason with this knowledge to draw inferences, solve problems, and make decisions.

Ontologies provide a structured vocabulary for representing knowledge, acting as formal domain specifications, and defining its entities, concepts, attributes, and relationships. It fosters a common understanding among different stakeholders and computational agents. Ontologies can systematically structure complex domains, allowing for the seamless integration of disparate sources of information and facilitating interoperability across heterogeneous systems. An ontology can also be seen as a set of two groups of statements: *TBox* and *ABox*. *TBox* statements describe a domain of interest by defining classes and properties as a domain vocabulary. Complementary, *ABox* statements describe facts associated with the conceptual model of *TBox*.

Researchers and developers rely on specific languages to bring the conceptual models defined in the ontology as machine-readable artifacts. One of them is the Web Ontology Language (OWL)[6], a semantic web language proposed by the W3C that programs can exploit to verify the consistency of an ontology (knowledge base) or to make implicit knowledge explicit. Along with OWL, the W3C consortium develops other languages to support axioms or rules (ABox statements), like the Semantic Web Rule Language (SWRL)[7] and the Shapes Constraint Language (SHACL)[8]. Several ontology editors support such languages as the Protege Ontology Editor[MUSEN, 2015].

Semantic reasoning means inferring knowledge over a given ontology using the *ABox* and *TBox* statements. Thus, semantic reasoners play a crucial role in KR&R by enabling automated inference and deduction based on the encoded knowledge. They employ a variety of inferential mechanisms, including deductive, inductive, and abductive reasoning,

[6] available at <https://www.w3.org/TR/owl2-overview/>
[7] available at <https://www.w3.org/submissions/SWRL/>
[8] available at<https://www.w3.org/TR/shacl/>

to derive implicit knowledge from the explicitly represented information, thus augmenting the capabilities of knowledge-based systems. Among many available, Hermit[GLIMM et al., 2014] and Pellet[SIRIN et al., 2007] are well-known semantic reasoners that can interpret *ABox* statements written in OWL. Finally, we have SPARQL to enrich the semantic reasoning. It is a standardized language for querying data stored in a graph-based structure where information is connected through subject-predicate-object triples. SPARQL allows users to retrieve and manipulate this data by forming queries that specify these connections.

2.3 Ontology-Driven Conceptual Modeling

Conceptual modeling is a paramount process in various domains where creating abstract representations of real-world systems is a demand [MYLOPOULOS, 1992]. They focus on the main concepts and how they relate, omitting unnecessary detail. This simplification fosters a shared understanding among stakeholders, facilitating effective communication and collaboration and serves as a blueprint for researchers and developers to deliver a solution.

Although traditional conceptual modeling languages, such as UML and EER, have been proven effective over the years, they can lack formal logical rigor, potentially leading to inconsistencies when facing complex models. According to Verdonck *et al.* [VERDONCK et al., 2015], one of the approaches to deal with such modeling challenges is to use ontology-driven conceptual modeling (ODCM). It leverages the use of ontologies - formal descriptions of concepts and their relationships - enforcing a more structured approach, ensuring the model adheres to predefined rules, and improving clarity. Moreover, this approach facilitates the integration of models across different domains, as ontologies can be shared and reused. An empirical study [VERDONCK et al., 2019] revealed that novice modelers came up with higher quality models when applying the ODCM technique compared to other novice modelers applying the traditional conceptual modeling technique. Moreover, the results of the empirical study showed advantages when applying an ODCM technique rather than a traditional one on a more challenging and advanced scenario without demanding more effort from the modelers.

Hence, ontology-driven conceptual modeling favors systems designers working with larger, more complex information systems than traditional conceptual modeling. It brings benefits such as increased re-usability and reliability, sophisticated representation of the domain being modeled, and a higher level of domain understanding by its modelers and users [VERDONCK et al., 2019].

2.3.1 Ontology Enginnering

Ruy *et al.* [RUY et al., 2017] describes ontology in the semantic web context as a formal representation of a common conceptualization of a universe of discourse. Characterized mainly by a taxonomy and a set of inference rules, they can be used in a particular application to outline possible relationships and constraints on using those terms. According to the same authors, the academic literature classifies ontologies using diverse perspectives, including generality levels. In this sense, ontologies can be classified into domain, core, and foundational. While domain ontologies describe concepts from a specific domain (lowest generality level), such as semantic sensor ontology [HALLER et al., 2018] or heterogeneous networks ontology [ZHOU; GRAY; MCLAUGHLIN, 2019], foundational ontologies span across many fields, providing general concepts and turning into a domain-independent ontology, such as DOLCE [BORGO et al., 2022] and UFO [GUIZZARDI, 2005]. Finally, core ontologies lie between foundational and domain ontologies, providing structural knowledge in a specific field that can span across different application areas in the same field. Therefore, higher-level ontologies can be used to support the development of low-level ontologies.

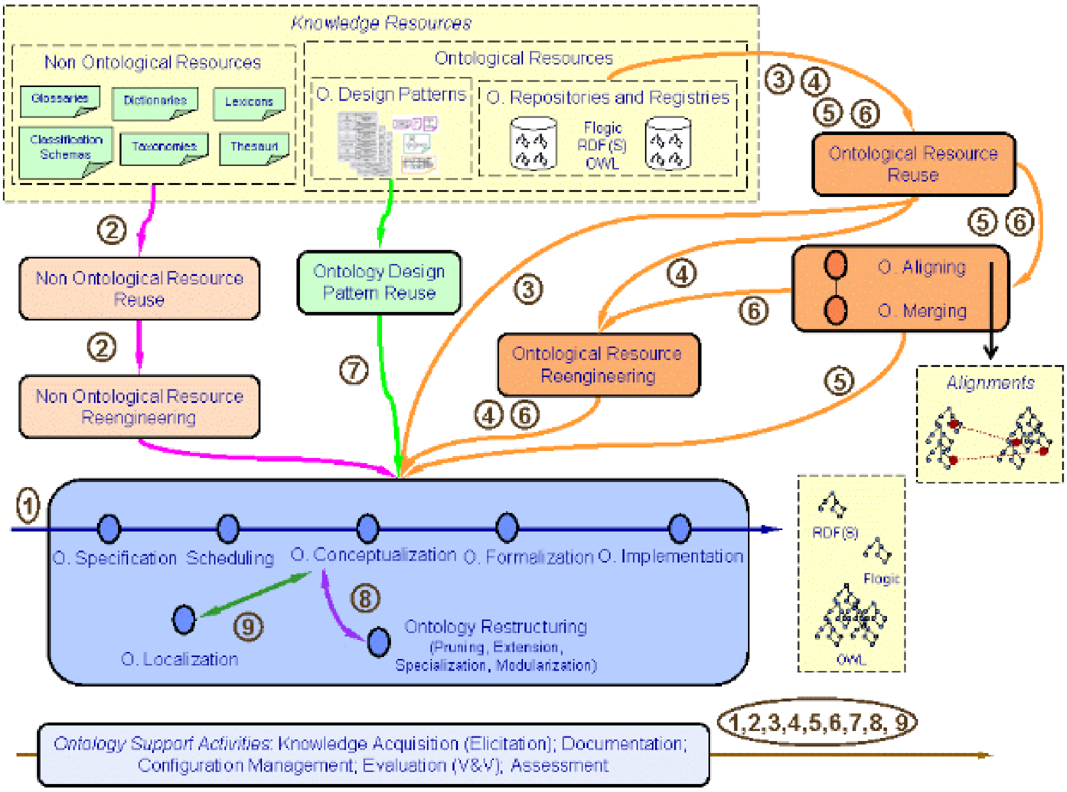
Regardless of the generality of the ontology, it should follow a development process known as ontology engineering. We chose the NeOn Methodology and the SABiO Approach among the available ontology engineering processes to guide our ontology development. The former is a highly cited process in academia that inspired many others. The latter materialized the ODCM concepts by clearly distinguishing two artifacts: the reference ontology, supported by a foundational ontology, and an operational ontology that machines can use.

2.3.1.1 The NeOn Methodology

The NeOn Methodology, proposed by Gómez-Pérez *et. al* [SUÁREZ-FIGUEROA; GÓMEZ-PÉREZ; FERNÁNDEZ-LÓPEZ, 2012; SUáREZ-FIGUEROA; GóMEZ-PéREZ; FERNáNDEZ-LóPEZ, 2015], aims to provide a development framework for ontology-based systems as an answer to the increasing complexity of the Semantic Web, represented by the large number of collaborative ontologies built by distributed teams which are embedded into ontology networks. These networks may either include existing ontologies, ontology mappings, and ontologies in continuous evolution, or ontologies whose development was based on reusing available ontological and/or non-ontological resources such as glossaries, lexicons, classification schemes, and thesauri, among others.

The methodology development was guided by four main principles: scope generality, technology independence, the precise definition of processes and activities, and easy assimilation by software developers and ontology practitioners. In this sense, the methodology encompasses nine different scenarios as the outcome of using a divide-and-conquer approach by decomposing the general problem of ontology development into different subproblems to be solved. Figure 8 shows each scenario decomposed into different processes and activities defined in the NeOn Glossary of Processes and Activities [SUÁREZ-FIGUEROA; GÓMEZ-PÉREZ, 2008]. Usually, these scenarios are combined to solve a specific need for ontology development.

Figure 8 – Scenarios for building ontology networks



Source: [SUÁREZ-FIGUEROA; GÓMEZ-PÉREZ; FERNÁNDEZ-LÓPEZ, 2012].

The *From specification to implementation* scenario is the first and most important development scenario since it is the backbone of ontology building using the NeOn Methodology. In this scenario, developers build the intended ontology from the ground without reusing existing knowledge resources. First, they simultaneously employ two activities: knowledge acquisition, which should endure the whole development, and the ontology requirements specification, where developers should specify the ontology requirements. The outcome of this last activity is a document called ontology requirements specification document (ORSD), where the following items should be described: the purpose, the scope, and the implementation language of the ontology network, the target group, the intended uses of the ontology network, and the set of requirements the ontology network should fulfill in the form of competency questions (CQs). Once this phase is completed, it is recommended that the terms appearing in the ORSD in available knowledge resources be investigated. The outcome of the investigation allows developers to know which resources can be elected for reuse. The authors suggest that, after executing these activities, developers should carry out the activities of conceptualization, formalization, and implementation by using other well-known frameworks such as METHONTOLOGY[LOPEZ et al., 1999] or On-To-Knowledge[STAAB et al., 2001].

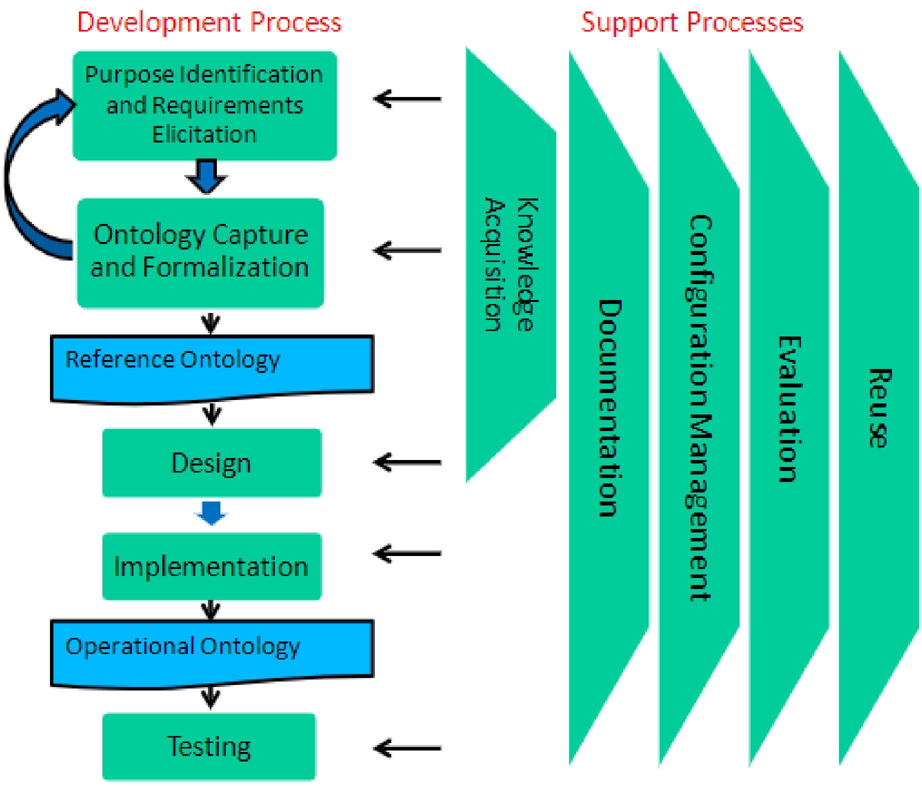
The second scenario (*Reusing and Re-engineering Non-Ontological Resources*) prescribes carrying out the non-ontological resource(NOR) reuse process. There, developers should decide, according to the ORSD requirements, which NORs can be reused in the ontology being developed. In this case, a re-engineering process should transform the selected NORs into ontologies. The *Reusing Ontological Resources* scenario is the third proposed scenario. Here, developers reuse existing ontological resources for building ontology networks. These resources can be used entirely, or only a subset of them, or only its ontology statements, depending on how frequently the collected terms in the ORSD appear. For instance, if the needed resources must be implemented in another language, developers can re-engineer following the fourth scenario (*Reusing and Re-Engineering Ontological Resources*). In this case, the re-engineering process may involve ontological resource reverse engineering, resource restructuring, and/or resource forward engineering. These activities can happen at different levels (specification, conceptualization, formalization, and/or implementation), and their results should be integrated into the corresponding activity of the first scenario.

The fifth scenario (*Reusing and Merging Ontological Resources*) deals with developers reusing and merging existing ontological resources to develop the envisioned ontology. This scenario arises when ontological resources in the same domain are selected for reuse, hoping to create a new ontological resource from two or more ontologies while possibly overlapping source ontological resources. In the *Reusing, Merging and Re-engineering Ontological Resources* scenario, developers follow the same sequence of activities of the fifth scenario. However, they can decide to re-engineer ontological resources instead of merging them as they are. The seventh scenario (*Reusing Ontology Design Patterns*) deals with reusing ontological design patterns to reduce the modeling complexities, aiming to speed up the modeling process or to check the adequacy of modeling decisions. The *Restructuring ontological resources* scenario is the eighth described scenario in the NeOn framework. In this scenario, developers should restructure ontological resources to integrate them into the built ontology network. It can be done by modularizing the ontology in different ontology modules, pruning unnecessary ontology branches, extending the base ontology with new concepts and relations, or specializing those branches that require more granularity and including more specialized domain concepts and relations. Finally, the ninth scenario (*Localizing Ontological Resources*) deals with ontology localization. Developers must adapt an existing ontology to one or various languages and culture communities to obtain a multilingual ontology.

2.3.1.2 The Systematic Approach For Building Ontologies - SABiO

The Systematic Approach for Building Ontologies (SABiO) is an ontology engineering framework proposed by Ricardo Falbo [FALBO, 2014]. Highly influenced by the NeOn Methodology, Falbo proposes a more concise ontology development framework with five phases: *Purpose Identification and Requirements Elicitation*, *Capture and Formalization*, *Design*, *Implementation* and *Test*. Each phase comprises several activities supported by several processes, as portrayed in Figure 9. Since Falbo adequately describes the phase activities and the supporting process in his work, we focus on briefly describing the development phases.

Figure 9 – SABiO's processes



Source: [FALBO, 2014].

The distinguishing feature of the approach is the differentiation of domain reference and operational ontologies. A domain reference ontology (or **reference ontology**) is defined as a particular conceptual model. In contrast, a domain operational ontology (or **operational ontology**) is a machine-readable implementation version of the reference ontology. Broadly, while the reference ontology is the focus of the first two development phases, the Design phase transforms it into an operational ontology. Finally, the implementation and testing of the operational ontology is the focus of the last two phases. It is important to note that the author suggests an incremental and iterative development rather than a sequential approach that a step-by-step presentation of the development phases may suggest.

At the *Purpose Identification and Requirements Elicitation* phase, the ontology developer should start identifying the purpose of building the ontology and where it should be used. Right after, she/he begins to elicit its requirements. These requirements can be classified as functional and non-functional requirements. Non-functional requirements refer to general aspects unrelated to the ontology content, such as reasoning performance and availability, maintainability, and implementation requirements. On the other hand, functional requirements refer to the content to be represented by the ontology. While developing an ontology, the competence questions approach is one of the tools used to derive the functional requirements. Gruninger [GRUNINGER, 1995] defines Competence Questions (CQs) as questions that the ontology should be able to answer, determining what is relevant to the ontology or, in other words, determining its scope. There are different strategies to derive such questions. The ontology developer can start decomposing complex questions into simpler ones (top-down approach) or, on the contrary, create simple questions that will later be composed into complex ones (bottom-up approach). Also, the developer can start writing domain-relevant questions that will be decomposed or composed later into simple or abstract ones (middle-out approach).

Next, at the *Capture and Formalization* phase, the main goal is to capture the domain conceptualization using competency questions. It is supported by the knowledge acquisition process, where domain experts and sources of consolidated knowledge (e.g., books, papers, international standards, and reference models, among others) are consulted. Then, the conceptual modeling activity starts, where concepts and relations are identified in the domain, combining the competency questions with the knowledge acquired from domain experts and other related sources. After organizing the domain concepts in taxonomies, the developer is ready to build the reference ontology. At this point, Falbo suggests that a foundational ontology should ground the reference ontology, providing a sound identification and organization of the domain elements. In this sense, he suggests using OntoUML, a UML class diagram profile incorporating ontological micro-theories from the Unified Foundational Ontology (UFO), a foundational ontology proposed by Giancarlo Guizzardi[GUIZZARDI, 2005]. This conceptual modeling language will be presented at Section 2.3.2. So, by the end of this phase, a reference ontology is delivered.

In some cases, delivering the reference ontology is enough, and the approach must no longer be followed. However, there are cases where an operational ontology must also be delivered based on the reference ontology. Hence, the ontology developer will deliver the operational ontology in the *Design* phase of SABiO. However, unlike the reference ontology, the operational ontology is designed and implemented in a machine-readable ontology language, focusing on guaranteeing desirable computational properties. Initially, the developer has to complement the list of technological non-functional requirements for the operational ontology and then define the environment in which it will be implemented. Once the environment is defined, she/he needs to review the ontology modularization drafted at the beginning of the project and define the ontology architecture based on technological non-functional requirements and the built environment.

In the last phases (*Implementation* and *Test*), the derived operational ontology is implemented in the chosen operational language and tested against several cases. Again, the competency questions play an important role in the overall ontology creation. While essential for gathering domain concepts and relations in the *Capture and Formalization* phase, here they are the ontology testing backbone. According to Falbo, a test case comprises a query in the implementation environment, a data instantiation according to the ontology being tested (input), and an expected result (output). In this scenario, a query is the materialization of a competence question. The ontology developer should run the test cases in different fragments, such as sub-ontologies and integrated parts until they reach the test of the whole ontology.

2.3.2 OntoUML and The Unified Foundational Ontology (UFO)

OntoUML is a modeling language conceived as a fragment of the UML 2.0 supported by the concepts of the Unified Foundational Ontology (UFO) [GUIZZARDI et al., 2015]. Over the years, many research, industrial, and government institutions worldwide have adopted it, creating a body of language patterns and anti-patterns [RUY et al., 2017]. As a UML profile, various existing UML modeling tools can be used, such as the Visual Paradigm Modeling tool, which, along with a proper plugin[9], can model UML classes along with UFO's meta-classes stereotypes. Therefore, OntoUML became a modeling language with formal and real-world semantics explicitly defined in UFO, whose formal syntactic constraints grammatically bound their set of valid models.

In recent years, UFO became one of the most successful foundational ontologies supporting ontology-driven conceptual modeling. Developed by Giancarlo Guizzardi and associates [GUIZZARDI et al., 2015], it gathers developments from other foundational ontologies such as GFO[LOEBE et al., 2022], DOLCE[BORGO et al., 2022], and the Ontology of Universals underlying OntoClean[GUARINO; WELTY, 2009] in a single coherent foundational ontology, being able to represent universals, particulars, endurants, and perdurants. It is usually presented in three 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 main concepts of UFO-A and UFO-B, the reification and truthmaking patterns, and the taxonomy of relations

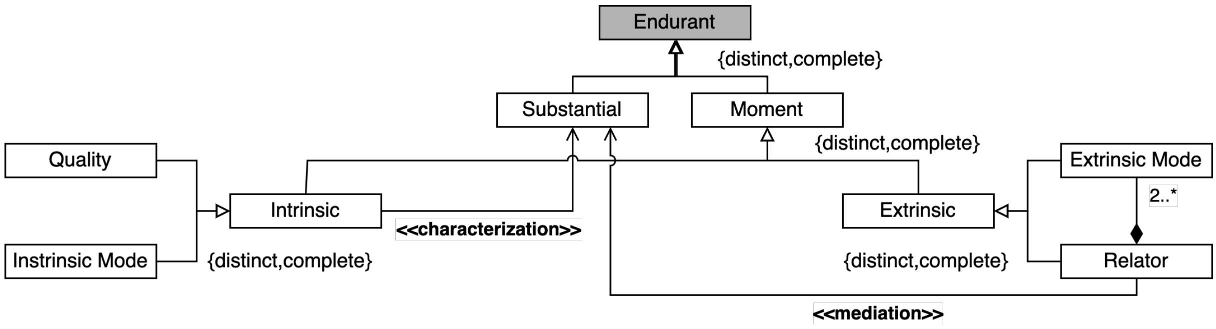
9 available at <https://github.com/OntoUML/ontouml-vp-plugin>

2.3.2.1 UFO's Theory Of Endurants

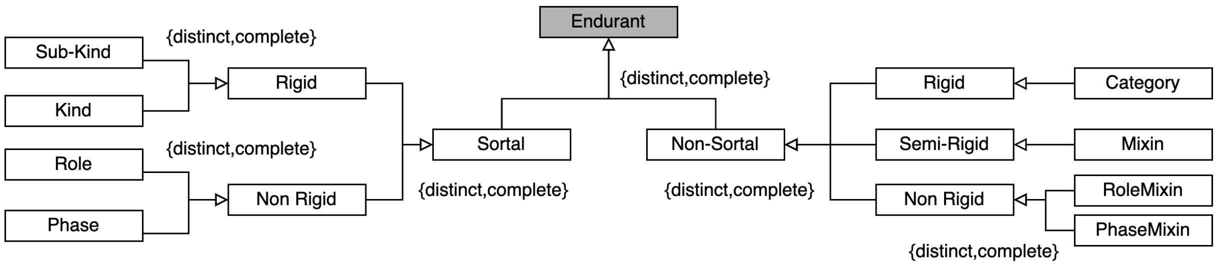
Although many conceptual modeling languages have artifacts that aim to model types whose instances are object-like entities, also known as Endurants, ontology-driven languages, such as OntoUML, enhance the distinction between types. Unlike traditional conceptual modeling languages, such as ER or UML, 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.

Figure 10 – Fragament A of the Unified Foundational Ontology (UFO)

(a) UFO-A taxonomy based on the principle of existential dependency



(b) UFO-A taxonomy based on the principle of identity



Source: Adapted and inspired by [FONSECA et al., 2019].

Figure 10a shows the taxonomy based on the Principle of Existential Dependency. As described in [FONSECA et al., 2019], 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, a particular relation between Substantials and Moments is 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. Finally, Moments are specialized into two types: **Intrinsic** and **Extrinsic** Moments. While Intrinsic Moments depend only on the individual that bears them to exist, Extrinsic Moments depend on another individual to subsist.

Intrinsic Moments are also specialized in **Quality** and **Intrinsic Modes**. According to [GUIZZARDI, 2005], "Modes are intrinsic moments that are not directly related to quality structures", which means it can not 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 or RGB scale, respectively. On the other hand, a headache or an ability to speak a foreign language are Intrinsic Modes as they can not be expressed in terms of a measurement unit. In addition, other Moments can describe them, such as intensity in the case of a headache. In this sense, a special inherence relation between Substantials and Intrinsic Moments is called **characterization**.

Extrinsic Moments are specialized in **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 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 Figure 10a).

From another point of view, Endurants are specialized based on the principle of Identity, as portrayed in Figure 10b. It distinguishes types that specify a single principle of identity to judge if an instance is the same as another instance or not and those that provide distinct identity principles. Moreover, it states that *while changes can undergo over an individual, his/her identity remains the same* [FONSECA et al., 2019]. Thus, **Sortals** are types of Endurants that hold a single identity principle while **Non-Sortal** types do not.

Sortals can be **Rigid** and **Anti-Rigid**. Instances of the Rigid type can not 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.

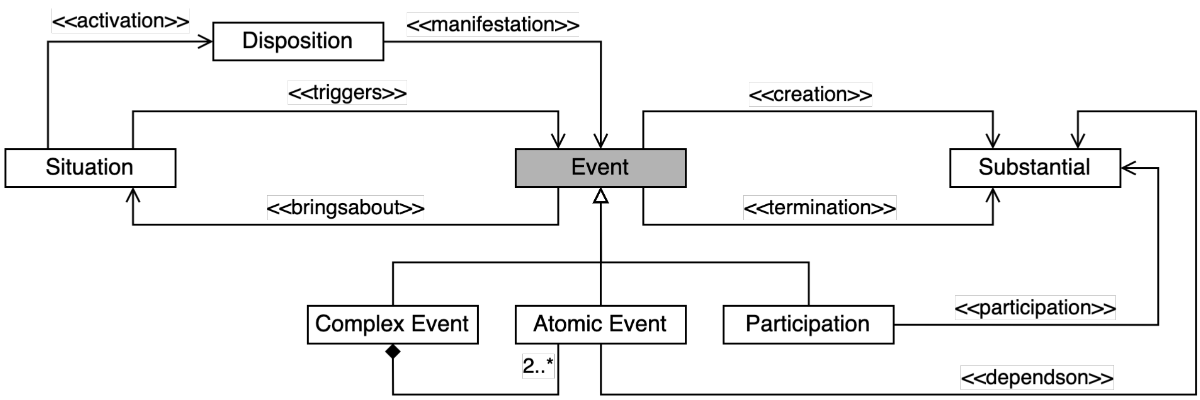
To clarify the above definitions, let us assume Person is a Kind, and that an instance of Person can be, biologically, a Man or a Woman. Thus Man and Woman may be Subkinds of Person. Also, Child and Adult are Phases that an instance of Person can assume, depending only on their intrinsic properties such 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. Like Sortals, Non-Sortals are distinguished by their rigidity. 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.

2.3.2.2 UFO's 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[10]. Figure 11 presents the main Perdurant concepts and the relationships between them and the Endurants concepts.

Figure 11 – Fragment B of the Unified Foundational Ontology (UFO)



Source: Adapted and inspired by [GUIZZARDI et al., 2013] .

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

The theory of Perdurants or the UFO-B fragment conceived by [GUIZZARDI et al., 2013] 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 only manifest 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.* [GUIZZARDI et al., 2013].

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 can not 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 [GUIZZARDI et al., 2013], 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 Figure 11). On the other hand, Complex Events can be decomposed, separating each part according to its dependent object or participant. Also, a portion of an Event exclusively dependent on a single object is called **Participation**. Moreover, the creation and destruction of Endurants 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 on which they depend, the temporal properties of Events define the temporal properties of objects. These temporal properties are similar to the qualities described in UFO-A. Hence, they can be mapped in a suitable quality structure or property value space, allowing several alternative quality spaces to be associated. 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.

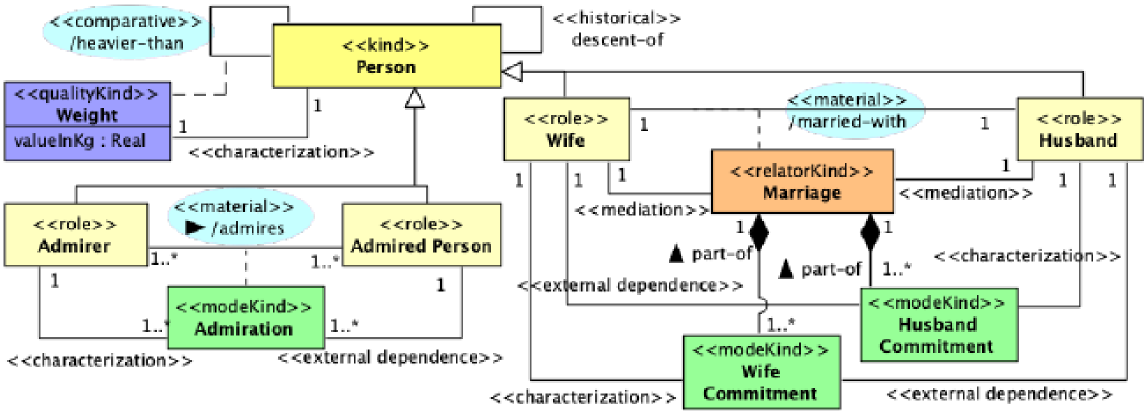
2.3.2.3 Taxonomy Of Relations

Describing entities and their relations are fundamental parts that any conceptual modeling approach must provide. According to Fonseca *et al.* [FONSECA et al., 2019], one of the goals that conceptual modeling researchers have been chasing over the years is to present a clear distinction between the ontological nature of relations. To accomplish that, many of them have been using the reification process as a way to talk about relations. This process can be defined as the *standard technique in conceptual modeling, which consists of including in the domain of discourse entities that may otherwise be hidden or implicit* [GUARINO; GUIZZARDI; SALES, 2018]. Like other researchers, Giancarlo Guizzardi used the reification approach to expose hidden relation characteristics while proposing the original version of UFO ontology [GUIZZARDI, 2005]. In this version, an entity called **relator** represents the reification of a relation between two relata. The relator mediates the relationship between two relata, becoming its truthmaker. This proposal for relation reification represented a great step for conceptual modeling as it allowed to put light on many practical problems such as disambiguation of cardinality constraints, transitivity of part-whole relations, and proper modeling of anadic relations, among many others [GUARINO; GUIZZARDI; SALES, 2018].

Consequently, Guizzardi proposed a taxonomy distinguishing relations types: material and formal. Material relations were formally defined as relations that presuppose the existence of a relator, composed of EDMs representing reciprocal obligations and commitments between relata, which are all historically dependent on a common external foundation event. On the other hand, formal relations were defined as not material. However, this classification was put in check due to systematic subversion of the language by UFO users, like reification in formal relations such as comparative relations and the recognition of single-side material relations. Other orthogonal relation distinctions, such as internal/external and descriptive/non-descriptive, were introduced to overcome this limitation. Fonseca *et al.* [FONSECA et al., 2019] describe internal relations as relations that hold in virtue of the intrinsic property of the relata, while external relations are the ones that are reducible to relevant properties of the relata. Looking at the other dimension, Guarino *et al.* [GUARINO; GUIZZARDI; SALES, 2018] define a descriptive relation as *a relation that holds in virtue of some qualities that are existentially dependent on one or both its relata*. In contrast, non-descriptive relations do not show such dependency. Adding those dimensions allowed researchers to produce a more detailed classification of relation types and a review of UFO's relation meta-categories.

Figure 12 provides an example that helps understand UFO's relation taxonomy and the related OntoUML relation stereotypes. The comparative relations among objects or events are the main representatives of **internal descriptive relations**. These relations are exclusively held in virtue of internal properties. For instance, the «comparative» stereotype

Figure 12 – OntoUML patterns for relations reification



Source: [FONSECA et al., 2019] .

in OntoUML decorates such relations holding between endurant types of the same kind (e.g. `Weight`), which may require the usage of a reification pattern to reveal their truthmakers. On the other hand, whenever a relation holds in virtue of at least one relational moment inhering in at least one relatum, they are considered as **external descriptive relations**. These relations can be single-sided whenever they hold in virtue of one or more moments inhering in just one relatum, or they can be multi-sided whenever they hold in virtue of at least two moments, each inhering in a different relatum. This last case represents the original conception of UFO's material relation. Figure 12 shows examples of both cases. On the left side, the `admires` relation is stereotyped as «material», supported by the `Admiration` EDM - its truthmaker -, which inheres in `Admirer` and is externally dependent on the `AdmiredPerson`. Note that there is no obligation or commitment from the `AdmiredPerson` towards the `Admirer`. On the right, we have the classical Marriage example, having reciprocal obligations and commitments between `Wife` and `Husband`, which composes the `Marriage` relator, the truthmaker of the `married-with` relation, also stereotyped as «material».

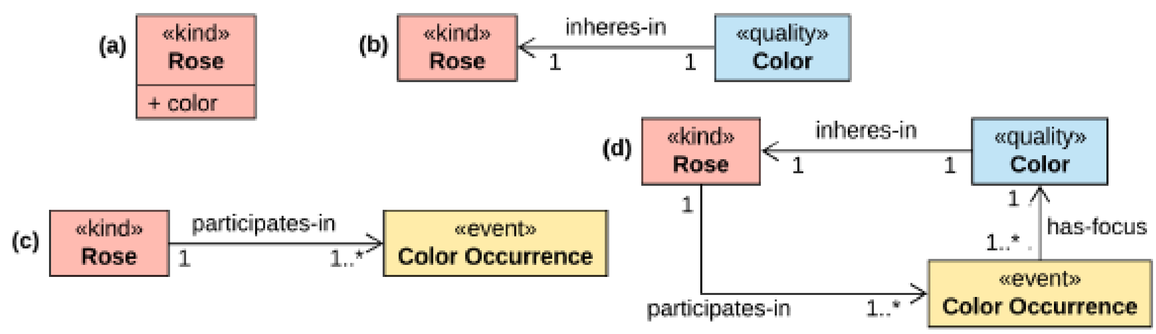
Internal non-descriptive relations represent different sorts of existential dependencies. For instance, OntoUML stereotypes with «characterization» relations representing the inherence between moments and their bearers. Associations stereotyped with «mediation» bind a relator to each endurant type mediated by it. In contrast, associations stereotyped with «external dependence» bind an externally dependent mode to some endurant on which its instances depend. Finally, the truthmakers of **external non-descriptive relations** are entities completely external to their relata. In other words, they do not inhere in them, are not parts of them, and do not participate in them. Figure 12 shows it using the `descent-of`, being stereotyped as «historical» in OntoUML.

2.3.2.4 Truthmaking Patterns

Guarino *et el.* [GUARINO; GUIZZARDI; SALES, 2018] present the concept of truthmakers (TM) as a solution for properly choosing what should be reified in a domain of discourse. They are entities responsible for the alleged truth of propositions that originate from transforming a language construct (typically, a predicate) into a domain element rather than a mere decision to expand the domain itself. In this sense, the authors propose a systematic approach to account for the various truthmaking patterns (TMPs) associated with different properties and relations. They also state that TMPs are the generalization of the well-known reification process in conceptual modeling since they account for the fact that, in some cases, *when we want to "talk" of a property or a relationship, we don't reify it directly, but we rather reify its TMs.*

Truthmakers are classified into two types: strong and weak. Strong truthmakers are TMs that make a proposition true due to its essential nature, while weak truthmakers turn a proposition true due to its actual nature. Thus, while a strong truthmaking relation holds essentially, a weak truthmaking relation holds contingently. Based on that, Guarino *et al.* [GUARINO; GUIZZARDI; SALES, 2018] proposes two general truthmaking patterns: partial, which can be weak or strong TMP, and full, as a combination of weak and strong TMPs. Due to the context of our research work, we shall describe only the TMPs for intrinsic moments and single-sided relations using examples. Other truthmaking expansions can be reached by using the exact mechanism.

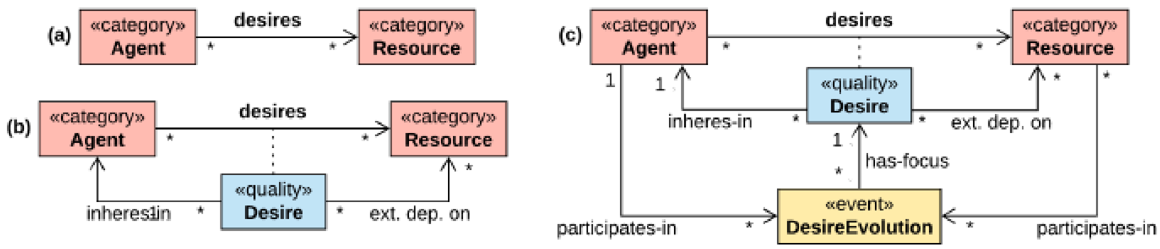
Figure 13 – Truthmaking patterns for intrinsic moments



Source: [GUARINO; GUIZZARDI; SALES, 2018] .

Figure 13 shows the truthmaking pattern process for a quality (an intrinsic moment). In Figure 13-a, the typical representation of the color property of a rose is expressed as an attribute whose value is mapped into a certain quality space. However, we must apply a truthmaking pattern to provide more information about the color of the rose color. In Figure 13-b, the weak TMP emerges when the quality is reified as a separate class, becoming a first-class citizen. On the other hand, in Figure 13-c, a strong TMP emerges because what is reified is the color occurrence event. Hence, the first reification makes it possible to describe how the quality interacts contingently with the world (e.g., how a person interacts with the rose, the color of a rose located in its corolla, among others). The second reification, however, provides spatiotemporal information (e.g., how long the redness of the rose lasted). According to Guarino *et al.* [GUARINO; GUIZZARDI; SALES, 2018], combining both partial TMPs provides the maximum expressivity a quality reification can get (Figure 13-d).

Figure 14 – Weak and full truthmaking patterns for single-sided relations.



Source: [GUARINO; GUIZZARDI; SALES, 2018] .

Likewise, Figure 14 shows the truthmaking pattern process for a single-sided external descriptive relation. Figure 14-a shows an attitudinal relation (`desires`) between an `Agent` and a `Resource`. However, to provide more information about the relation, we must reify it, like in Figure 14-b. Thus, the weak TM of a relation is one of the types accepted in UFO's ontology to become a truthmaker (an EDM or a relator). However, if we want to provide time-related information to the relation, we must reify the event which has focus on. Consequently, the full expressivity presented in Figure 14-c is accomplished by combining the weak and strong TMPs previously presented.

2.3.3 FAIR Principles

The FAIR principles were first presented by Wilkinson *et al.* [WILKINSON et al., 2016] as an effort to provide guidelines for enhancing the findability, accessibility, interoperability, and reusability of digital assets, particularly research data and metadata. By adhering to these principles, researchers can ensure their data is easily discovered, accessed, and understood by others, maximizing its potential for future use and collaboration. Each principle can be broadly described as follows:

Findability: Data should be discoverable through persistent identifiers and detailed descriptions using common vocabularies. This allows researchers to locate relevant datasets for their work efficiently.

Accessibility: Mechanisms should be in place to allow access to the data, with clear information on any restrictions or permissions required. This ensures researchers can obtain the data they need to reproduce or build upon existing studies.

Interoperability: Data and its accompanying metadata (descriptive information) should be formatted to be understood and integrated with other datasets. This promotes seamless exchange and analysis of data across different research projects.

Reusability: Data should be presented with clear documentation and contextual information to facilitate its reuse in future research endeavors. This allows researchers to interpret and leverage the data confidently for new discoveries.

Over the years, researchers and developers have been working on producing assessment tools to evaluate the FAIRness degree of research data, with the F-UJI[11][HUBER; DEVARAJU, 2021] and FOOPs[12] [GARIJO; CORCHO; POVEDA-VILLALÓN, 2021] as representatives available on the Web.

[11] available at <https://www.f-uji.net/index.php?action=test>
[12] available at <https://foops.linkeddata.es/FAIR_validator.html>

3 RELATED WORKS

Evaluating existing ontologies is an essential phase of an ontology-building process [FALBO, 2014; SUáREZ-FIGUEROA; GóMEZ-PéREZ; FERNáNDEZ-LóPEZ, 2015]. 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, two domain ontologies stand out for research to support a mobility management decision-support system based on semantic reasoning. The first one should represent the mobile wireless network elements involved in the handover process, and the second one should be able to represent network measurements to assist the same mobility process. The following sections show our research was conducted on these two domains.

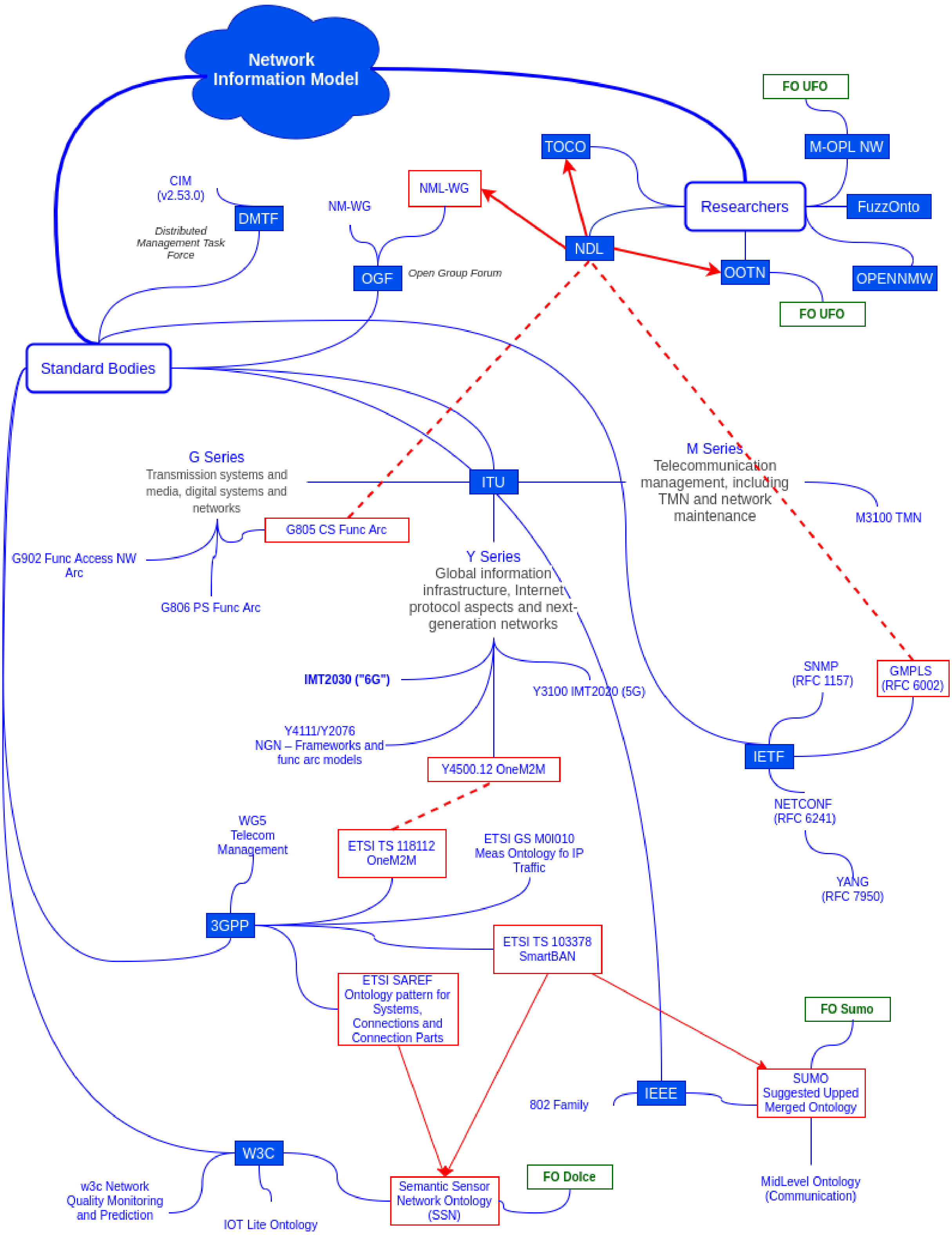
3.1 Network Ontologies

Our first attempt looking for solutions to the mobility management challenge in heterogeneous wireless networks was supported by the Google Scholar academic search engine[1] and the CAPES's academic research repository [2]. We used searching keywords like *always best connected*,*network selection*, *vertical handoff*, *vertical handover*, *network access* and *radio access network*, limiting searching window to retrieve academic artifacts between 2010 and 2020. The first repository retrieved around 1,500 related artifacts using these settings. After removing repeated entries and selecting them by title and abstract, we had 498 artifacts with known editors and publishers. The second repository returned 400 academic artifacts using the same searching criteria but adding the platform feature of selecting only pair-reviewed artifacts. After merging both results and removing duplicated entries, we started to search academic artifacts related to semantic reasoning and ontologies. At this point, we also looked at the telecommunication standard bodies described in Section 2.1.3 to find ontology specifications or products specific for describing network elements. Figure 15 shows a mind map representing the research network ontologies' result sets and how they were derived.

The network ontologies were divided according to their origins (blue boxes), i.e., if an ontology was proposed in the academic community or was recommended by any telecommunication or web standard bodies. The blue lines tie the research to their presented ontologies and the standard bodies to its recommendations. The red arrows indicate that an ontology was extended by another, as the dotted red lines mean that the connected ontologies had a meaningful influence on each other. Finally, the green boxes indicate if

[1] https://scholar.google.com/
[2] https://www-periodicos-capes-gov-br.ezl.periodicos.capes.gov.br/index.php?

Figure 15 – Network related ontologies research



Source: Prepared by author.

an ontology was created considering an upper ontology.

One of the most influential research efforts on ontologies for network description is the Network Description Language (NDL) [HAM et al., 2006; DIJKSTRA et al., 2008a; GHIJSEN et al., 2013]. 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 [ITU Telecommunication Standardization Sector (ITU-T), 2000a] and the IETF Generalized Multiprotocol Label Switching (GMPLS) [Network Working Group, 2015]. 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 [BARCELOS et al., 2016], 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 [ZHOU; GRAY; MCLAUGHLIN, 2019] 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 [AL-SAADI; SETCHI; HICKS, 2017] and OpenMobileNetwork [UZUN, 2018] also propose alternatives to it.

Similarly, the standard bodies have proposed their ontologies to represent network functions. The OneM2M ontology [ITU Telecommunication Standardization Sector (ITU-T), 2018] was proposed by the International Telecommunication Union (ITU) and detailed by the European Telecommunications Standards Institute (ETSI) [ETSI Partnership Project oneM2M, 2021], presenting a base ontology to describe machine-to-machine communication. Along with them, ETSI presented the SAREF core ontology [Technical Committee Smart Machine-to-Machine communications (SmartM2M), 2020] 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 [ALFREDO et al., 2010] is a core ontology that handles the domain of network performance measurement. It inspired works like the PingER [SOUZA et al., 2014], developed as a reference vocabulary

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

Table 1 – 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	Infrastructure Description	x		x			
ToCo	Infrastructure Description	x		x	x	x	x
FuzzOnto	Infrastructure Description					x	x
OpenMobileNW	Infrastructure Description				x	x	x
OneM2M	M2M Interoperability		x			x	
SAREF	IoT Interoperability		x			x	
PingER	Performance Measurement	x		x			
PingER-MOPL	Performance Measurement	x		x			
Our proposal	Mobility Management	x	x	x	x	x	x

and structure for round trip time (RTT) tests. [NUNES et al., 2015a] proposed an improvement of PingER ontology using the Measurement Open Pattern Language [BARCELLOS; FALBO; FRAUCHES, 2014], an ontology pattern language based on UFO's theory.

3.1.1 Gaps on Network Ontologies for Mobility Management

Evaluating all the previous recommendations and ontologies proposed by the academic community and the standard bodies, none seems adequate to deal with mobility management. To the best of the authors' knowledge, no network ontology properly represents one central 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, some issues 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 1 presents the researched ontologies and their coverage of these concepts, which are discussed as follows.

The neighborhood concept 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 [HAM et al., 2006; DIJKSTRA et al., 2008a; GHIJSEN et al., 2013] ontology deals with fixed networks, an communication infrastructure that does not need such concept. The FuzzOnto ontology [AL-SAADI; SETCHI; HICKS, 2017] states that it was created to support heterogeneous mobile networks, but the neighborhood concept does not appear. It only appears in ToCo [ZHOU; GRAY; MCLAUGHLIN, 2019] and OpenMobileNetwork [UZUN, 2018] 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 [Technical Committee 1, 2019] and by the ITU-R V.662-3 [ITU Radiocommunication Sector (ITU-R), 2005] 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 information transfer 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 [Technical Specification Group Services and System Aspects, 2021b] 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.

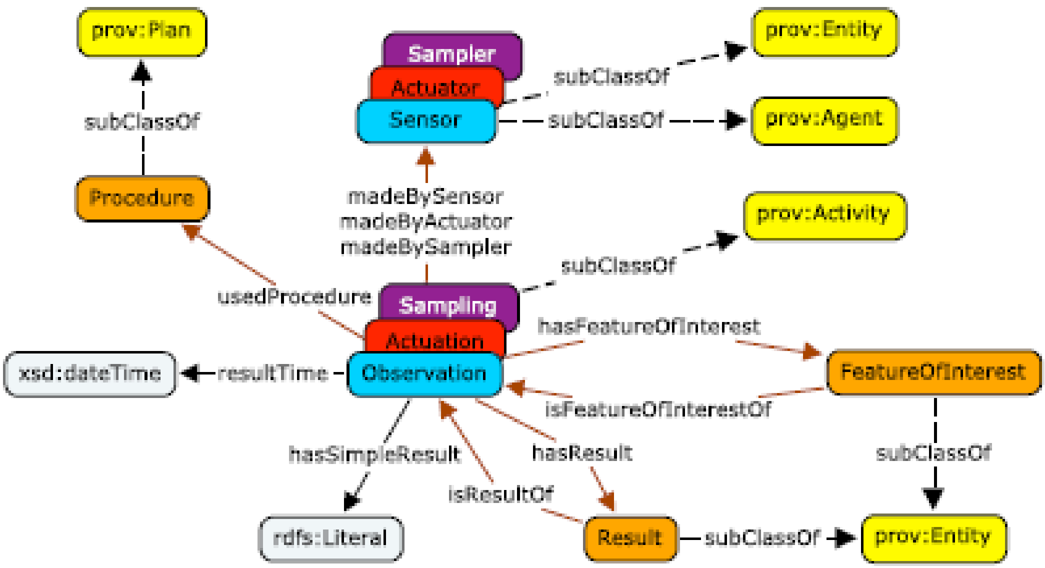
[4] <https://www.merriam-webster.com/thesaurus/link>
[5] <https://www.collinsdictionary.com/dictionary/english-thesaurus/link>

3.2 Measurement Ontologies To Support Mobility Management

The research on network ontologies showed the need for a new ontology to handle mobility management properly in mobile wireless networks. In addition to representing their elements and relationships, this new ontology must also provide ways to represent attribute measurements over time. Our research on supporting ontologies for measuring was biased in finding candidates supported by UFO or any other related foundational ontology. This effort aims to avoid possible ontology misalignment since OntoUML was a promising candidate to be our conceptual modeling language for describing the mobile network elements.

Thus, three ontologies designed for representing measurement caught our attention as candidates for reusing: the Sensor, Observation, Sample, and Actuator (SOSA) ontology[HALLER et al., 2018; JANOWICZ et al., 2019], the Measurement Ontology Pattern Language (M-OPL)[BARCELLOS; FALBO; FRAUCHES, 2014], and the Quality Value Attribution Situation described in the gUFO ontology [ALMEIDA et al., 2019].

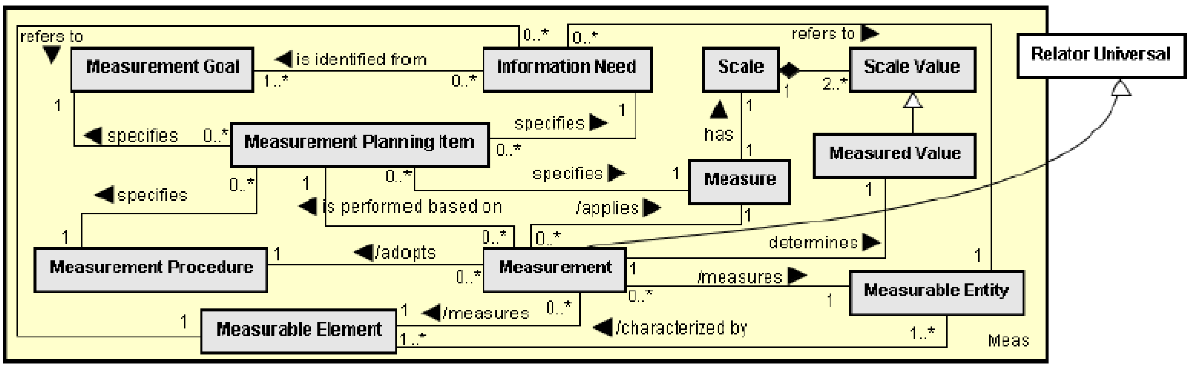
Figure 16 – SOSA's core structure aligned with PROV-O



Source: [JANOWICZ et al., 2019].

The SOSA ontology is a formal, lightweight, general-purpose specification for representing entities that perform observation, actuation, and sampling actions. The OGC and the W3C consortia developed it, and the DOLCE foundational ontology supports it [BORGO et al., 2022]. As shown in Figure 16, *Sensors* are entities able to reveal the value of a property that characterizes other entities known as *Feature of Interest*. The process or act of determining such values is called an *Observation*, which leads to a result represented either by a literal (*SimpleResult*) or by a resource (*Result*). Also, the ontology distinguishes how the acting agent carries out the result of an act. While it uses the object property *PhenomenonTime* to represent the time that the *Result* of an act applies to the *Feature of Interest*, the data property *ResultTime* specifies the instant of time when the act was completed. The sequence of instructions to guarantee that the related actions are reproducible and representative is described in an observation's *Procedure*. In certain circumstances, *Observations* may not be carried out on the entire feature. Instead, they were carried out using *Samples*. Like *Observations*, *Sampling* can be specified by a standalone *Procedure* or part of an observation procedure that determines how to obtain the samples. Finally, observations can trigger actions called *Actuations*, performed by entities called *Actuators*. All entities playing the roles of Sensors, Samplers, or Actuators can be mounted on a *Platform*.

Figure 17 – MOPL's measurement pattern.

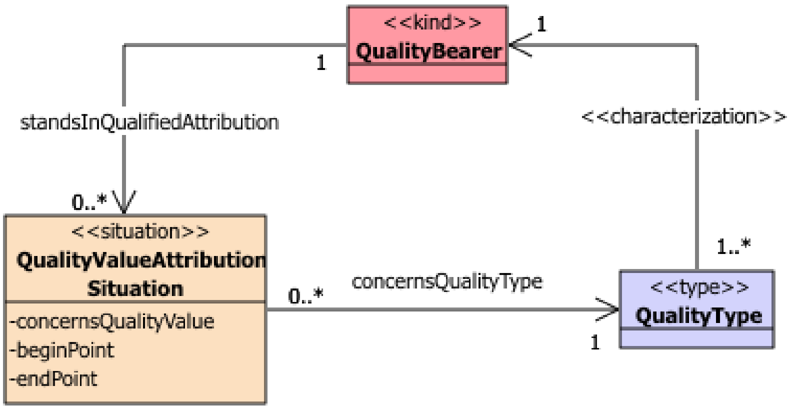


Source: [BARCELLOS; FALBO; FRAUCHES, 2014].

The Measurement Ontology Pattern Language (M-OPL) provides an adaptable framework for conceptualizing and representing measurement across diverse domains. Guided by UFO, it is organized into six pattern groups: *Measurable Entities*, *Measures*, *Measurement Units*, *Measurement Procedures*, *Measurement Planning*, and *Measurement & Analysis*, whose goal is to deal with the process of data collection and analysis, as shown in Figure 17. In this pattern, *Measurement* is performed based on a *Measurement Planning Item*. It measures a *Measurable Element* of a *Measurable Entity* by applying a *Measure* and adopting a *Measurement Procedure*. The result is a *Measured Value*. A *Measured Value* refers to a value of the measure *Scale*. Thus, *Measured* Value can be seen as the role played by a *Scale Value* when associated with a particular *Measurable Element* in a particular measurement. The *Measurement* is meta-categorized as a UFO's Relator Universal since it connects the entities involved in a measurement.

The Quality Value Attribution Situation (QVAS) is a pattern presented as part of gUFO's ontology [ALMEIDA et al., 2019], a lightweight implementation of UFO. It is one of the specializations of the UFO *Situation* concept, representing certain entities' configurations that can be comprehended as a whole [ALMEIDA; COSTA; GUIZZARDI, 2018]. According to gUFO developers, the QVAS goal is to represent a specific situation when keep-

Figure 18 – The quality value attribution situation pattern from gUFO



Source: Adapted from [ALMEIDA et al., 2019].

ing track of quality values over time is necessary. A *gufo:QualityValueAttributionSituation* can have multiple instances simultaneously, all standing in a unique mutable quality bearer. The pattern presented in Figure 18 offers an object property to identify the quality type being tracked (*gufo:concernsQualityType*) and a data property (*gufo:concernsQualityValue*) to hold the attributed value.

3.2.1 Shortcomings On Reusing Measurement Ontologies

We evaluated the measurement ontologies candidates for reuse using the following criteria: (i) **availability**, to verify if the ontology to be reused is accessible; (ii) **foundational ontology alignment**, to understand how the ontology concepts are grounded in their respective foundational ontologies and how they align with UFO concepts and (iii) **representation**, to understand how measurement is represented according to the foundational concepts of the ontology, distinguishing who bears the measurement result and if the measuring device is represented.

Using the gUFO's Quality Value Attribution Situation would be the most straightforward reuse since it is already part of UFO's lightweight implementation. It avoids aligning the foundational concepts since we foresee using the same foundational ontology to describe mobile wireless networks. However, the pattern is anchored around **UFO's Situation** concept, which can not be mistaken with **UFO's Event** concept. The vocabulary description for the Measurement concept suggests that it represents an act, a perdurant categorized as an Event in UFO. Although it is not clear in gUFO's documentation for this pattern, we infer that the *gufo:QualityValueAttributionSituation* concept may represent the result of the act of attributing a value to a quality, not the act itself. This inference is reinforced by looking at the relation between events and situations since the former *bringsAbout* the latter [GUIZZARDI et al., 2013]. In this pattern, this particular type of situation acts as a binding agent holding the quality being measured and its assigned value at a specific time. Unfortunately, there is no representation of the measuring device.

Another possible straightforward reuse that would avoid any ontology alignment effort is the M-OPL ontology [BARCELLOS; FALBO; FRAUCHES, 2014] since it also uses UFO as its foundational ontology. However, it is not available for direct use as an ontology pattern. Instead, it serves as a developing blueprint for UFO-supported measurement ontologies. Initially, the measurement concept was conceived as a UFO's Relator, a categorization for entities able to bind other entities. Although many reference ontologies were proposed considering this initial conceptual view [NUNES et al., 2015b; RICHETTI; BAIAO, 2018], later research efforts and developments changed it, now categorizing a Measurement as a **UFO's Event** [SANTOS et al., 2019; CAMPOS; REGINATO; ALMEIDA, 2019; SANTOS, 2021]. These later research efforts also brought the measuring device representation. Like gUFO's Quality Value Attribution Situation, the Measurement concept in M-OPL acts as the binding entity holding the quality and its assigned value at a specific instant in time.

SOSA, a well-known publicly available W3C ontology, is dedicated to assigning values to Observations, which serve as a proxy for measurement. Created using DOLCE as its foundational ontology, Observations are categorized as DOLCE Events, following the ontology alignment approach with other well-known ontologies such as OBO-E and PROV-O. Although UFO and DOLCE are different foundational ontologies, the development of the former was inspired by the latter. This close relationship between the two foundational ontologies suggests the potential for a concept alignment between UFO and DOLCE, as portrayed in Table 2, using SOSA's main entities as the comparison elements between the two foundational ontologies.

Table 2 – Aligning DOLCE and UFO concepts using SOSA entites for comparison

SOSA	Type	DOLCE	UFO
sosa:Procedure	subclass of	dul:Method	gufo:Event
sosa:Sensor	subclass of	dul:Object	gufo:Substantial
sosa:Observation	subclass of	dul:Event	gufo:Event
sosa:ObservedProperty	subclass of	dul:Quality	gufo:Quality
sosa:Platform	subclass of	dul:Object	gufo:Substantial
sosa:FeatureOfInterest	subclass of	owl:unionOf (dul:Event dul:Object dul:InformationEntity)	owl:unionOf(gufo:ConcreteIndividual gufo:AbstractIndividual)
sosa:Result	subclass of	owl:unionOf (dul:Region dul:Object)	owl:unionOf(gufo:ConcreteIndividual gufo:AbstractIndividual)

Differently from the gUFO's Quality Value Atributtion Situation pattern and M-OPL, SOSA provides different ways to map the result of a quality observation. It can map it directly to its value or to an entity called *Result* that can hold the assigned value. SOSA also provides two different ways to represent time. An Observation has a *resultTime* data property, which is interpreted as the point in time that the result of the Observation is delivered, and a *phenomenonTime* object property, which is interpreted as the period when the act unfolds. Finally, the measuring device in SOSA - the Sensor - is the focal element of the ontology.

Table 3 summarizes the coverage of the selected measurement ontologies according to our analysis criteria. The first row of Table 3 refers to the availability criteria, while the second and third rows refer to the foundational ontology alignment criteria. The remainder of the rows refer to the representation criteria.

Table 3 – Comparision between measurement ontologies features

Ontology Feature	SOSA	M-OPL	QVAS	Our Proposal
Availability	Yes	No	Yes	Yes
Foundational Ontology Support	DOLCE	UFO	UFO	UFO
UFO Alignment	Partial	Total	Total	Total
Measurement Meta-Class	dul:Event	gufo:Event	gufo:Situation	gufo:Event
Measurement Result Mapping	dul:Region $\cup$ dul:Object	gufo:Event	gufo:Situation	gufo:Mode
Measuring Device Entity	Yes	Yes	No	Yes

In summary, all the evaluated measurement ontologies have the same approach for mapping the measurement result: they directly map it to the measurement action. However, based on recent studies of reification patterns ([GUARINO; GUIZZARDI; SALES, 2018]), we argue that this direct mapping is not recommended, at least in the conceptual modeling phase. Thus, we propose that the measurement action, the measured quality, and the measurement result should be represented separately and keep their natural mapping throughout the ontology development process.

4 REPRESENTING MOBILITY MANAGEMENT IN MOBILE COMMUNICATION NETWORKS

This chapter aims to provide a reference ontology capable of adequately characterizing the entities and relations involved in the mobility management of mobile communication networks. The following sections describe the purpose of identifying the foreseen reference ontology, its requirements, the knowledge capture, and the derived conceptual models. We follow the SABiO approach described in Section 2.3.1 to derive such artifacts, using particular NeOn guidelines where SABiO was not specific.

4.1 Purpose Identification

Building an ontology to represent the elements and relationships on a mobile wireless network provides a semantic-based reasoning tool as part of possible solutions for a decision-support system designed to handle mobility management in a heterogeneous mobile wireless network.

Although not exhaustive, we foresee the following list of handover decision use cases where the ontology can help, such as (i) providing ubiquitous coverage with seamless connection; (ii) providing adequate service level; (iii) saving power consumption of the handset battery ; It is important to point out that such cases can be used simultaneously. It is out of the scope of this work to investigate the priority among them.

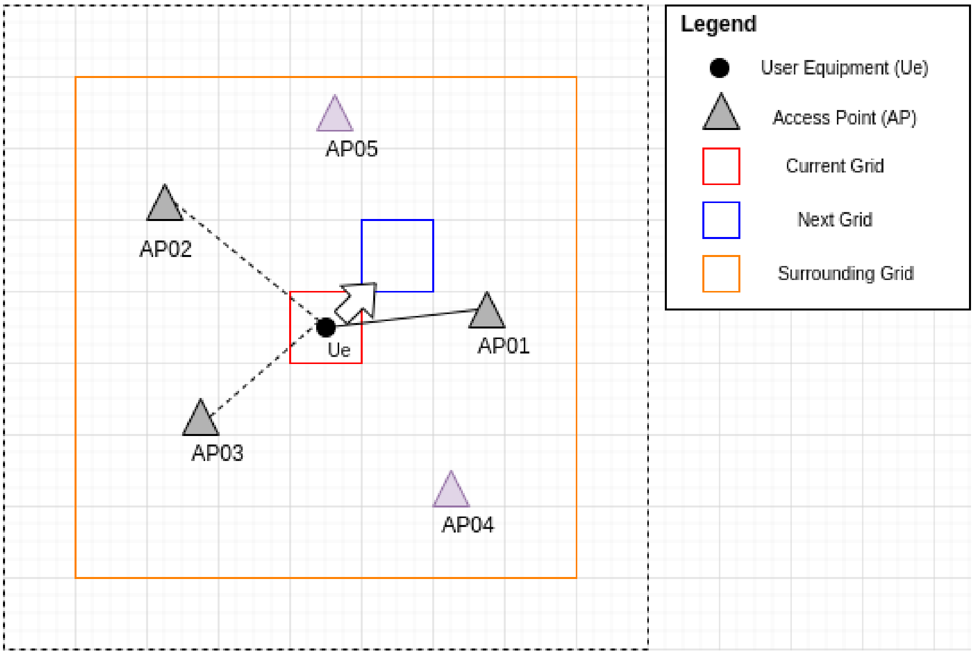
Finally, the intended user of the proposed ontology is primarily the mobile wireless network entity responsible for managing mobility, like the MME node in the 3GPP 4G network, as shown in Figure 7, or the Authorization and Mobility (AMF) function in the 3GPP 5G network. However, the desired ontology development intends to represent any network node capable of reasoning, such as a cognitive radio.

4.2 Functional Requirements

The functional requirements of an ontology can be derived using the competency questions (CD). We used the intended use cases described in Section 4.1 as the starting point for writing user stories, our source for formulating the competency questions. This section describes the *Providing Ubiquitous Coverage with Seamless Connection* scenario and the related top-down competency questions and their dependencies (CQD) for exemplification. The complete set of top-down competency questions derived from the remaining scenarios is presented in Appendix B.

The primary goal of a mobile wireless network is to maintain its connection with the handset or user equipment (Ue) through one of its access points (AP). The mobile network uses the handover process described in Section 2.1.6 to accomplish that. From the user's point of view, his handset is always connected to the mobile network, and the process of moving between APs is transparent. Considering the Always Best Connected & Served scenario, the goal of the mobile wireless network is to provide ubiquitous coverage with a seamless connection, regardless of the radio access technologies (RAT) available. In this scenario, we infer that the Ue's capacity to operate multiple RATs and the necessary interoperability between them is given.

Figure 19 – Ubiquitous coverage and seamless connection scenario



Source: Prepared by author.

Figure 19 presents a common scenario in a heterogeneous mobile network. AP01, AP02, and AP03 (gray triangles) share the same radio access technology (RAT), while AP04 and AP05 (light-gray triangles) share another RAT. In this case, Ue can attach itself to both RATs and is connected to the mobile network through a serving AP (AP01) and moving inside a geographic area (dotted square). It constantly monitors the received signal from its serving AP - the received serving signal. Whenever it becomes lower than a configured handover threshold plus a configured handover hysteresis, it starts the handover process by monitoring the received signal from surrounding APs declared as its neighbors (neighbors signals). This is the case in the scenario pictured in Figure 19, when the received serving signal deteriorates when Ue moves from the red grid to the blue grid, triggering the handover process.

Once the Ue selects the strongest signal from one of the serving AP's neighbors and no issues regarding the targeted AP's capacity to handle a new connection are found, this new AP begins to handle the Ue connection with the mobile network. Therefore, this neighbor AP becomes the new Ue's serving AP, and the former serving AP becomes a neighbor AP. If a mobile network operates only with one RAT, the handover process is straightforward and less prone to interruptions (drop calls). However, when it needs to deal with multiple RATs, the process becomes slower and prone to errors as the Ue needs to switch between RATs while running the handover process, even for a few milliseconds, to scan other frequencies and get basic information about these other RATs. The more the Ue has different and available RATs, the slower the handover process will become, becoming too long to allow a smooth handover and, in the worst case, interrupting the connectivity with the mobile network.

Table 4 – Competency questions - ubiquitous coverage

CQ	**Question**	**CQD**
1	Is the Ue attached to the best-serving AP for the ubiquitous coverage scenario?	2,3,4
2	Is the received signal strength from the serving AP lower than the handover threshold?	14,15
3	Is the received signal strength from the serving AP's neighbors greater than that from the serving AP?	16
4	Would there be any received signal strength that is higher than that currently received and would be generated by an AP that shares the same RAT as an inactive communication board in the Ue?	5,14,10
5	Which access points share the same RAT as the inactive communication cards in the Ue that would generate signals whose received power would be higher than that currently received?	6
6	What nearby APs share the same RAT as the inactive comm boards?	7,12
7	What RATs do the inactive communication boards in the Ue use ?	9
8	Which communication board is active ?	9
9	Which communications boards are available for this Ue's IMEI ?	11
10	Where is the Ue heading?	12,13
11	What is Ue's IMEI?	
12	What is the current Ue's position?	
13	What is the last Ue's position?	
14	What is the current strength of the received serving signal?	
15	What is the configured handover threshold?	
16	What is the strength of the received signals from the serving AP neighbors?	

However, the handover process can be fulfilled with richer and better information about the mobile network as an alternative for scanning frequencies for different RATs. Let us assume that Ue sends its position periodically, where the mobility management decision support system can constantly evaluate the most adequate attachment to the mobile network. Along with the position information, the Ue can send other data, such as the serving and neighbor received signal properties like strength (or power), operating frequency, and operating bandwidth. It can also send the Ue's maker identity (e.g., cell phone's IMEI), the current battery level, etc. For instance, with the makers' identity of the Ues, it is possible to evaluate how many network interfaces and RATs are available. Together with the position information, it is not only possible to establish where the Ue is (red square) and where it is heading (blue square) but also to evaluate all the surrounding APs (and their RATs) that the Ue did not previously scan. The surroundings to retrieve the unknown APs can be defined by a search ring (orange square) configured by the geographic clutter type (e.g., urban, suburban, rural). Table 4 shows the competency questions extracted from this scenario.

4.3 Ontology Capture and Formalization

According to the SABiO development approach, we can capture the main elements and relationships of our intended network reference ontology at this phase. The following sections show our domain conceptualization based on the competence questions generated so far, supported by consolidated knowledge based on classic books in the domain ([TANENBAUM; WETHERALL, 2011; KUROSE; ROSS, 2016]) as well as on the several telecommunications standard bodies recommendations, especially the ones dedicated to vocabulary definition.

One of SABiO's recommendations at this phase is to use a foundational ontology to support the development of reference ontologies. Among some well-known foundational ontologies such as DOLCE [BORGO et al., 2022], SUMO [NILES; PEASE, 2001], GFO [LOEBE et al., 2022] and BFO [OTTE; BEVERLEY; RUTTENBERG, 2022], we chose the Unified Foundational Ontology as our supporting upper ontology. There are two clear advantages to using UFO in this work over others. First, there is a wide supporting group of researchers and practitioners helping each other to use it properly. Also, thanks to the development of a plugin[1] by UFO researchers to work with the Visual Paradigm Modeling Tool [2], ontology developers are able not only to design a reference model with automatic syntactic validation according to UFO theories but also to export OntoUML-based class diagrams as operational ontologies written in OWL. This last feature saves developers time by delivering an operational ontology ready to be tested in ontology-driven tools.

[1] available at <https://github.com/OntoUML/ontouml-vp-plugin>
[2] available at <https://www.visual-paradigm.com/download/community.jsp>

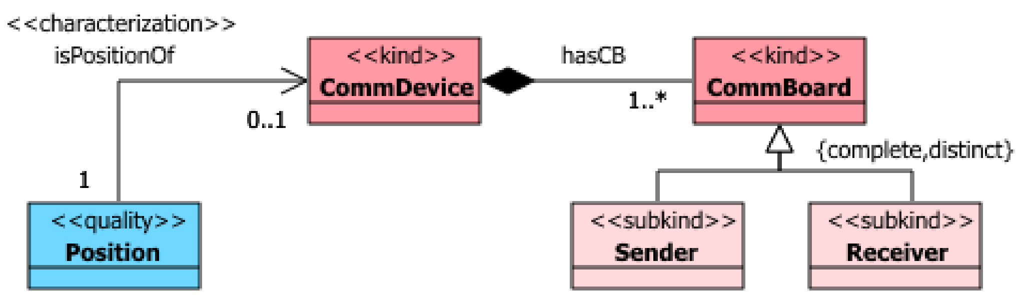
4.3.1 Nodes and Links Characterization

The vocabulary recommendations converge to define communication as the process of transferring information according to agreed conventions [ITU Radiocommunication Sector (ITU-R), 2005; Technical Committee 1, 2019; Telecommunications Industry Association, 2022]. 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 the analyses conducted by Barcelos using OntoUML to describe fixed communication networks [BARCELOS et al., 2011; BARCELOS et al., 2016], we used the same conceptual modeling language to improve our understanding of which entities, relationships, and processes are involved in a communication scenario.

4.3.1.1 The Taxonomy of Communication Boards

Several recommendations of the standard bodies suggest how communication entities transfer information between them. Recommendations ITU-R V.662-3 and IEC 60050.701 [ITU Radiocommunication Sector (ITU-R), 2005; Technical Committee 1, 2019], define `Signal` as *a physical phenomenon one or more of whose characteristics may vary to represent information.* Differently, the ITU-T recommendation Z.100 [(ITU-T), 2021] 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 [Telecommunications Industry Association, 2022] provides several definitions for `Signal`, one of them as *a detectable transmitted energy that can be used to carry information.* Hence, the communication between two entities occurs when a `Signal`, which may represent `Information`, is generated and transmitted by an entity defined as a `Sender` and is detected by another entity defined as a `Receiver`. Although many different real-world entities could be considered communication entities, such as the elements of acoustic systems or even human hearing and speech systems, the scope of this work restricts them to the set of electronic devices able to transmit and/or receive electromagnetic `Signals`.

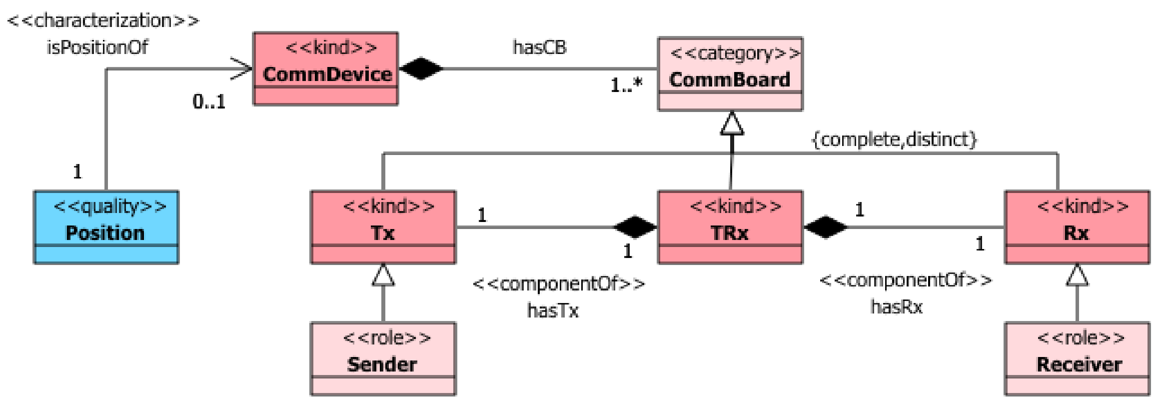
Figure 20 – `Sender` and `Receiver` as subkinds of `CommBoards`



Source: Prepared by author.

Unfortunately, giving a meaningful name to characterize these communication entities was not trivial. For instance, many other network ontologies named them as `Interface` [HAM et al., 2006; DIJKSTRA et al., 2008b; GHIJSEN et al., 2013; ZHOU; GRAY; MCLAUGHLIN, 2019]. However, the captured knowledge revealed that this term is semantically overloaded. It can refer either to a physical device or communication boundary between two communicating layers as depicted in Section 2.1.4. Other terms like `Device` and `Card` were also considered, but the same semantic overload was found in the academic literature and several vocabulary recommendations. Thus, the communication entities in this work are defined as communication boards (`CommBoard`)s, which can be part of other entities defined as communication devices (`CommDevice`)s being characterized by their `Positons`. Figure 20 shows the outcome of this first modeling approach.

Figure 21 – `Sender` and `Receiver` as roles of `Tx` and `Rx`

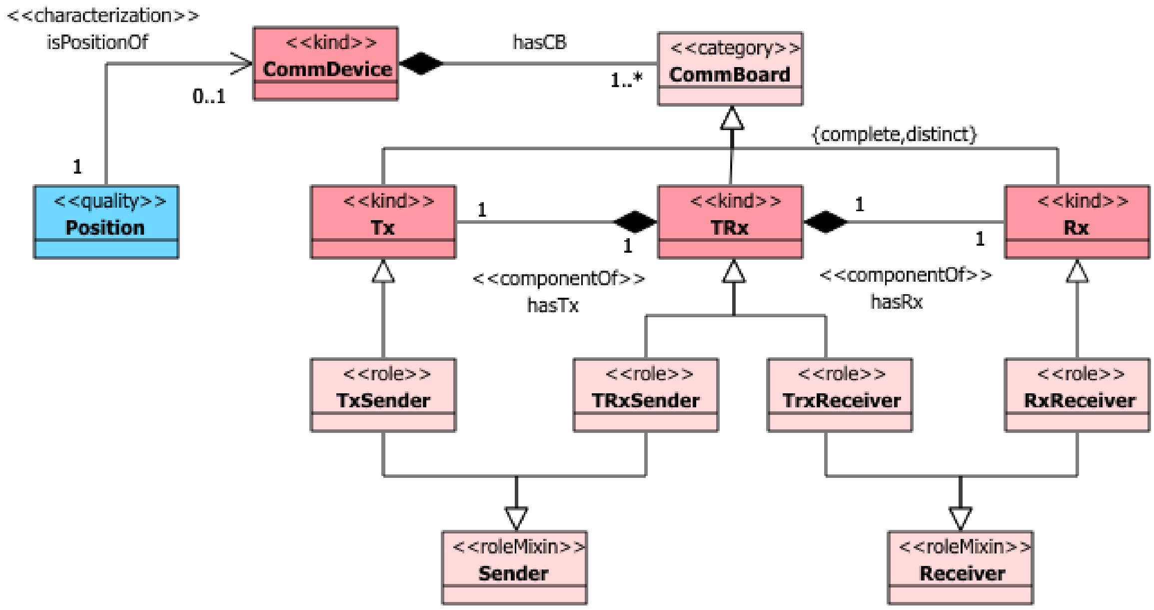


Source: Prepared by author.

Although the previous definitions suggest that `Sender` and `Receiver` are subkinds of `CommBoard`, which gives them a rigid characteristic, other captured knowledge shows it differently. The description of how simplex and duplex communications take place in Section 2.1.2 shows that there are communication entities that only transmit, others that only receive, and others that are capable of transmitting and receiving. Therefore, due to this anti-rigid behavior, `Sender` and `Receiver` become roles that `CommBoard` may play. Moreover, Section 2.1.2 suggests that `CommBoard` is a category of communication entities which can be specialized in three distinct entities: a transmitter (`Tx`), which has only a transmitting circuit; a receiver (`Rx`), which has only a receiving circuit; and a transceiver (`TRx`), as a composition of one `Tx` and one `Rx`. In this case, `Sender` is the role a `Tx` can play while `Receiver` is the role a `Rx` can play. Figure 21 presents this modeling outcome.

Nevertheless, the modeling approach in Figure 21 imposes the representation of a `Tx` and a `Rx` whenever a `TRx` needs to play the role of `Sender` and `Receiver`. This approach prevents representing `TRx` as a whole while playing these roles, a representation often found while reviewing the captured knowledge. Figure 22 presents an alternative to overcome

Figure 22 – `Sender` and `Receiver` as a category of roles played by `Tx`,`Rx` and `TRx`



Source: Prepared by author.

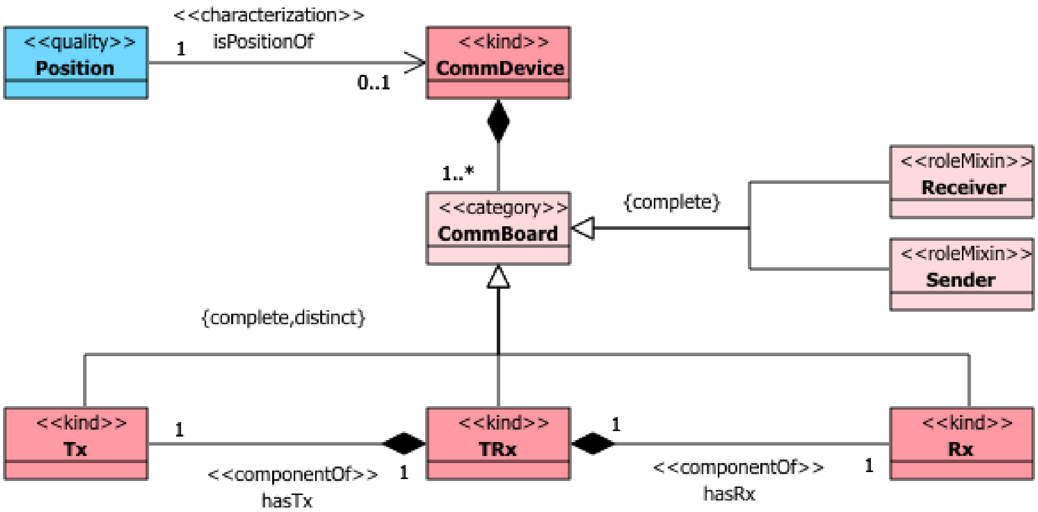
such limitations. Now, `Tx` plays the role of `TxSender` and `TRx` plays the role of `TRxSender`. Both roles are specializations of a broader category of roles called `Sender`. Likewise, `Rx` plays the role of `RxReceiver` and `TRx` plays the role of `TRxReceiver`. Like before, both roles are specializations of a broader category of roles called `Receiver`. Unfortunately, this modeling approach allows the representation of the same roles as they were distinct entities. To avoid this, Equations 4.1 and 4.2 prevent a `TRx` represented by the composition of a `Tx` and a `Rx` to play the roles of `Sender` and `Receiver`.

$$\forall a, b(TRx(a) \wedge Tx(b) \wedge hasTx(a, b)) \rightarrow \neg Sender(a) \tag{4.1}$$
$$\forall a, b(TRx(a) \wedge Rx(b) \wedge hasRx(a, b)) \rightarrow \neg Receiver(a) \tag{4.2}$$

Finally, Figure 23 shows an equivalent variant of the model proposed in Figure 22. This distinct approach for modeling rolemixins is proposed by Ruy *et al.* [RUY et al., 2017]. Nevertheless, this approach allows representing `Receiver` as a role of `Tx` and `Sender` as a role of `Rx`, a situation that must not be allowed. To keep this concise representation, two new restrictions are added: Equation 4.3 forbids a `Tx` to play the role of a `Receiver` and 4.4 forbids a `Rx` to play the role of a `Sender`.

$$\forall a(Tx(a) \rightarrow \neg Receiver(a)) \tag{4.3}$$
$$\forall a(Rx(a) \rightarrow \neg Sender(a)) \tag{4.4}$$

Figure 23 – Communication board taxonomy using succinct rolemixin variant

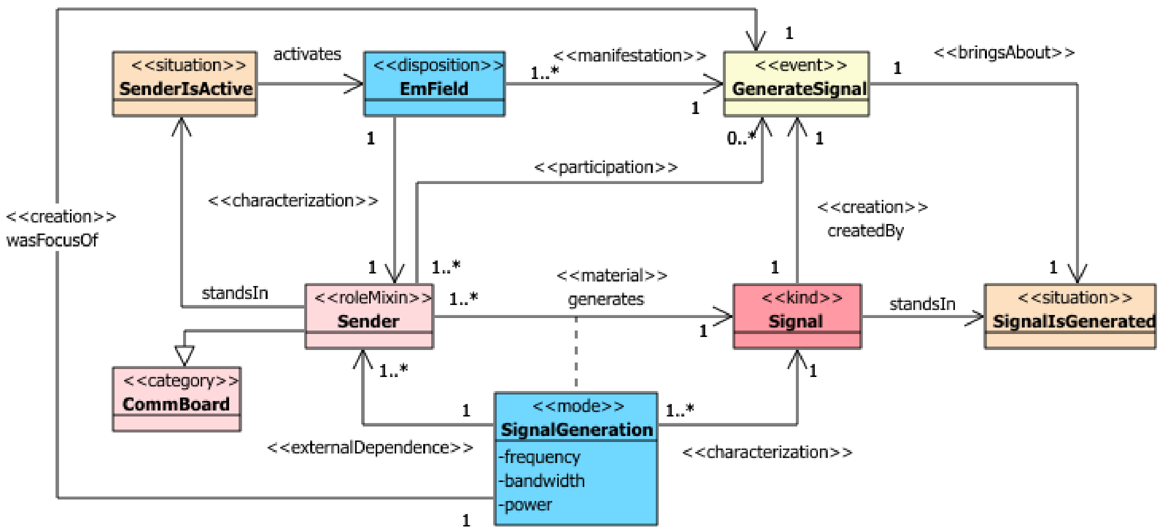


Source: Prepared by author.

4.3.1.2 The Basic Bonding Between Transmitters and Receivers

Let us consider a simple wireless communication scenario where there are only two `CommBoards`: one `Tx` and one `Rx`. Figure 24 shows the beginning of the bonding process between these two entities.

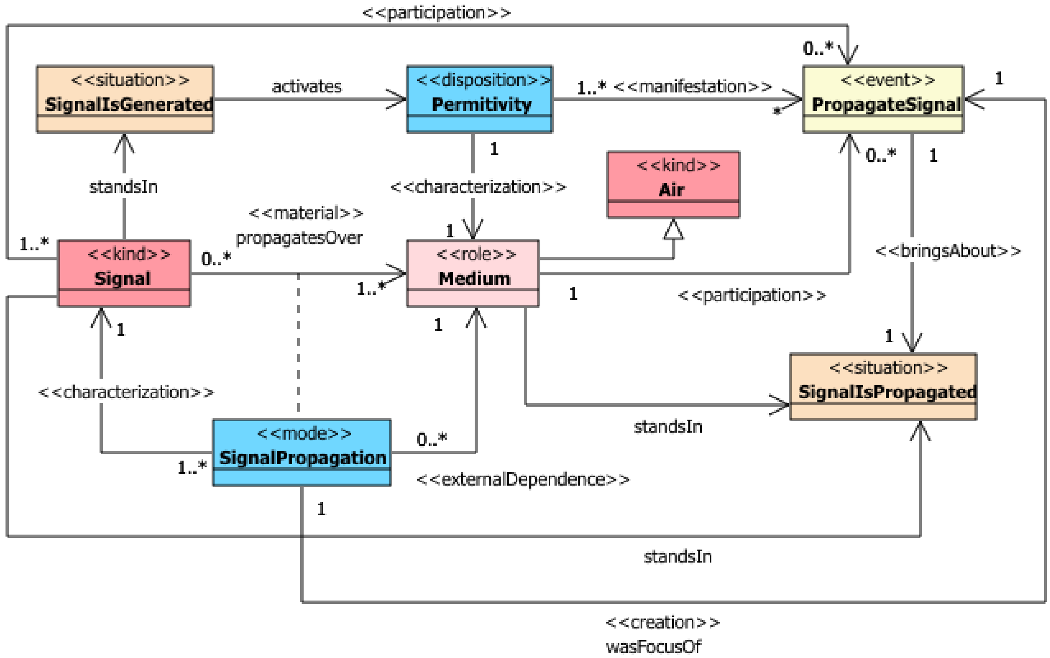
Figure 24 – Bonding creation process - phase 01 - signal generation



Source: Prepared by author.

It starts right after the event of powering up the `Tx`, which will play the role of a `Sender`. It brings about a new `Sender` situation (`SenderSituation`). Once established, this situation may activate the `Sender`'s disposition to create oscillating electromagnetic fields (`EmField`). Whenever the disposition is activated, these oscillations produce an

Figure 25 – Bonding creation process - phase 02 - signal propagation



Source: Prepared by author.

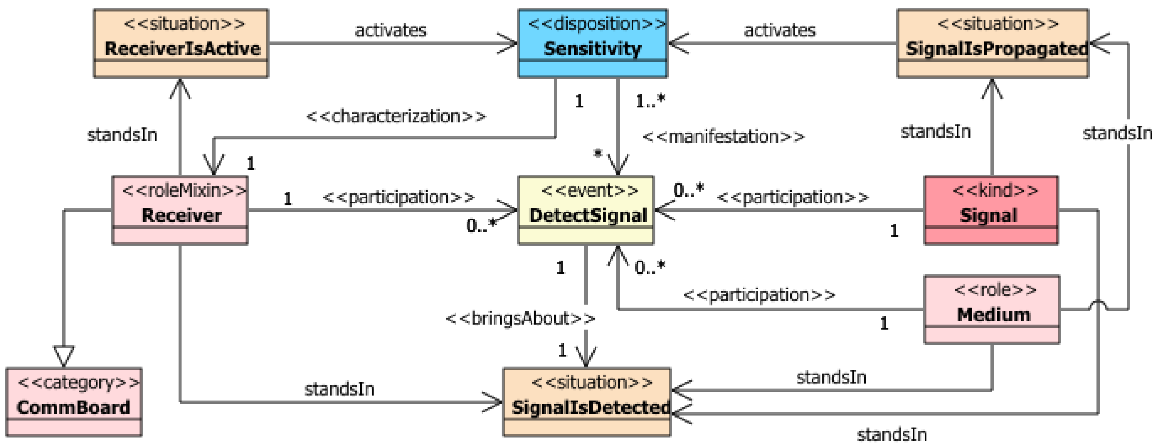
electromagnetic signal (`Signal`), which is created in the `GenerateSignal` event as the manifestation of the `EmField` disposition, having the participation of `Sender`. Also, it is the foundation of the truthmaker (`SignalGeneration`) that supports the material relationship between `Sender` and `Signal`, characterizing the latter with properties such as frequency, bandwidth, and power, and externally dependent of the former. Finally, the `GenerateSignal` event brings about a new situation called `SignalIsGenerated` where `Signal` stands in.

Moving forward in our scenario, the fact that a `Signal` is generated by a `Sender` is insufficient for its detection by a `Receiver`. Before that, it must 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* [Technical Committee 1, 2019]. Many entities can play the role of a `Medium`: coaxial, fiber optic cables, atmospheric air (`Air`), among others. Figure 25 shows that the `SignalIsGenerated` situation may activate the capacity of the `Medium` to propagate the `Signal` - the magnetic permittivity (`Permittivity`). As soon as it is activated, this disposition is manifested by an event (`PropagateSignal`), having `Signal` and `Medium` as its participants. This event is the foundation of the truthmaker (`SignalPropagation`) that holds the material relation between `Signal` and `Medium`, bringing about a new situation (`SignalIsPropagated`), where both `Signal` and `Medium` stand in.

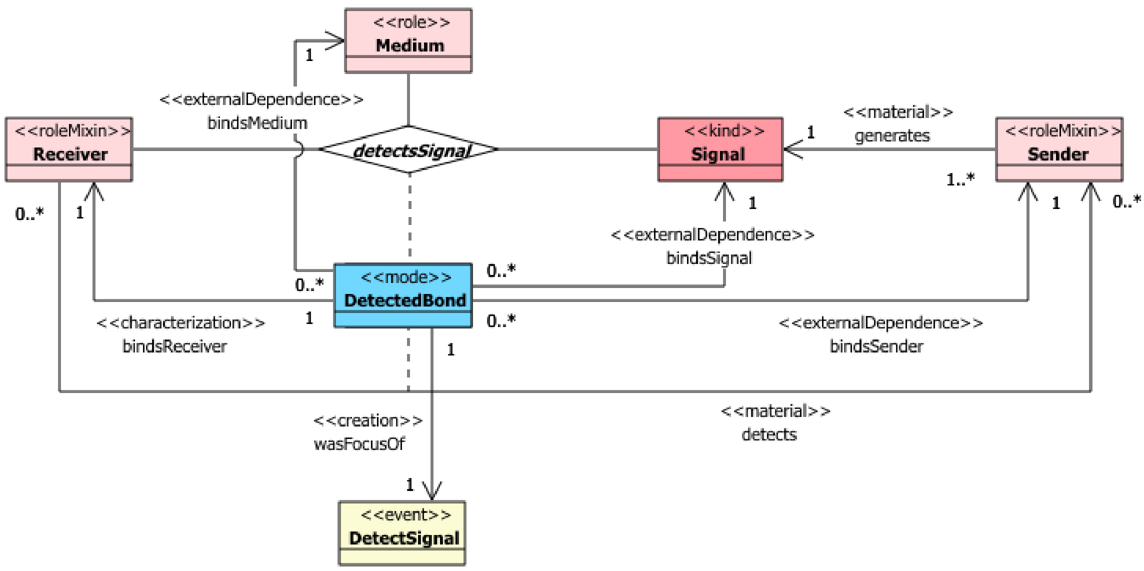
Figure 26a presents the final phase of the bonding process between `Sender` and `Receiver`. Like the first phase, this one starts right after the `Rx`, playing only the role of a `Receiver`, is powered up, bringing about a new situation (`ReceiverSituation`). But, even when established, this new situation is insufficient to activate the `Receiver`'s disposition (`Sensitivity`) capable of detecting the `Signal`. To activate the `Sensitivity` disposition, the presence of the `SignalIsPropagated` situation in a given space-time frame is also necessary. Then, whenever both situations are present, they may activate the `Sensitivity` disposition, manifested by the `DetectSignal` event. Having `Signal`, `Medium`, and `Receiver` as participants, this event brings about a new situation called `SignalIsDetected` where `Signal` stands in. At this point, the `Receiver` detects the `Signal`. For clarity, this relation is detailed in Figure 26b.

Figure 26 – Bonding creation process - phase 03 - signal detection

(a) Process of signal detection



(b) Bonding between `Sender`, `Signal`, `Medium` and `Receiver`



Source: Prepared by author.

The last interaction reveals the expected result of our description: the relation *detectsSignal* binding a `Receiver` to a `Signal` propagated by a `Medium` and generated by a `Sender`, as portrayed in Figure 26b. However, the analysis of this material relation raises a question: According to UFO theory, what is the ontological nature of the truthmaker that supports it?

In our scenario, a `Receiver` detects a `Signal` when a subset of the former's electromagnetic (EM) properties matches the same properties of the latter. This is characterized by activating the `Sensitivity` disposition in Figure 26a. In this sense, the `Receiver` is committed towards the `Signal`, although it is not reciprocal. To illustrate it, let us consider the selection of a broadcast radio station. Selecting a radio station means that we are choosing an EM property of the `Receiver` that allows the reception of the `Signal` generated by the `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 a `Medium` to reach the `Receiver`. In our scenario, the EM properties of the `Signal` and of the `Receiver` have to match with at least a subset of the EM properties of the `Medium`. However, the EM properties of the `Medium` do not change to allow the `Signal` to propagate, and neither do they change to match the EM properties of the `Receiver`.

Therefore, the truthmaker `DetectedBond` that binds `Signal`, `Medium` and `Receiver` and supports the relation *detectsSignal* 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 `DetectedBond` is also an EDM. Finally, to accommodate a common description used in the domain, we also propose a derived relation (*detects*) between `Receiver` and `Sender`. As portrayed in Figure 26b, it is supported by the same truthmaker that supports the *detectSignal* - the `DetectedBond`.

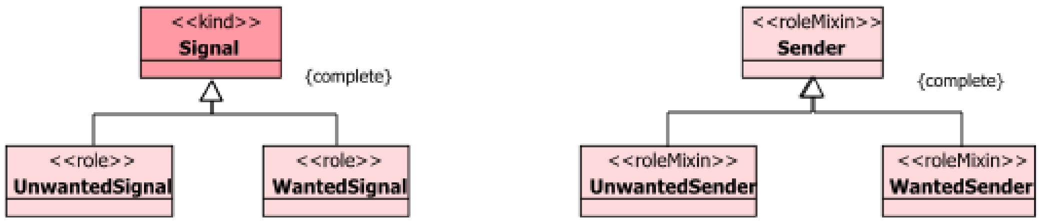
4.3.1.3 The Decoded Bond

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.

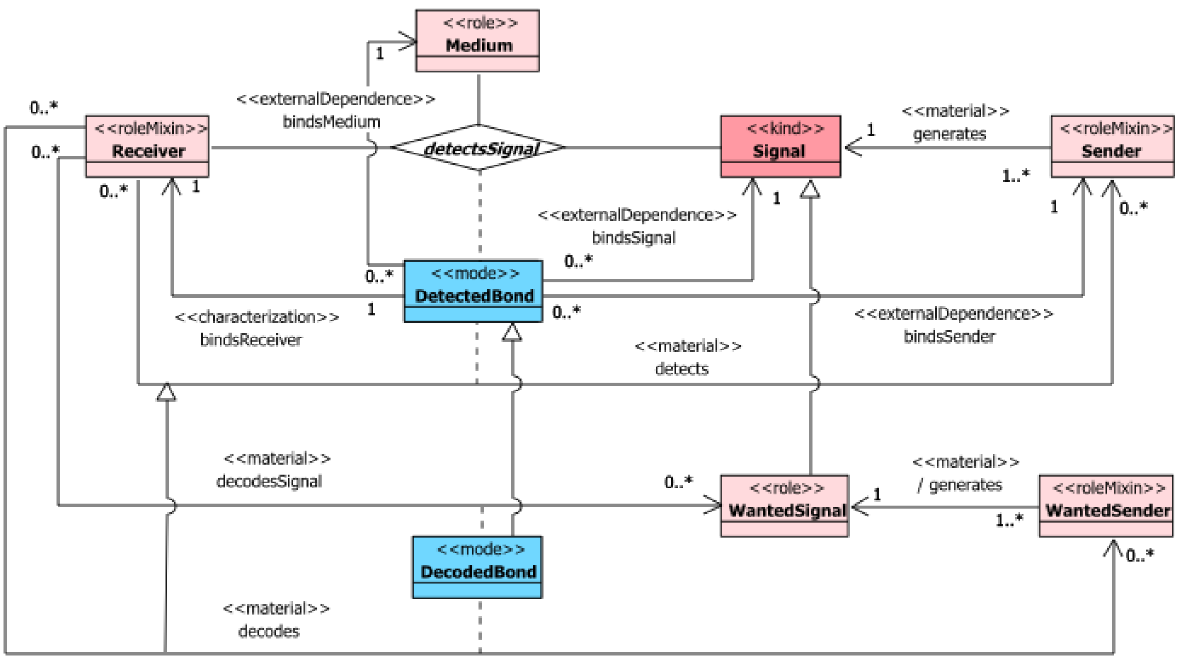
The definition of interference given by [ITU Radiocommunication Sector (ITU-R), 2005] states that it is *a disturbance of the reception of a wanted signal caused by interfering signals, noise, or electromagnetic disturbance.* It also defines noise as *any variable physical phenomenon apparently not conveying 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, we infer that the `Receiver` and the `Sender` have the same communication technology. In this sense, we propose that `WantedSignal` is a role of `Signal` whenever the `Receiver` decodes it, as Figures 27a and 27b reveal. The new relation *decodesSignal* formed between the `Receiver` and the `WantedSignal` is a specialization of the *detectsSignal* relation and has `DecodedBond`, a specialization of `DetectedBond`, as its truthmaker. Finally, we propose a new relation between `WantedSender` and `Receiver` to maintain consistency - the *decodes* relation. It is a specialization of the *detects* relation that is also supported by the `DecodedBond`.

Figure 27 – Creation of `DecodedBond`

(a) Taxonomy of `Sender` and `Signal`



(b) `DecodedBond` as a specialization of `DetectedBond`

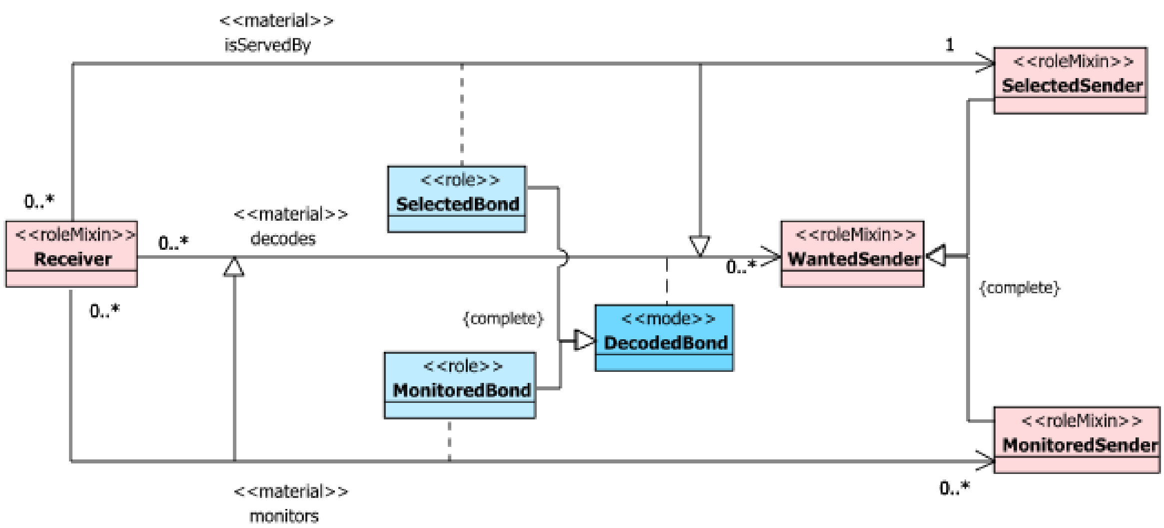


Source: Prepared by author.

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 can not 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 can not decode it. In this case, the Medium deteriorates the Signal so that the Receiver can not 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 Figure 26b.

In many communication systems, the Receiver has to deal with only one Wanted Sender. However, there are other systems, like the mobile networks, where the Receiver has to simultaneously deal with several WantedSenders. Although only a subset may be chosen to transfer information, others must 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 2.1.6. 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 [3]. As a result, it creates new specialized relationships of the DecodedBond pictured in Figure 28.

Figure 28 – SelectedBond and MonitoredBond as roles of the DecodedBond



Source: Prepared by author.

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

Now, an externally dependent mode (EDM) called `SelectedBond` supports the material relation between a `SelectedSender` and a `Receiver`. Moreover, another EDM 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 2.1.6. For instance, the HO process in a 3GPP 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.

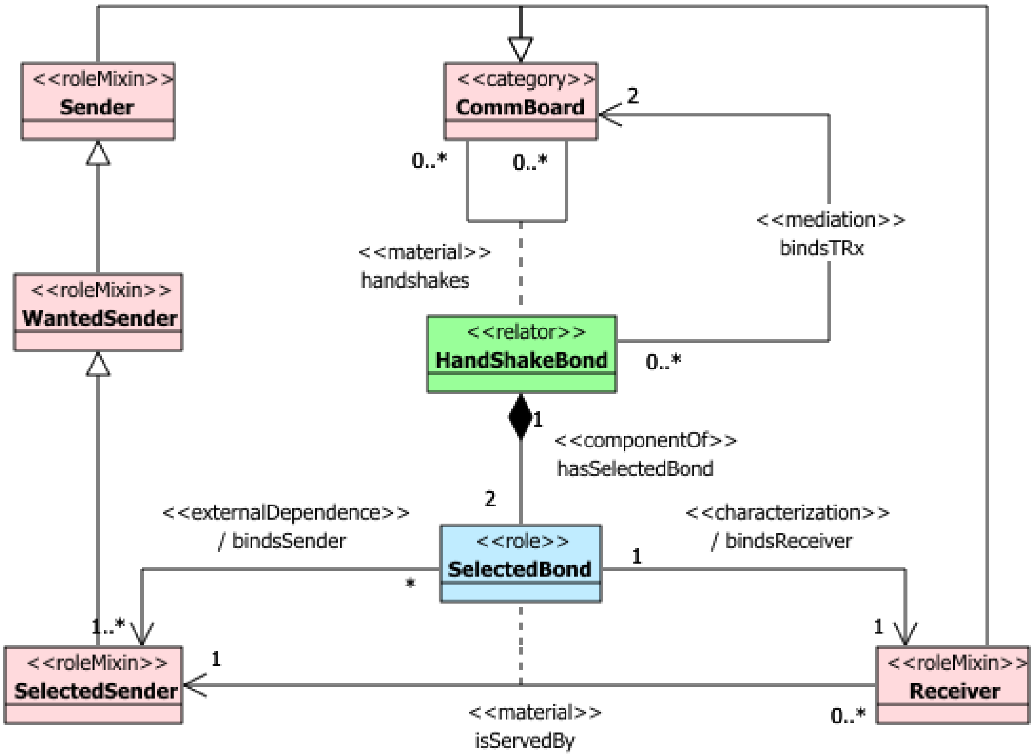
4.3.1.4 The HandShake Bond

In some communications, an agreement must be fulfilled before exchanging information. Again, the TIA Glossary of Telecommunication Terms [Telecommunications Industry Association, 2022] 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 before information exchange*. From this definition, we infer that `CommBoards` that need prior agreement before starting information exchange needs the ability to transmit **and** receive `Signals`. Thus, according to the proposed model in Section 4.3.1.1, only `TRxs` can fulfill communications agreements. And, since they share information as described in Section 4.3.1.3, only `SelectedBonds` between `TRxs` must appear as reciprocal pairs.

Figure 29 shows the agreement that guarantees information delivery. A `HandShake Bond` binds two `CommBoards` representing the obligations and commitments that both relata need to fulfill. Consequently, both parts must share information, limiting the types of `CommBoards` that can accomplish it. Thus, Equation 4.5 restricts that only distinct `TRxs` can be part of such a relationship. However, they must create reciprocal binds between `TRxs` able to share information before creating such agreement bonding. In this sense, a reciprocal pair of `SelectedBonds` have to be formed previously. The truthmakers of this pair represent the commitments and obligations of both `TRxs`, becoming then part of the truthmaker that supports the agreement bonding - the `HandShakeBond`. Equation 4.6 proposes the existence of reciprocal `SelectedBonds` to support the `HandShakeBond` as their composition.

$$\forall a, b(handshakes(a, b) \rightarrow (TRx(a) \wedge TRx(b) \wedge (a \sqsubseteq \neg b)) \tag{4.5}$$

Figure 29 – Communication agreement between TRxs



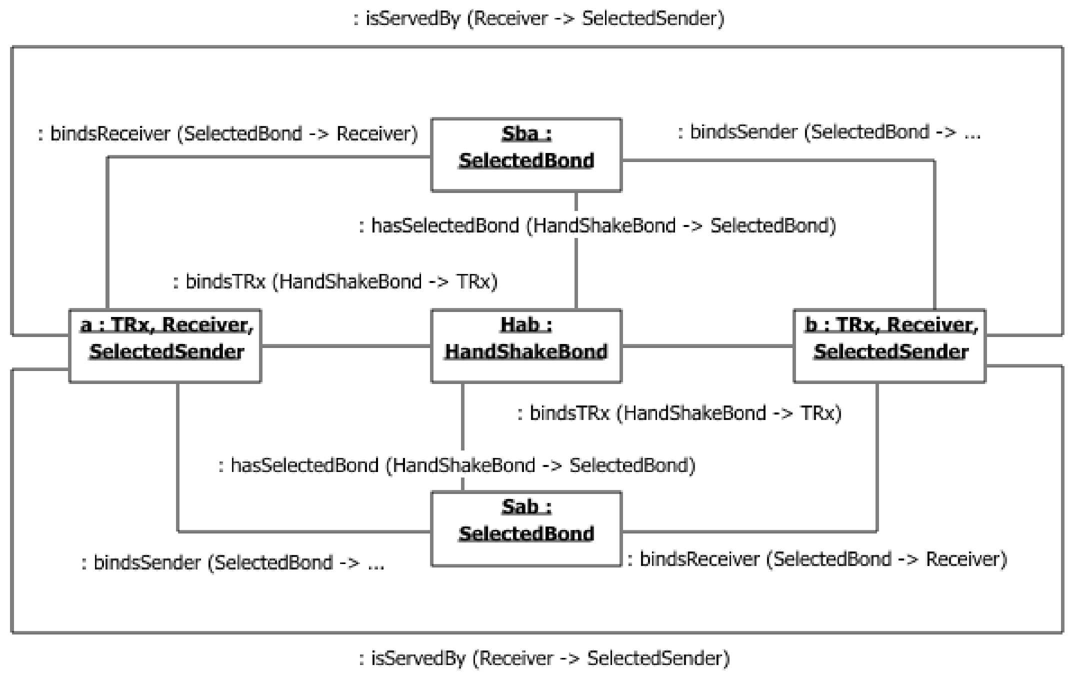
Source: Prepared by author.

$$\forall a,b,c(TRx(a) \wedge TRx(b) \wedge HandShakeBond(c) \wedge bindsTRx(c,a) \wedge bindsTRx(c,b) \rightarrow \exists d,e|SelectedBond(d) \wedge SelectedBond(e) \wedge bindsReceiver(d,b) \wedge bindsSender(d,a) \wedge bindsReceiver(e,a) \wedge bindsSender(e,b) \wedge hasSelectedBond(c,d) \wedge hasSelectedBond(c,e) \quad (4.6)$$

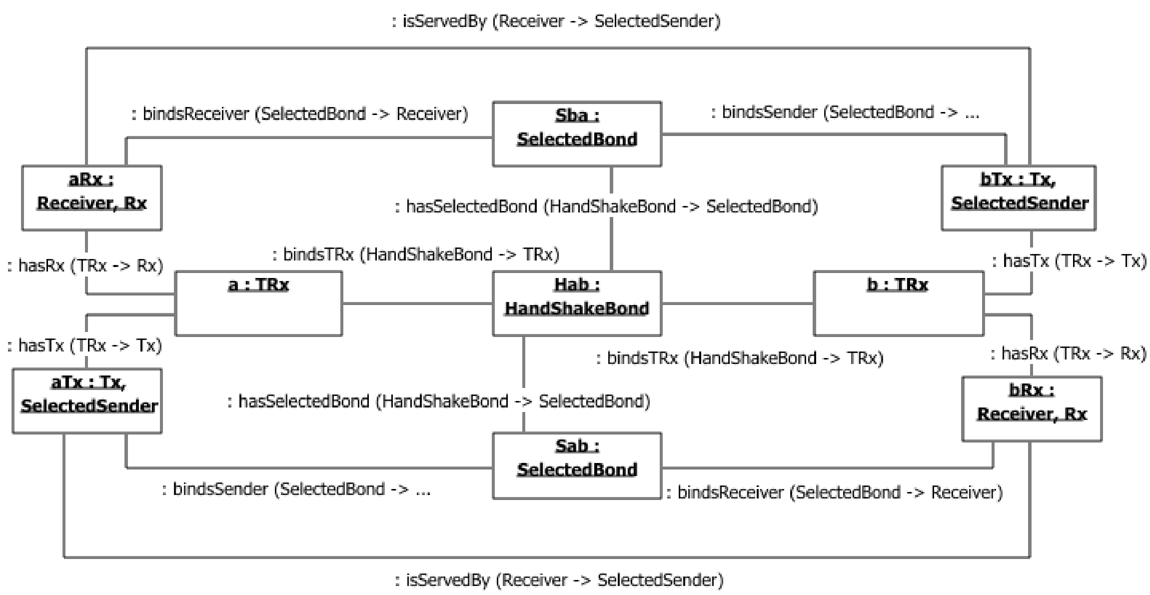
This new bond between TRxs highlights two interesting points. First, a HandShake Bond existentially depends on SelectedBonds. Also, HandShakeBond and SelectedBonds may bind different entities, depending on how TRxs are represented. The object diagram in Figure 30 presents their differences. In Figure 30a, TRx is represented as a whole, directly playing the roles of SelectedSender and Receiver. In this case, SelectedBond and HandShakeBond bind the same entity - TRx. However, if we represent TRx as a composition of Tx and Rx, it becomes clear that different entities are bonded. In Figure 30b, while the HandShakeBond binds TRxs, SelectedBonds bind Txs playing the role of SelectedSender with Rxs playing the role of Receiver.

Figure 30 – `SelectedBond`s and `HandShakeBond` binding `TRx`s

(a) `SelectedBond`s and `HandShakeBond` binding `TRx`s represented as a whole



(b) `SelectedBond`s and `HandShakeBond` binding `TRx`s represented as a composition of `Tx` and `Rx`

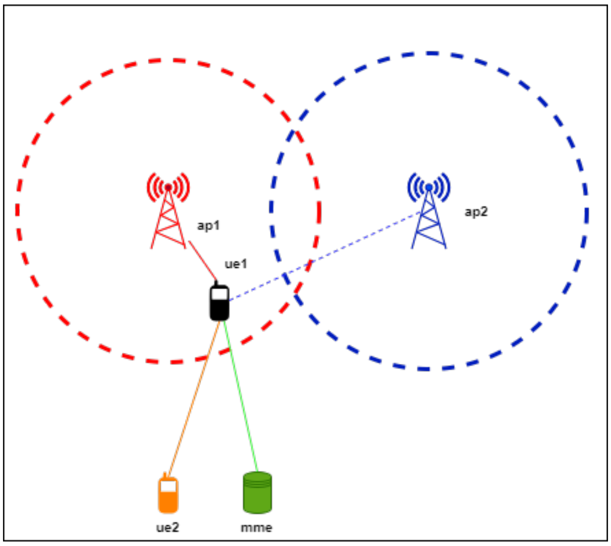


Source: Prepared by author.

4.3.1.5 Using The Bonding Concepts

Section 3.1.1 shows that 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 shown in Figure 31 to elaborate a UML sequence diagram (Figure 32) representing a simplified version of the mobile phone registration and connection process in a 4G mobile network [Technical Specification Group Radio Access Network, 2022]. While describing the process, we employ the conceptual models presented so far to support our analysis.

Figure 31 – 4G mobile network user registration scenario



Source: Prepared by author.

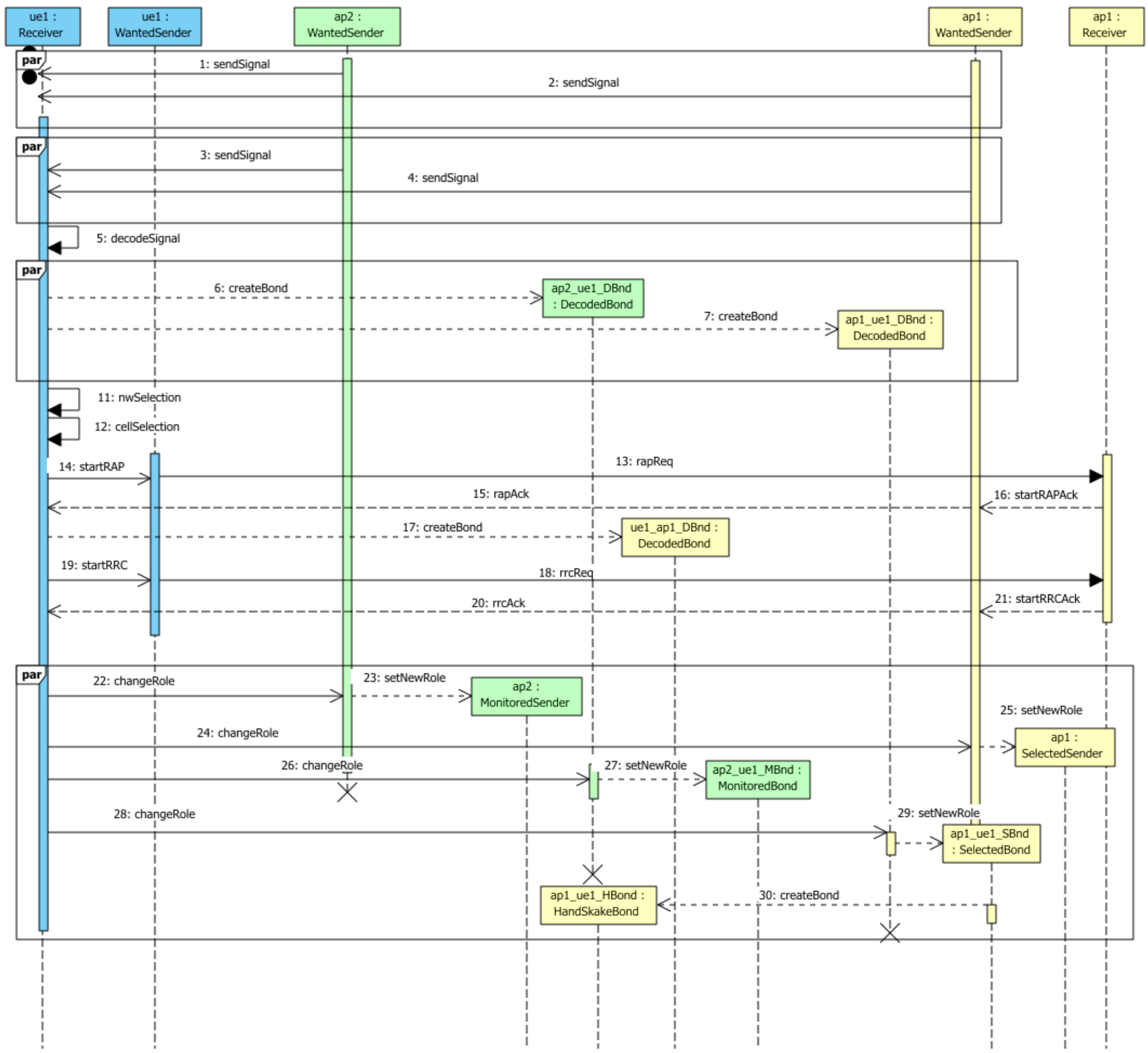
Let us assume that all communication entities are `TRx`s and active, except for `ue1` in Figure 31. Also, according to the concepts described in Section 2.1.1, `ap1:TRx` and `ap2:TRx` are access points (`AP`), while `ue1:TRx` is a user equipment (`Ue`). Since `ap1` and `ap2` are active, they transmit their `Signals`, playing the role of `Senders` (`ap1`: `Sender` and `ap2`:`Sender`).

Whenever `ue1` is active, it starts playing the role of a `Receiver` (`ue1`:`Receiver`), detecting and decoding the `Signals` coming from `ap1` and `ap2`. As soon as `ue1` decodes such `Signals`, they start to play the roles of `WantedSignals` and, consequently, `ap1` and `ap2` become `WantedSenders`, as shown at the top of the sequence diagram in Figure 32 [4]. 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`.

Right after, `ue1` starts the network and cell acquisition processes to select the appropriate access point. In our example, `ue1` selects `ap1` as its serving access point to the mobile network after the cell acquisition process terminates. However, selecting an access point is insufficient to allow information exchange. An agreement between these two entities has to be established first. According to the 3GPP recommendation TS 36.300 [Technical Specification Group Radio Access Network, 2022], this agreement is accomplished only

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

Figure 32 – The UML sequence diagram representing the interactions between entities in a simplified 4G registration and connection process.



Source: Prepared by author.

when the result of two processes initiated by `ue1`, 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 Figure 32 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`), is set. This bond is supported by the externally dependent mode (EDM) `ue1_ap1_DBnd` (`ue1_ap1_DBnd`: `DecodedBond`) and is the counterpart of the EDM `ap1_ue1_DBnd`. Then, after the success of the RAP and RCC processes, some roles cease to exist and are 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 EDM `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 EDM `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` and `ap1` is created, supported by a new relator (`ue1_ap1_HBnd: HandShakeBond`). The conceptual model applied in this example of registration and connection in a 4G mobile network helps us clarify the relationships between the communications entities and improves our understanding of what really `Link` and `Connection` are.

4.3.1.6 About Links and Connections

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.* The same recommendations define communication as *information transfer according to agreed conventions.* Hence, as a means of telecommunication, the recommendations suggest that a `Link` is formed when one point is responsible for generating a `Signal` that carries `Information` and is received by the other point. Looking at our model discussed in Section 4.3.1.3 and presented in Figure 27b, the `Link` entity does not correspond entirely to the `DecodedBond` entity at first glance. The `DecodedBond` represents the bond between communication entities playing the role of `WantedSender` and `Receiver` along with an entity playing the role of `Medium`. Thus, although the `Link` definition describes the bonding between two communication entities, it apparently ignores the one that plays the role of `Medium`. Thus, at first, `Link` and `DecodedBond` seem 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 usually 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 of `Medium`(e.g., radio, coaxial) or by `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 all 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 binding, but the former not representing `Medium` 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 defined as *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. For instance, recommendation ITU-T Recommendation E.417 [ITU Telecommunication Standardization Sector (ITU-T), 2005] 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 the previous ITU-T recommendation matches the `HandShakeBond` concept presented in our model. Moreover, as a `HandShakeBond` depends on `SelectedBonds` in our conceptual model to exist, we infer that the same dependency can be extended between `Connection` and `Link`.

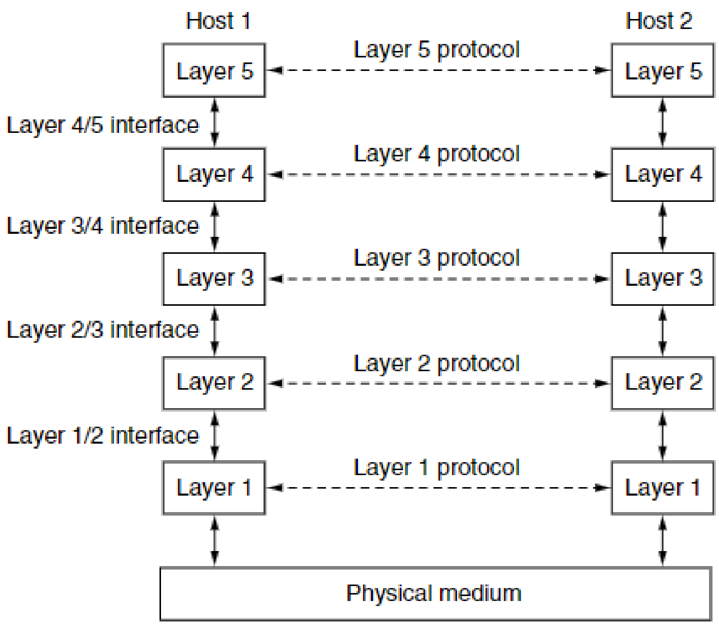
Hence, the definitions of `Link` and `Connection` provided by vocabulary recommendations are unclear if these entities bind the same communication entity. Our conceptual models show that `Tx`s and `Rx`s can create `Link`s, but not `Connection`s. Also, when `TRx`s are represented as compositions of `Tx` and `Rx`, `Link`s and `Connection`s bind different entities. While `Link`s are formed between `Tx`s and `Rx`s, `Connection`s are formed between the `TRx`s. Only in the case when `TRx`s are represented as a whole, as discussed in Section 4.3.1.1, `Link`s and `Connection`s bind the same entity. Finally, if `DecodedBond`s are `Link`s, then `SelectedBond`s and `MonitoreddBond`s are respectively `ServingLink`s and `NeighborLink`s in mobile wireless networks.

4.3.2 Communication Between Layers

Until now, we have evaluated the essential bonds that communication boards can establish between them. We were able to ontologically distinguish what `Link` and `Connection` really are and how they depend on each other. In this section, we focus on representing communication between entities based on the layered network architecture approach presented in Section 2.1.4. The goal is to provide the necessary representation to evaluate the effectiveness of the handover process.

The layered network design approach represents communicating entities through an abstraction called **layer**. Unfortunately, sources in the domain literature are unclear about what layer is. For instance, Tanenbaum and Wetherall [TANENBAUM; WETHERALL, 2011] does not define a layer directly. As Figure 33 shows, they propose that layers communicate with their peers (horizontal communication) in different communication devices (or hosts), offering services (vertical communication) to higher layers at the same communication device. On the other hand, the TIA Vocabulary [Telecommunications Industry Association, 2022] states that a layer is a *group of related functions performed*

Figure 33 – Layered network architecture design approach (repeated)



Source: [TANENBAUM; WETHERALL, 2011].

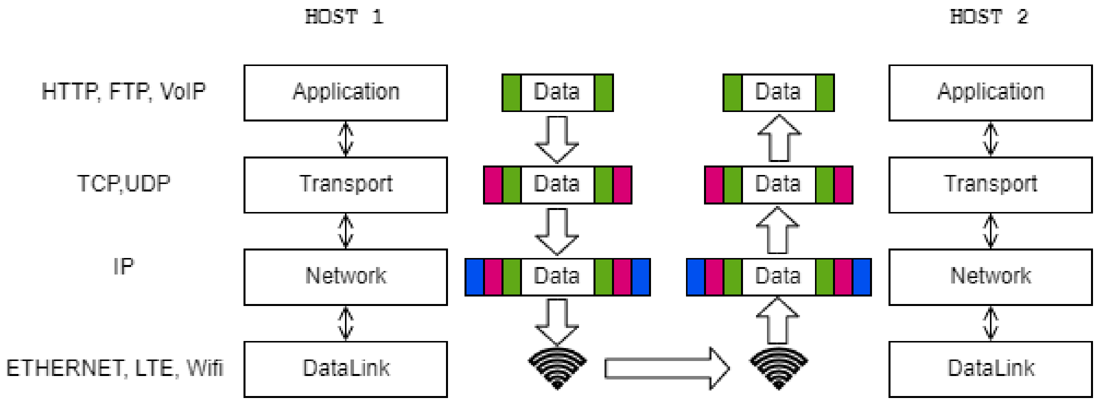
in a given level in a hierarchy of groups of related functions. Likewise, many ITU recommendations define layers in their own scope [ITU Telecommunication Standardization Sector (ITU-T), 1993; ITU Telecommunication Standardization Sector (ITU-T), 2000c; ITU Telecommunication Standardization Sector (ITU-T), 2000b], leading to different meanings.

However, the ITU Recommendation ITU-T Q.9 [ITU Telecommunication Standardization Sector (ITU-T), 1998] provides a definition that helps our conceptual modeling. It states that a layer is a group of one or more **entities** contained within an upper and lower logical boundary. Thus, we may infer that a layer is an abstraction that categorizes network entities by certain network services or functions based on a layered network reference model. Moreover, communication takes place between these layer entities rather than between layers, as the literature suggests. In this sense, we propose that there are two non-exclusive ways in which these layer entities can communicate with each other: (i) they can communicate as long as they are **not part of the same device** and have the **same protocol** and, (ii) they can communicate as long as they are **part of the same device**, and **one must provide services to the other**.

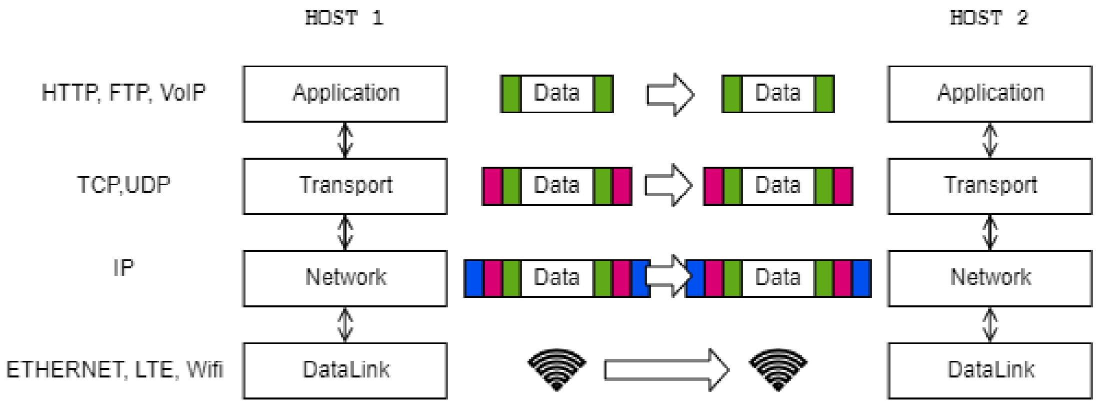
For instance, Figure 34 shows the information flow between two hosts using the abstraction of the four-layer TCP/IP reference model. In this scenario, a TCP program supports Web applications running on the same host through transport services. Therefore, the TCP program is categorized as belonging to the transport layer. Similarly, a UDP program supports VoIP applications through transport services that belong to the same

Figure 34 – Information flow between communication entities

(a) Actual information flow



(b) Virtual information flow

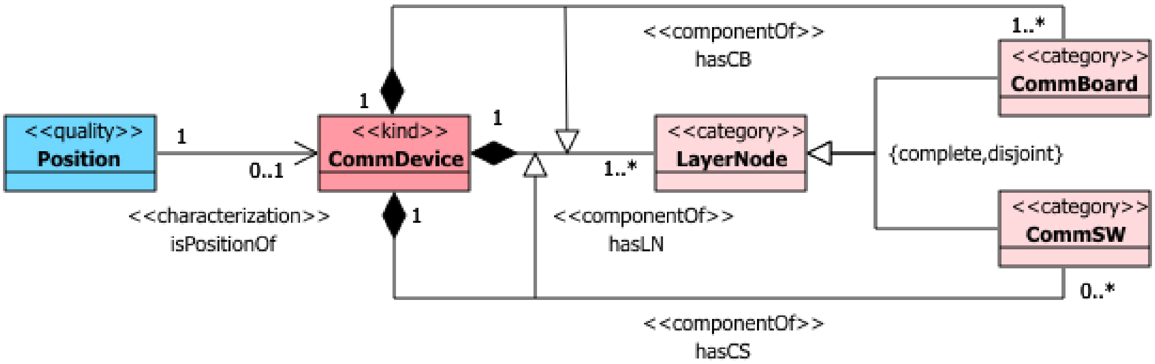


Source: Prepared by author.

transport layer. Thus, although TCP and UDP programs provide services to Web and VoIP applications in the same host (vertical communication in Figure 34a), they seem to communicate with their peers on a different host (horizontal communication in Figure 34b). Therefore, the information exchange between distinct hosts relies on top-down vertical communications between layer entities belonging to the same host. The information is physically exchanged between hosts when it reaches the lowest layer entity, regardless of how reference models classify it. For instance, the TCP/IP model names the lowest layer DataLink, while the OSI/ISO model names it the Physical layer. Nevertheless, the only entity that can do this is the physical entity we call `CommBoard` in Section 4.3.1.

We propose to call the entities grouped in a layer as `LayerNodes`, representing the generalization of two distinct entities: the `CommBoards` and the `CommSWs`, representing the category of software able to establish communication with other software or hardware. Therefore, `LayerNodes` now belong to a `CommDevice`, having at least one `CommBoard`, as shown in Figure 35

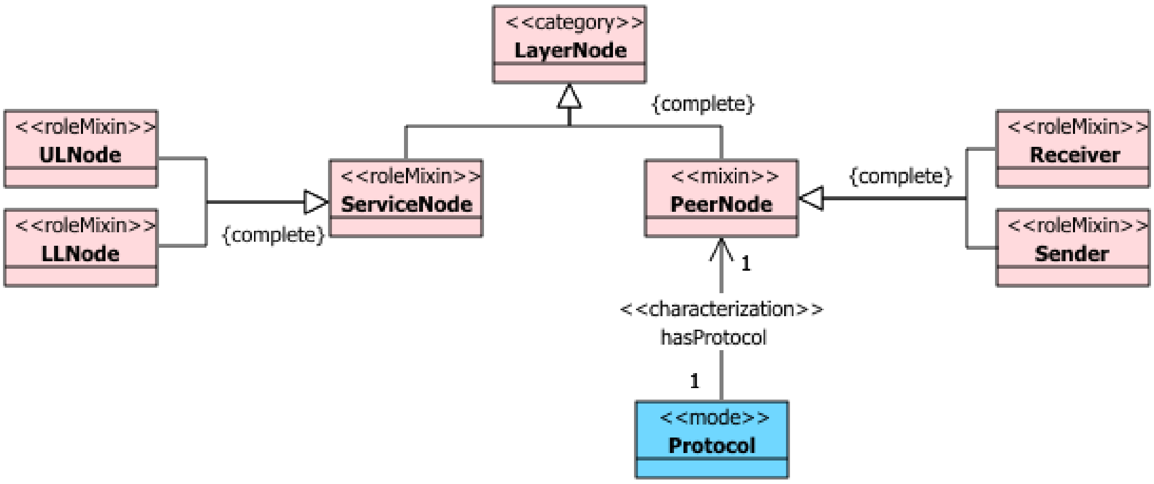
Figure 35 – LayerNodes composing CommDevices



Source: Prepared by author.

We also classify LayerNodes in Figure 36 according to their communication role with other LayerNodes. Also, we propose that a PeerNode is a role that a LayerNode plays when it "horizontally" communicates with another distinct LayerNode that shares the same communication Protocol. On the other hand, a LayerNode plays the role of a ServiceNode whenever it "vertically" requests and/or provides network services to another LayerNode in the same host. Whenever it requests a service, it plays the role of an upper layer node (ULNode). Otherwise, when it provides services, it plays the role of a lower layer node (LLNode).

Figure 36 – PeerNodes and ServiceNodes as roles of LayerNodes



Source: Prepared by author.

4.3.2.1 Peer Communication

All the conceptual modeling developed in Section 4.3.1 was grounded on the physical aspects and the actual information flow between communication entities, as pictured in Figure 34a. However, the layered network architecture design approach suggests that `LayerNode`s such as `CommSW`s can virtually exchange information with its peers just like a `CommBoard`s would. In this sense, we infer that they also play the roles of `Sender` and/or `Receiver`. And, consequently, could form `DetectBond`s and their specializations (`SelectedBond` and `MonitoredBond`). This analogy also brings an interesting fact: since `HandShakeBond`s can only be formed between `TRx`s, the `CommSW`s must transmit and receive to form the same association. Therefore, being a `Tx`, `Rx` or `TRx` is not only a specialization of `CommBoard`. It has become a specialization of `PeerNode` itself, which changes its meta-categorization, from rolemixin in Figure 36 to mixin. Figures 37a and 37b show this proposed extension of the conceptual models developed in Section 4.3.1, now considering the `PeerNode` as the ultimate communication entity between peers. Moreover, Equation 4.7 restricts `PeerNode` communication in the same `CommDevice`, while Equation 4.8 restricts `PeerNode`s communication between pairs with different `Protocol`s.

$$\begin{aligned}\forall a,b,c,d(CommDevice(a) \wedge CommDevice(b) \wedge LayerNode(c) \wedge LayerNode(d) \wedge \\ hasLN(a,c) \wedge hasLN(b,d) \wedge detects(c,d) \rightarrow (a \sqsubseteq \neg b))\end{aligned} \tag{4.7}$$

$$\begin{aligned}\forall a,b,c,d(PeerNode(a) \wedge PeerNode(b) \wedge Protocol(c) \wedge Protocol(d) \wedge \\ hasProtocol(a,c) \wedge hasProtocol(b,d) \wedge decodes(a,b) \rightarrow (c \equiv d))\end{aligned} \tag{4.8}$$

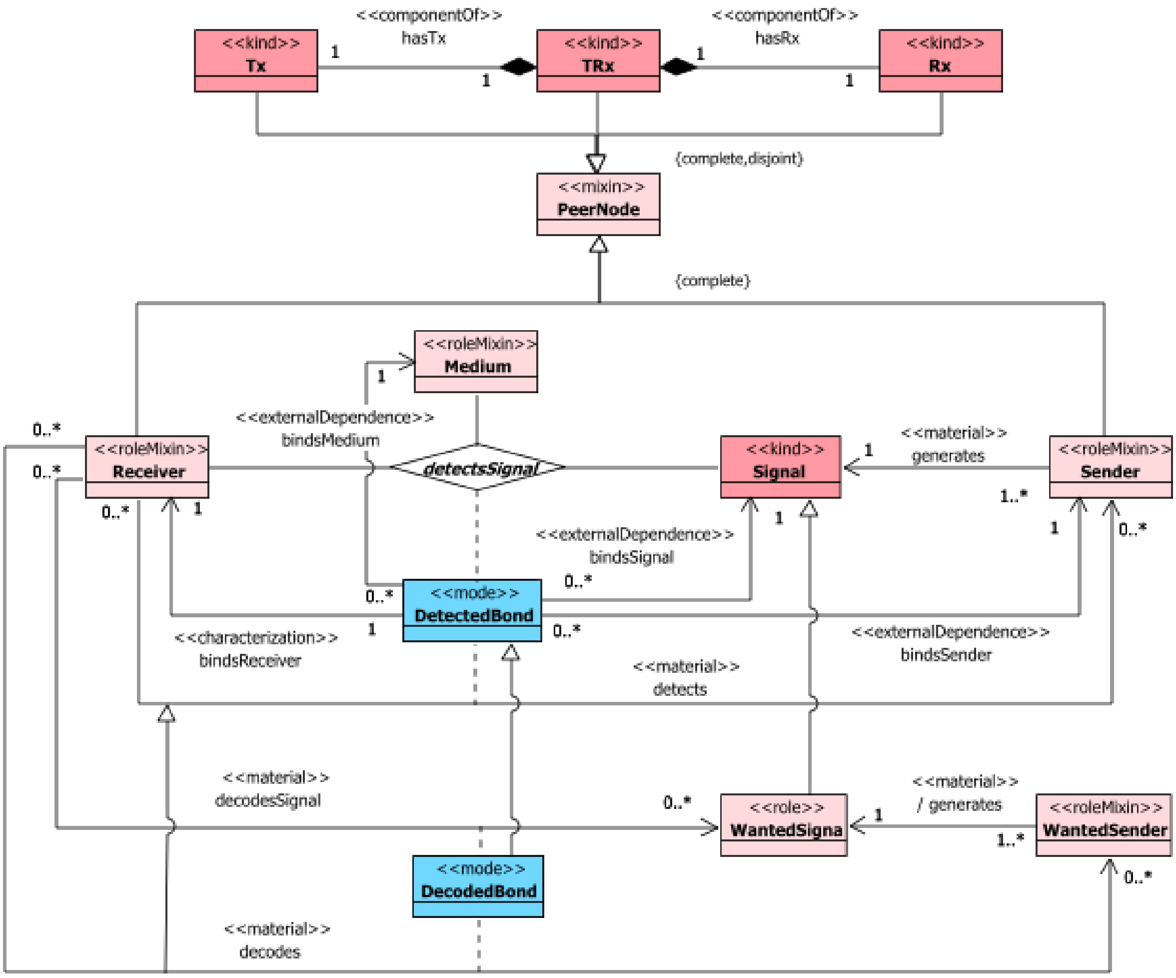
4.3.2.2 Service Communication

While `LayerNode`s communicate horizontally as `Peer`s, they also assume the role of a vertical node whenever they request and/or provide network services to other distinct`LayerNode`s at the same host. Unlike `PeerNode` communications, where the concepts of `Link` and `Connection` usually appear, `ServiceNode` communications do not use the same terminology. Hence, although it seems to fit the conceptual modeling approach, we chose not to represent them as we did with `PeerNode` since it is not expected to evaluate the performance of the handover process in this dimension. This evaluation is out of our research scope.

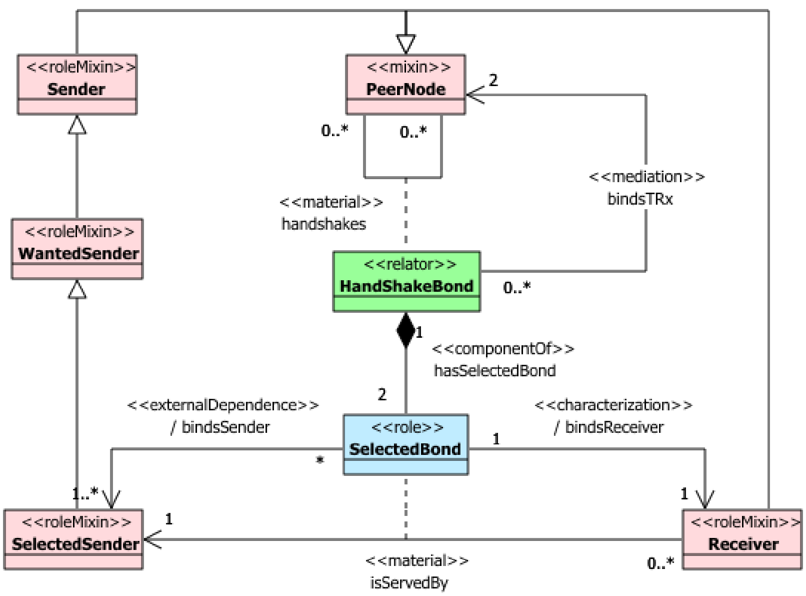
Figure 38 shows that a `LayerNode` acts as an upper `LayerNode` (`ULNode`) when it requests a network service to another distinct `LayerNode` acting as lower `LayerNode` (`LLNode`). Thus, a `ULNode` requests network services while a `LLNode` provides these services.

Figure 37 – Peer communication

(a) `DecodedBonds` between `PeerNodes`

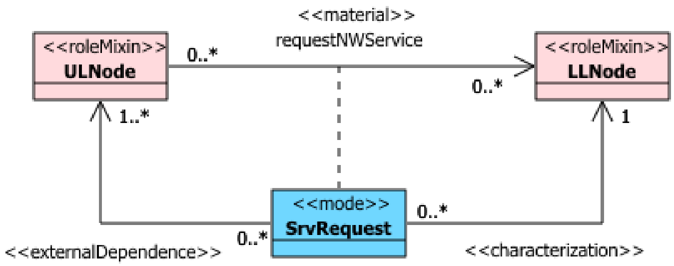


(b) `HandShakeBond` Between `PeerNodes`



Source: Prepared by author.

Figure 38 – Network service communication



Source: Prepared by author.

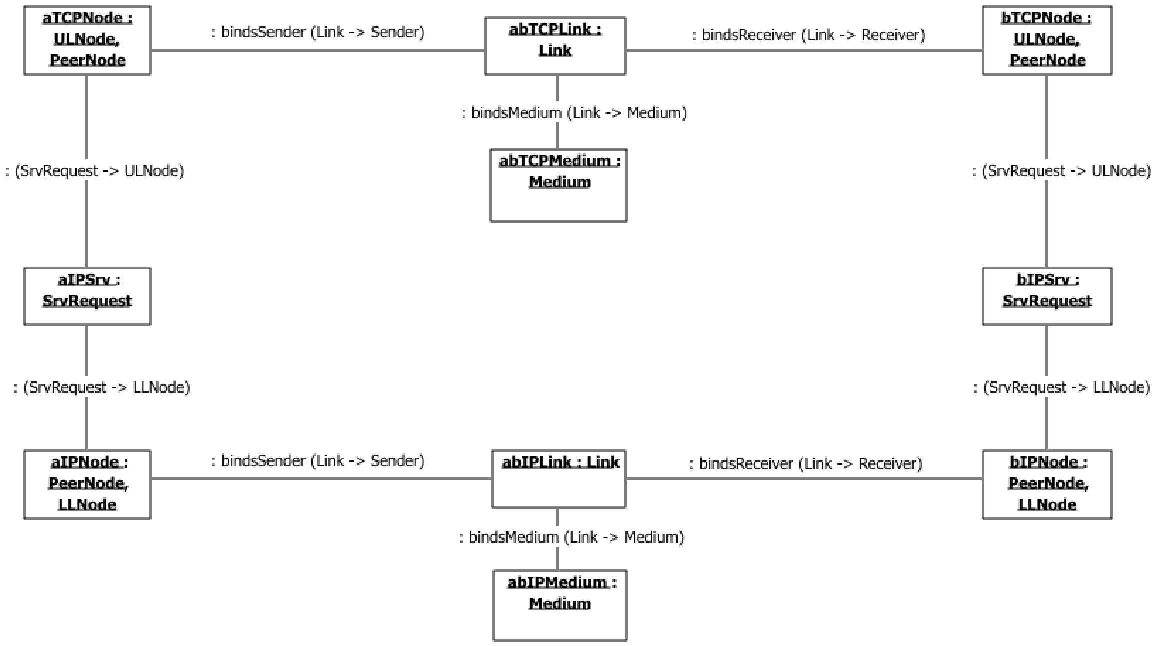
It is important to note that this relation must be unidirectional to sustain the hierarchy of a network architecture, as discussed in Section 2.1.4. For instance, if `TCPNode` and `IPNode` are instances of `CommSW` and `TCPNode` *requestService* `IPNode`, then it is forbidden to exist a relation `IPNode` *requestService* `TCPNode`.

At this point, it is worth analyzing how `PeerNode` and `ServiceNode` communications work simultaneously. The core of the handover process relies on it since it is necessary to sustain the communication between `Peers` that are also acting as `LLNodes` to keep the horizontal communication between `Peers` that are also acting as `ULNodes`. Figure 39 shows an object diagram to exemplify the above situation. Let us assume the communication between two hosts or `CommDevice` named `a` and `b`. Among `LayerNodes` that belong to `a` and `b`, `aTCPNode` and `aIPNode` belongs to `a` and `bTCPNode` and `bIPNode` belongs to `b`.

Hierarchically, `aTCPNode` requests network services from `aIPNode` as well as `bTCPNode` requests it from `bIPNode`. Whenever `aTCPNode` wants to send information to its peer `bTCPNode`, it wraps the information into a network service a `aIPNode` knows how to handle. Once in the `aIPNode`, it also begins to play the `PeerNode` role to forward the information to its peer in `b`. Whenever `bIPNode` receives the information coming from `aIPNode`, it forwards to `bTCPNode`. Although the information exchange between `aTCPNode` and `bTCPNode` happens as described previously, it seems they were exchanged directly between TCP nodes. Thus, according to our proposed conceptual model, we could describe the communication as `PeerNodes` and `ServiceNodes`. However, after evaluating Figure 39, a question comes up: what happens if the communication between `ULNodes` and `LLNodes` fails or if the communication between `LLNodes` acting as `Peers` fail?

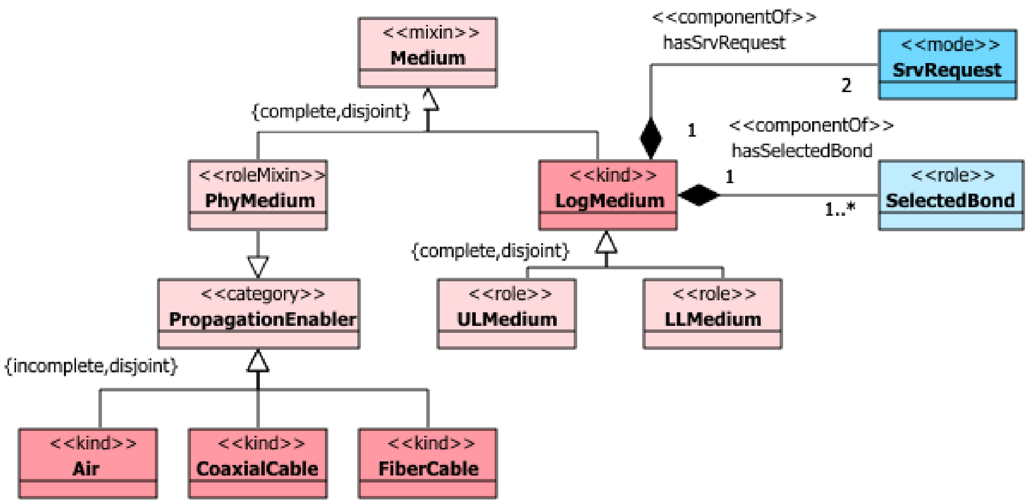
To handle this situation, we recall the definition of `Medium` in Section 4.3.1.2, where a `Medium` is the entity that allows a `Receiver` to detect and/or decode a `Signal` generated by a `Sender`. Considering that `PeerNodes` communication resembles the physical communication proposed in Section 4.3.1, we can infer that there is a `Medium` in each peer communication to allow a physical or a virtual `Signal` propagation as a result of our proposed modeling extension in Section 4.3.2.1.

Figure 39 – Object diagram representing `PeerNode` and `ServiceNode` communications



Source: Prepared by author.

Figure 40 – `Medium` taxonomy to support `PeerNode` communication



Source: Prepared by author.

In our case in Figure 39, we represent `abTCPMedium` and `abIPMedium` as the supporting `Medium` of the TCP and IP peer communication. However, unlike the entities that play the role of a physical `Medium`, such as coaxial cables, other different entities must be chosen to play this role.

In this case, we must improve the representation of `Medium`, specializing it as `PhyMedium` and `LogMedium` in Figure 40. While `PhyMedium` represents entities able to

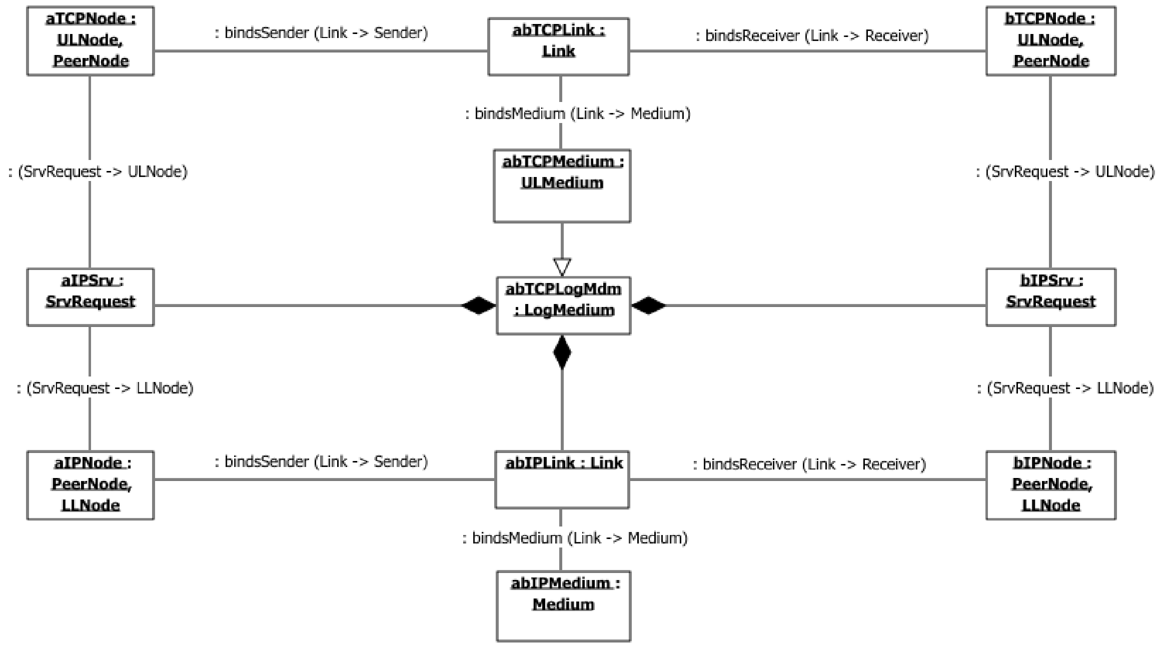


Figure 41 – Object Diagram Representing Peer Communication Dependencies

propagate actual `Signals`, `LogMedium` represents the collection of truthmakers that allows the communication between `Peers`, which are also classified as `ULNodes`. This collection is composed of the truthmakers that support the communication between `ULNodes` and `LLNodes` (`SrvRequest` along with the truthmaker that supports the peer communication in the lower layer (e.g., `abIPlink` instance in Figure 41). Once formed, this entity can play the `LogMedium` role. Consequently, the meta-categorization of `Medium` must change, from **role** to **mixin**, since it is now a category of entities whose specializations can have either a rigid (`LogMedium`) or a anti-rigid (`PhyMedium`) behavior.

The dependency representation between `PeerNode` and `ServiceNode` communications is paramount to reflect mobility management in mobile wireless networks properly. Regardless of the layer stack proposed by each standard body, the handover process usually happens in lower layers, maintaining communication in higher layers. Not representing such dependency would allow, for instance, the false continuity of user applications while physical communication fails.

4.3.3 Measuring Attributes of Mobile Network Entities

Usually, quality types are represented in conceptual modeling using attribute functions that map each instance to points in a quality structure [GUIZZARDI; ZAMBORLINI, 2014]. Usually, when they are reified to represent complex quality structures (e.g., color matrix) or their occurrence in time, the direct relation between qualities and their mapping into quality structures remains, as described by [ALBUQUERQUE; GUIZZARDI, 2013]. However, the researched measurement ontologies described in Section 3.2 do not keep this mapping. They present qualities and the respective assigned values as distinct properties of either an event, according to SOSA [HALLER et al., 2018; JANOWICZ et al., 2019] and later M-OPL works, or a situation, according to the Quality Value Attribution Situation approach presented in the gUFO ontology[ALMEIDA et al., 2019]. This section proposes a conceptual model approach inspired by Guarino *et. al.*[GUARINO; GUIZZARDI, 2015] that maintains the direct mapping between the quality and its assigned value.

4.3.3.1 Assigning A Value To A Mobile Network Attribute

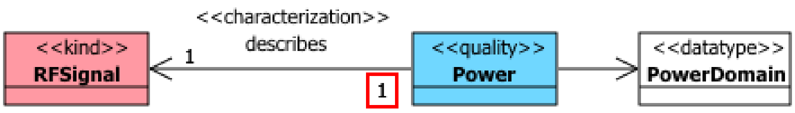
Let us use the mobility management scenario described in Section 4.2 along with the conceptual models proposed in Sections 4.3.1 and 4.3.2. In the scenario portrayed in Figure 31, `ap1` and `ap2` are instances of `TRx`s, playing the role of `Sender`. The `ue1` is an instance of `TRx` playing the role of a `Receiver`. Transceivers `ap1` and `ap2` respectively generate `ap1-sgn` and `ap2-sgn`, instances of `Signal`. These `Signal`s instances have `frequency`, `bandwidth`, and `power` as their attributes. As discussed in Section 2.1.6, the goal of the handover process is to keep services working while serving access point changes. So, to allow a seamless connection over the coverage area provided by the `ap1` and `ap2` in Figure 31, the wireless network needs to, at least, keep track of the strength (or power) of the signals that are decoded by `ue1`. Although other `Signal` attributes (or qualities) can be decoded and used to evaluate the need to change the `Link` between the `Receiver` and the `Sender`, such as `frequency` and `bandwidth`, we chose to use only the `Signal`'s `power` to start building our conceptual model.

So, to keep track of the value assigned to `power` over time, we first need to reify it, as proposed in [GUIZZARDI; ZAMBORLINI, 2014; GUARINO; GUIZZARDI; SALES, 2018] promoting this attribute to a first citizen entity (Figure 42a). Next, we add a temporal property with the assigned value for the reified quality. However, how do we model the multiple assigned values over time this reified quality may get? Guizzardi and Zamborlini [GUIZZARDI; ZAMBORLINI, 2014] suggest changing the cardinality of the *describes* relation in Figure 42b, moving from 1:1 to 1:N. Although this approach solves the problem of representing multiple value assignments, it also may lead to a model misinterpretation. In this scenario, the cardinality may represent two different things: (i) multiple value assignments of the `Power` quality over time or; (ii) `Signal` has multiple `Power` attributes, which is not the case.

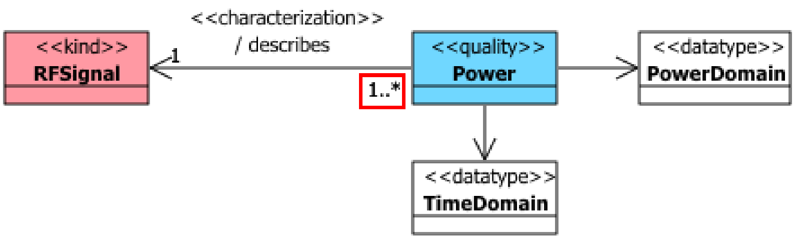
To avoid such misinterpretation, we use the capacity of UFO language that allows a moment to bear another moment [GUIZZARDI et al., 2015]. Thus, we propose that a reified quality can be characterized by another entity we call value assignment (`ValueAsgmt`), as described in Figure 42c. This new entity, meta-categorized as an intrinsic mode, bears all properties of the reified quality, such as the assigned value, the time, and the position of the assignment, among others. This approach saves the original conceptual model by

Figure 42 – Reification approaches

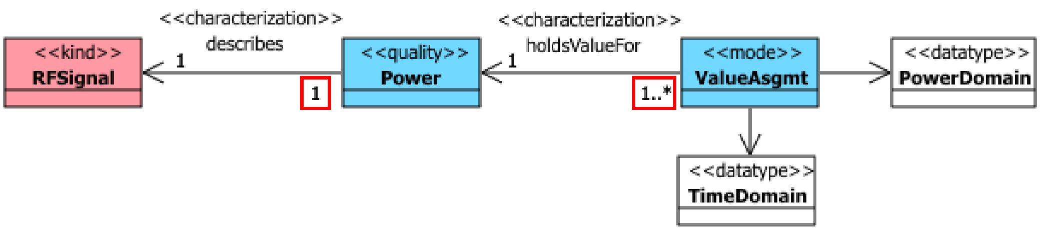
(a) Standard reification



(b) Reification proposed by [GUIZZARDI; ZAMBORLINI, 2014]



(c) Reification using an intermediary entity (`ValueAsgmt`)



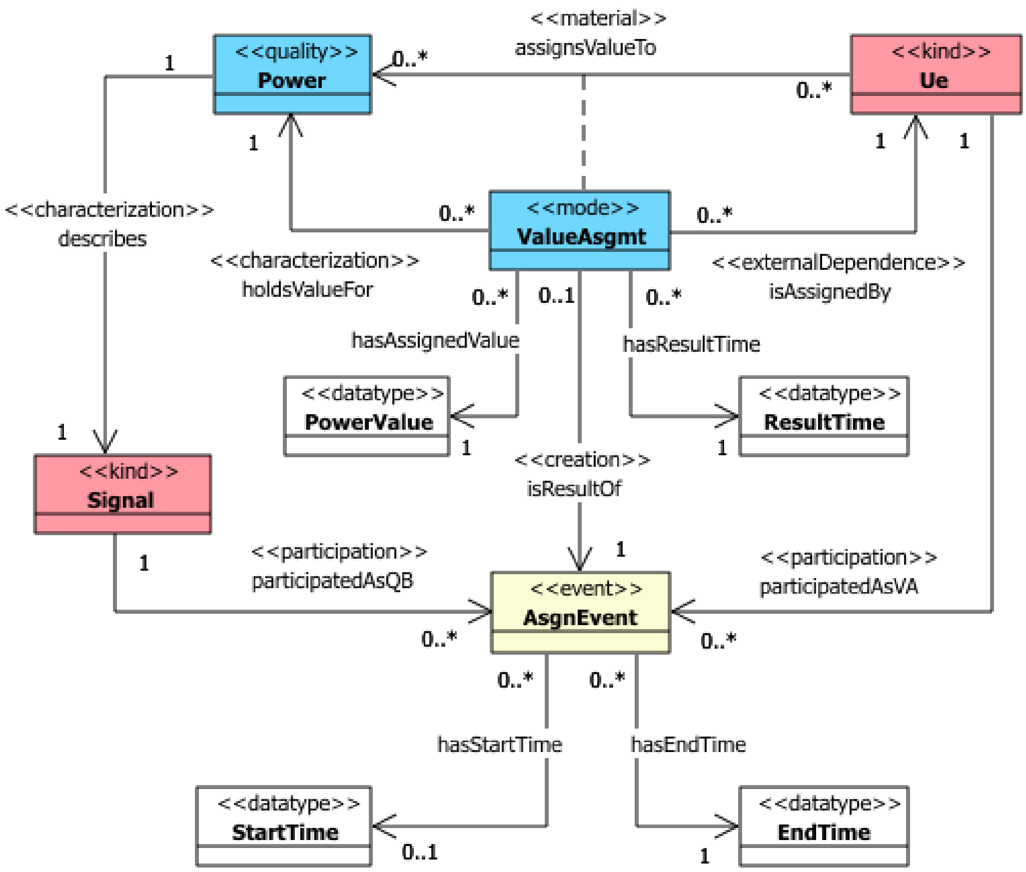
Source: Prepared by author.

preserving the 1:1 cardinality between the quality and its bearer as initially modeled.

Regardless of the possible approaches to represent multiple quality value assignments over time, the reification process also allows us to represent the entity responsible for the value assignment. In our motivational scenario, the `Ue` assigns a value to `Signal`'s `Power`, which is essential in the wireless network domain because the `Ue` is also the target of a possible handover evaluation. Thus, we propose that there is a material relation between `Ue` and `Power` (*assignsValueTo*), having `ValueAsgmt`, now meta-categorized as an extrinsic mode, the truthmaker of this unidirectional relation. This proposal is portrayed at the top of Figure 43.

However, the `ValueAsgmt` entity does not appear spontaneously. According to Guarino and Guizzardi [GUARINO; GUIZZARDI, 2015], an entity that makes a material relation between two relata true is founded by an event. Guarino et al. [GUARINO; GUIZZARDI; SALES, 2018] reinforces this view in their reification and truthmaking patterns studies. They suggest that a full truthmaking pattern describes how events set temporal properties in qualities. In this sense, we propose an event called `AsgnEvent`,

Figure 43 – Quality value assignment in mobile wireless network domain



Source: Prepared by author.

which represents the act of assigning a value to a quality and is the foundation of `ValueAsgmt`. Considering our motivational scenario, `AsgnEvent` has `Ue` and `Signal` as its participants, starting at (`StartTime`) and ending (`EndTime`), resulting in the `ValueAsgmt`. As a direct consequence of this modeling proposal, the association between `AsgnEvent` and `ValueAsgmt` sets the temporal property that allows keeping track of quality changes. Since the `EndTime` property of `AsgnEvent` is the point in time when a quality value assignment is eventually completed, the time value assigned to `AsgnEvent`'s `EndTime` must be the same set to `ValueAsgmt`'s `ResultTime` (Equation 4.9. Finally, we set the minimum cardinality towards `ValueAsgmt` to zero, acknowledging that an assigning value event may not lead to a successful value assignment. The proposed relation between `AsgnEvent` and `ValueAsgmt` and its consequences are presented at the bottom of Figure 43.

$$\forall a, b(AsgnEvent(a) \land ValueAsgmt(b) \land isResultOf(b, a) \land \\ hasEndTime(a, \{t\}) \rightarrow hasResultime(b, \{t\}) \quad (4.9)$$

It is important to note that the relation between `ValueAsgmt` and `AsgnEvent` provides more than temporal properties exchanging. It suggests that, conceptually, assigning a value to a quality (an event) should not be confused with the result of the act itself. This understanding is also presented in SOSA ontology while defining `phenomenonTime` and `resultTime` properties. Janowicz *et al.*[JANOWICZ et al., 2019] suggest that the *resultTime* data property is a point in time that the result of an observation is delivered. On the other hand, the *phenomenonTime* object property is interpreted as the period when the observation unfolds.

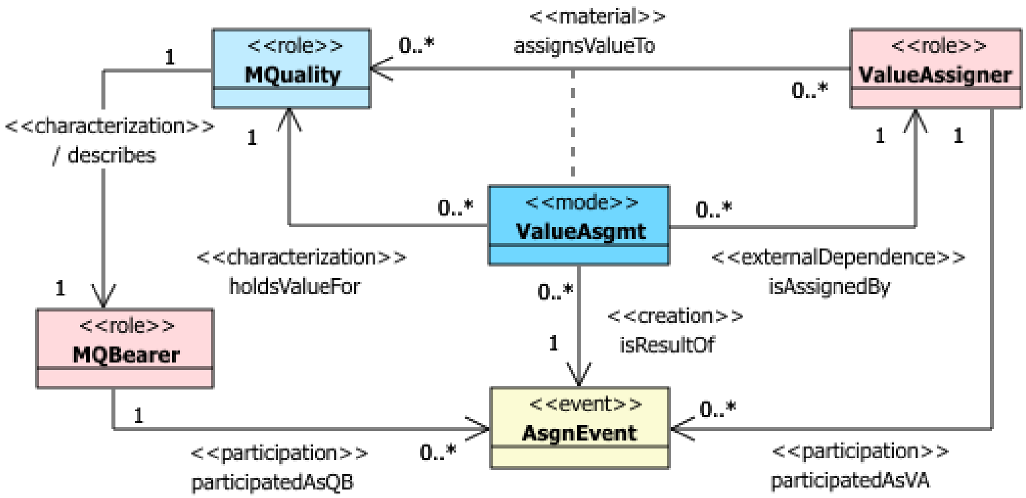
4.3.3.2 A Broader Conceptual Model For Value Assignment

In Section 4.3.3.1, we evaluated the act of assigning a value to a quality and its result by using a simple handover process scenario in a wireless network. There, we chose to use one reified quality (`Power`) of one quality bearer (`Signal`) to propose a way to collect quality assigned values over time while preserving the original cardinality between the quality and its bearer. We also acknowledge that a quality value is assigned by a value assigner (`Ue`) and is the result of an event of assigning a value (`AsgnEvent`). In this section, we propose a broader conceptual model for assigning values to qualities based on the case presented before. We focus on extending the model to other domains and handling the aggregation of complex value assignments and their related events.

In our motivational scenario, the `Signal` bears other qualities rather than `power`, such as `frequency` and `bandwidth`. Sometimes, values are assigned to these qualities in the same assigning event. Also, other quality bearers, such as the `Ue` and the `AP`, may simultaneously have values assigned to their qualities, such as `ipAddress`. Therefore, other entities in the mobile wireless network domain can play the role of quality bearers. But, looking at other domains, the value assignment approach in Section 4.3.3.1 seems to fit. For instance, we can have a domain dedicated to measuring the weight and height of a person. In this case, `Weight` and `Height` are qualities that bear the quality bearer `Person` having a `Scale` as its value assigner. Hence, we propose a general model in Figure 44 to apply our comprehension of how quality values can be assigned to qualities in any domain.

The `MQuality` represents a role that any quality whose values change over time - a mutable quality - can play. Consequently, the entity that bears mutable qualities starts playing the role of `MQBearer`. On the other hand, we may have an entity responsible for assigning a value to the `MQuality`, which can play the role of a `ValueAssigner`. Hence, a `ValueAsgmt` binds a `MQuality` and a `ValueAssigner`, which is the result of a `AsgnEvent`, having `MQBearer` and `ValueAssigner` as its participants. This general approach also changes the cardinality of the relation between `ValueAsgmt` and `AsgnEvent` since a single AsgnEvent may result in multiple `ValueAsgmt`. For instance, considering our motivational scenario in Section 4.3.3.1, an instance of `AsgnEvent` can produce multiple instances of `ValueAsgmt` while an instance of `Signal` plays the role of `MQBearer` and an instance of

Figure 44 – A reference ontology for quality value assignment



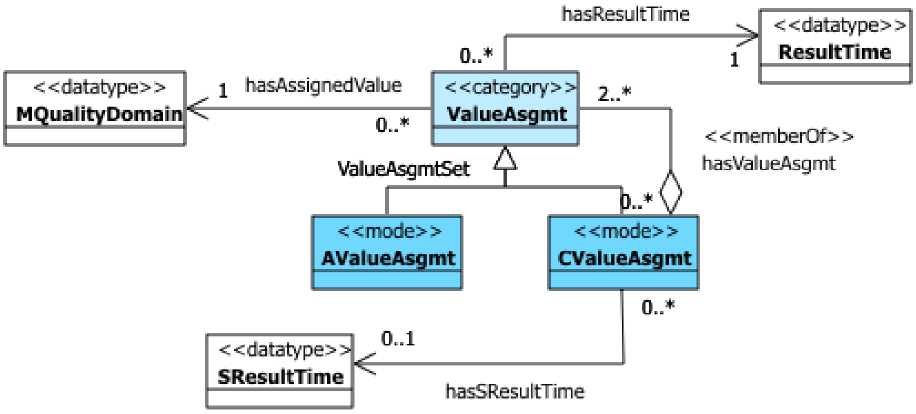
Source: Prepared by author.

`Ue` plays the role of `ValueAssigner`. Each instance of `ValueAsgmt` holds a value for each instance of the reified qualities of the `Signal` (`Power`,`Frequency` and `Bandwidth`).

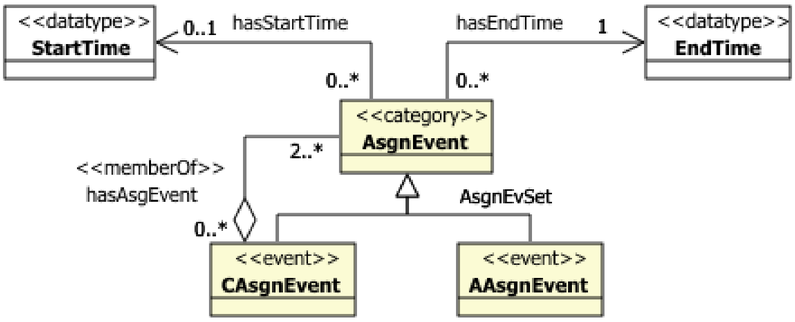
Another aspect that emerges while developing a broader conceptual model is how to handle the aggregations of value assignments and events. Figures 45a and 45b show our effort to model the aggregations of value assignments and assigning events. First, we define an atomic value assignment (`AValueAsgmt`) as a value assignment that holds a raw value to a single `MQuality` in a particular instant of time (`ResultTime`). On the other hand, a complex value assignment (`CValueAsgmt`) represents the aggregation of other value assignments. Although they also hold a value to a particular `MQuality`, it represents an aggregation of other values depending on how the aggregation was performed. Likewise, they are also characterized by a `ResultTime` but may have a starting result time (`SResultTime`) as a reflection of possible aggregation in time. In this sense, `ValueAsgmt` becomes a category of value assignments that generalizes (`AValueAsgmt`) and (`CValueAsgmt`). Taking the same approach, we define an atomic assigning event (`AAsgnEvent`) as an event that leads to a (`AValueAsgmt`). In contrast, a complex atomic assigning event (`CAsgnEvent`) leads to either a `AValueAsgmt` or a `CValueAsgmt`. Both events have a start (`StartTime`) and an ending time (`EndTime`) and, therefore, they can be specializations of a broader entity we hereafter call `AsgnEvent`.

Figure 45 – Value assignment aggregations

(a) Aggregation over value assignments



(b) Aggregation over events



Source: Prepared by author.

5 DESIGNING AN OPERATIONAL ONTOLOGY FOR MOBILITY MANAGEMENT

In this chapter, we keep following the SABiO approach and deliver operational ontologies based on the reference ontologies proposed in Chapter 4. In the next sections, we transform the reference ontologies into operational ontologies, investigating possible optimizations such as transforming material relations and suppressing single roles. Right after, we enrich the operational ontologies with reference ontology restrictions by using the semantic rules languages. Finally, we document them to follow the FAIR principles.

5.1 From A Reference To An Operational Ontology

Besides supporting the creation of sound conceptual models based on UFO foundational ontology, OntoUML has another interesting feature. Due to its active community of developers and users, a plugin[1] has been developed to work with the Visual Paradigm Modeling Tool [2]. Thus, ontology developers can design a reference model with automatic syntactic validation according to UFO theories and export OntoUML-based class diagrams as operational ontologies written in OWL, saving development time by delivering an operational ontology ready to be tested. However, we first should review some design aspects before transforming the reference ontologies proposed in Chapter 4 into operational ontologies. Our review focused on ontology modularization, material relations reification, and implementing entities playing roles.

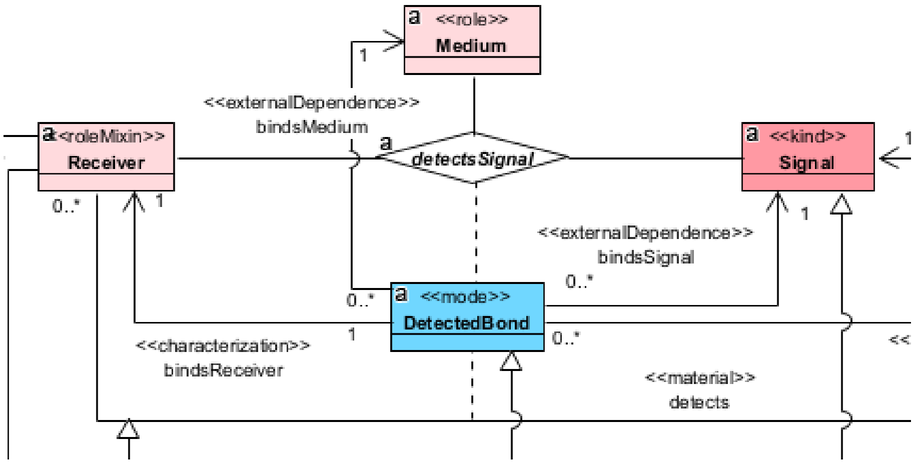
The reference ontologies proposed in Sections 4.3.1,4.3.2, and 4.3.3 sought to present the elements needed to support mobility management in mobile communication networks through semantic reasoning. Thus, the developed reference ontologies in Chapter 4 not only describe the necessary elements of a mobile communication network but also the process of assigning values to the attributes that characterize these elements over time. All the derived concepts and relations could be part of the same operational ontology. However, as discussed in Section 4.3.3, we have foreseen that the proposed reference ontology for quality value assignment could be used in other domains. Thus, we maintained the separation we had followed while developing the conceptual model: one reference ontology describing the mobile network elements and the other describing quality value assignments. Consequently, we derived two operational ontologies: one named "Heterogeneous Telecommunication Network Ontology" (**hint**) for the mobile network elements description and one named "Quality Value Assignment Ontology" (**qvas**) for quality value assignments descriptions.

1 available at <https://github.com/OntoUML/ontouml-vp-plugin>
2 available at <https://www.visual-paradigm.com/download/community.jsp>

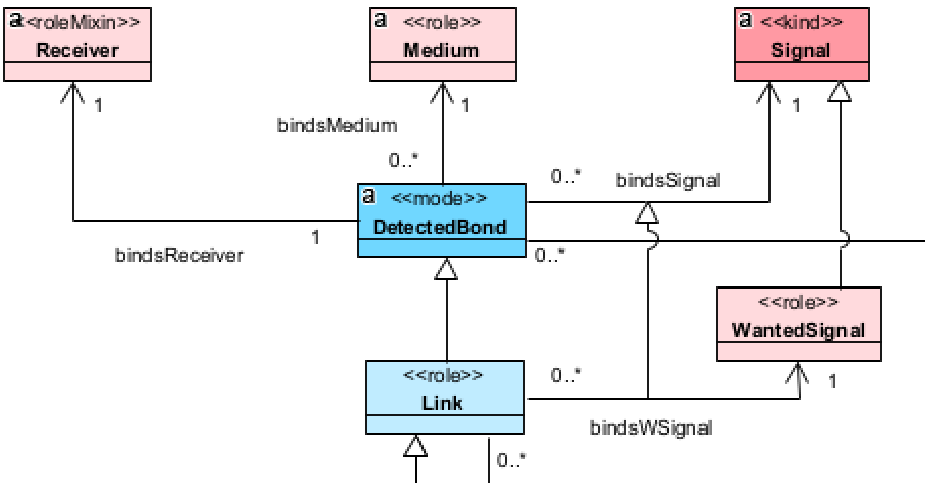
We also foresee that the proposed reference ontology for describing mobile wireless network elements (**hint**) could represent other communication networks, such as wired networks, or be optimized to represent one communication layer at a time. However, we left this work for future endeavors due to time and scope restrictions.

Figure 46 – Transformation of ternary relations

(a) Ternary relation in the reference ontology



(b) Ternary relation in the operational ontology

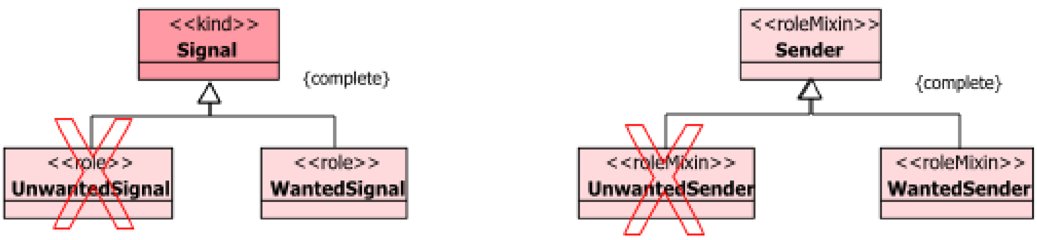


Source: Prepared by author.

One advantage of using UFO as our supporting foundational ontology is its inherent ability to represent the reification of material relations. At the ontology formalization phase using OntoUML, we simultaneously represent material relations and their reification (or truthmaker), improving our ontology conceptualization, especially concerning cardinality and n-ary relations analysis. However, at the design phase, we may choose which makes sense to keep. Thus, we reviewed all proposed material relationships to identify which one could be replaced by its truthmakers. For instance, we chose to remove the reified `SignalPropagation` EDM and keep the relation *propagatesOver(Signal, Medium)* since it was used only to describe a concept. On the other hand, all other material relationships proposed in the reference models were replaced by their truthmakers since we have to decorate such relationships with duration and performance indicators (e.g., throughput and latency), among others. It was especially needed to represent the ternary relationship `Signal-Medium-Receiver`. Figures 46a and 46b show an example of such transformation, where the ternary relation `detectsSignal` in the reference model is reified to (`DetectedBond`) in the operational model.

Finally, we reviewed all entities meta-categorized as **roles**. While representing roles in reference ontologies improves domain conceptualization and communication, it may lead to unnecessary descriptions in operational ontologies. For instance, let us take the reference model pictured in Figure 47. as an example. While it is important to communicate the possible roles of `Signal` and `Sender` in the reference ontology, it is not useful to represent `UnWantedSignal` and `UnWantedSender` in the operational ontology. We, therefore, suppressed them in the operational ontologies. Other roles were reviewed as candidates for suppression, such as `ULNode` and `LLNode`. They are the only generalization set of `ServiceNode` relating only with each other. However, in this case, the roles provide the means for building restrictions and should not be suppressed (e.g., `Commboard` can only play the role of `LLNode`).

Figure 47 – Candidates for role supression



Source: Prepared by author.

After these reviews and adjustments, we re-checked their syntactic consistency. Finally, we created the operational ontologies (**hint** and **qvas**) as machine-readable artifacts written in OWL using the export feature of the OntoUML plugin in Visual Paradigm. As research artifacts, both ontologies should be FAIR complaint, as described in Section 2.3.3. In this sense, we improve our operational ontologies as follows:

Findability: Both operational ontologies were registered at the Internet Archive organization to receive persistent URLs as unique identifiers. The **hint** and **qvas** can be respectively founded at <https://purl.org/s2c2/hint> and <https://purl.org/s2c2/qvas>

Accessibility: Both ontologies are available under CC BY 4.0 license [3]

Interorability and Reusability: All concepts and relationships are described in the ontology using standard vocabularies such as Dublin Core and RDFS.

5.2 Setting Ontology Restrictions

The exported operational ontologies are incomplete unless we can apply the restrictions detected while developing the reference ontologies. Unfortunately, the OntoUML plugin does not support describing restrictions and transforming them into a semantic web rule language. To overcome this limitation, we used the Protege Ontology Editor[4][MUSEN, 2015] along with its SWRL plugin to complement **hint** and **qvas** with the required restrictions.

Each equation described in Chapter 4 is transformed into semantic web rules using OWL Axioms or SWRL. Tables 5,6 and 7 show the transformations for **hint** ontology while Table 8 shows the transformation for **qvas** ontology.

[3] available at <https://creativecommons.org/licenses/by/4.0/legalcode>

[4] available at <https://protege.stanford.edu/>

Table 5 – Transformation of `CommBoards` taxonomy restrictions into semantic web rules

Op. Ontology	**hint**
Ref. Ontology Eq.	$\forall a(Tx(a) \rightarrow \neg Receiver(a))$
Rule Transf. Language	**OWL Axiom**
Rule Statement	`:Receiver owl:disjointWith :Tx`

(a) Reference Ontology Equation 4.3

Op. Ontology	**hint**
Ref. Ontology Eq.	$\forall a(Rx(a) \rightarrow \neg Sender(a))$
Rule Transf. Language	**OWL Axiom**
Rule Statement	`:Sender owl:disjointWith :Rx`

(b) Reference Ontology Equation 4.4

Op. Ontology	**hint**
Ref. Ontology Eq.	$\forall a, b, c(TRx(a) \wedge Tx(b) \wedge Rx(c) \wedge (hasTx(a, b) \vee hasRx(a, c) \rightarrow \neg(Sender(a) \wedge Receiver(a))$
Rule Transf. Language	**SWRL**
Rule Statement	$TRx(?a) \wedge Tx(?b) \wedge hasTx(?a, ?b) \wedge Sender(?a) \wedge Sender(?b) \rightarrow sameAs(?a, ?b)$ $TRx(?a) \wedge Rx(?b) \wedge hasRx(?a, ?b) \wedge Receiver(?a) \wedge Receiver(?b) \rightarrow sameAs(?a, ?b)$

(c) Reference Ontology Equation 4.1

Table 6 – Transformation of `HandShakeBond` restrictions into semantic web rules

Op. Ontology	**hint**
Ref. Ontology Eq.	$\forall a, b(handshakes(a, b) \rightarrow (TRx(a) \wedge TRx(b) \wedge (a \sqsubseteq \neg b))$
Rule Transf. Language	**SWRL**
Rule Statement	$TRx(?a) \wedge TRx(?b) \wedge HandShakeBond(?c) \wedge bindsTRx(?c, ?a) \wedge bindsTRx(?c, ?b) \rightarrow differentFrom(?a, ?b)$

(a) Reference Ontology Equation 4.5

Op. Ontology	**hint**
Ref. Ontology Eq.	$\forall a, b, c(TRx(a) \wedge TRx(b) \wedge HandShakeBond(c) \wedge bindsTRx(c, a) \wedge bindsTRx(c, b) \rightarrow \exists d, e \vert SelectedBond(d) \wedge SelectedBond(e) \wedge bindsReceiver(d, b) \wedge bindsSender(d, a) \wedge bindsReceiver(e, a) \wedge bindsSender(e, b) \wedge hasSelectedBond(c, d) \wedge hasSelectedBond(c, e)$
Rule Transf. Language	**SWRL**
Rule Statement	$TRx(?a) \wedge TRx(?b) \wedge HandShakeBond(?c) \wedge bindsTRx(?c, ?a) \wedge bindsTRx(?c, ?a) \wedge SelectedBond(?d) \wedge SelectedBond(?e) \rightarrow bindsReceiver(?d, ?b) \wedge bindsSender(?d, ?a) \wedge bindsReceiver(?e, ?a) \wedge bindsSender(?e, ?b) \wedge hasSelectedBond(?c, ?d) \wedge hasSelectedBond(?c, ?e)$

(b) Reference Ontology Equation 4.6

Table 7 – Transformation of `PeerNode`s restrictions into semantic web rules

Op. Ontology	**hint**
Ref. Ontology Eq.	$\forall a, b, c, d(CommDevice(a) \land CommDevice(b) \land LayerNode(c) \land LayerNode(d) \land hasLN(a, c) \land hasLN(b, d) \land detects(c, d) \rightarrow (a \sqsubseteq \neg b))$
Rule Transf. Language	**SWRL**
Rule Statement	$CommDevice(?a) \land CommDevice(?b) \land LayerNode(?c) \land LayerNode(?d) \land Link(?e) \land hasLN(?a, ?c) \land hasLN(?b, ?d) \land bindsReceiver(?e, ?c) \land bindsSender(?e, ?d) \rightarrow differentFrom(?a, ?b)$

(a) Reference Ontology Equation 4.7

Op. Ontology	**hint**
Ref. Ontology Eq.	$\forall a, b, c, d(PeerNode(a) \land PeerNode(b) \land Protocol(c) \land Protocol(d) \land hasProtocol(a, c) \land hasProtocol(b, d) \land decodes(a, b) \rightarrow (c \equiv d))$
Rule Transf. Language	**SWRL**
Rule Statement	$PeerNode(?a) \land PeerNode(?b) \land Protocol(?c) \land Protocol(?d) \land Link(?e) \land isProtocolOf(?c, ?a) \land isProtocolOf(?d, ?b) \land bindsReceiver(?e, ?a) \land bindsSender(?e, ?b) \rightarrow sameAs(?c, ?d)$

(b) Reference Ontology Equation 4.8

Table 8 – Transformation of `ValueAsgmt` restrictions into semantic web rules

Op. Ontology	**qvas**
Ref. Ontology Eq.	$\forall a, b(AsgnEvent(a) \land ValueAsgmt(b) \land isResultOf(b, a) \land hasEndTime(a, \{t\}) \rightarrow hasResultime(b, \{t\})$
Rule Transf. Language	**SWRL**
Rule Statement	$AsgnEvent(?a) \land ValueAsgmt(?b) \land isResultOf(?b, ?a) \land endTime(?a, ?value) \rightarrow resultTime(?b, ?value)$

(a) Reference Ontology Equation 4.9

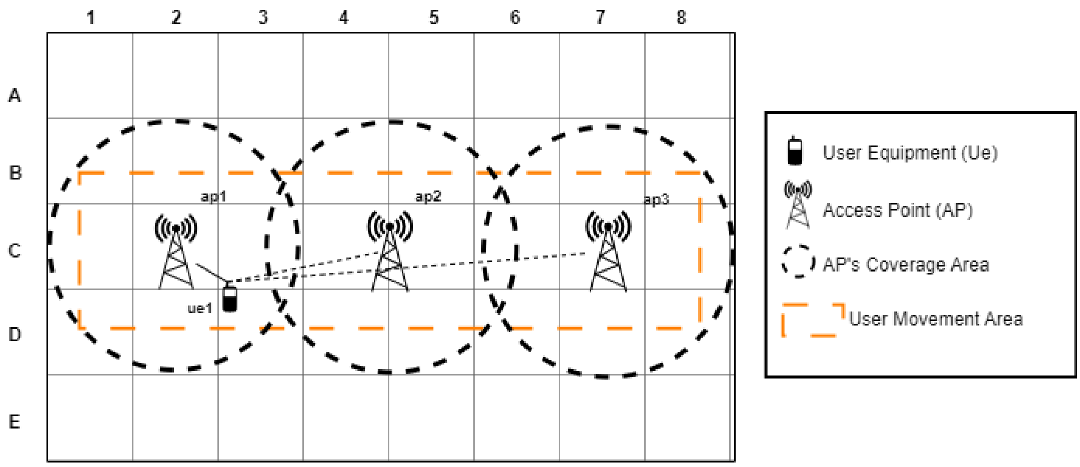
6 THE UBIQUITOUS COVERAGE USE CASE

The goal of this chapter is twofold: (i) show that developed operational ontologies can represent the mobile wireless network elements along with the configuration and measurement of their attributes and; (ii) show that the reasoning capacities can support the handover process. We propose a hypothetical scenario, setting the expected behavior and building the environment to simulate the scenario.

6.1 The Emulation Scenario For The Ubiquitous Coverage Case

Figure 48 shows our emulation scenario representing a hypothetical mobile wireless network comprising three access points (`ap1`,`ap2`, and `ap3`) covering an area inside a cartesian coordinate grid. This wireless network provides communication services for a user's equipment (`ue1`), which can move around a delimited movement area (dashed orange line).

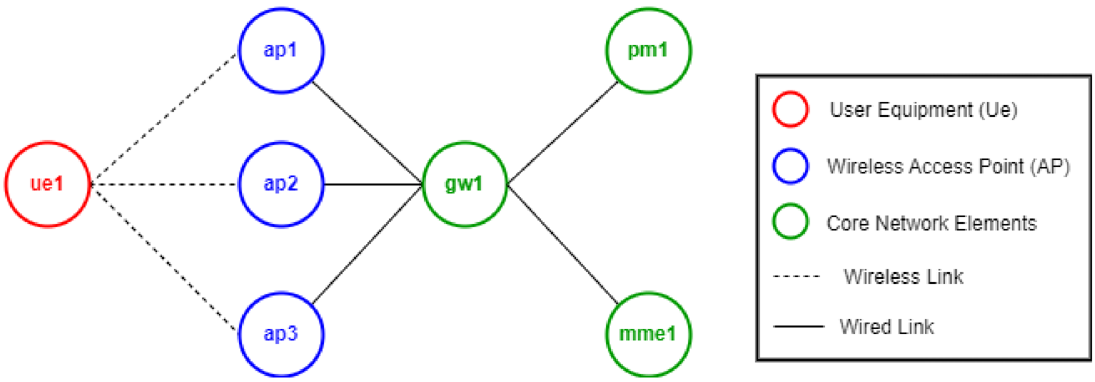
Figure 48 – The wireless network for the emulation scenario



Source: Prepared by author.

Figure 49 presents the topology of the envisioned wireless network. The three access points allow `ue1` to use the network services whenever they are selected as `ue1`'s serving AP. These APs are wired-attached to a gateway (`gw1`), allowing data transfer between `ue1` and the performance monitoring server (`pm01`) acting as `ue1`'s network performance testing point. Also, `gw1` provides communication between the APs and the network mobility management entity (`mme1`), which has two responsibilities. First, it is responsible for storing the radio frequency(RF) environment and the network performance test results produced by `ue1` to enrich the `mme1` decision-support system. It is also responsible for evaluating the current attachment between `ue1` and its serving AP according to the ubiquitous coverage use case presented in Section 4.2.

Figure 49 – The network topology of the emulation scenario

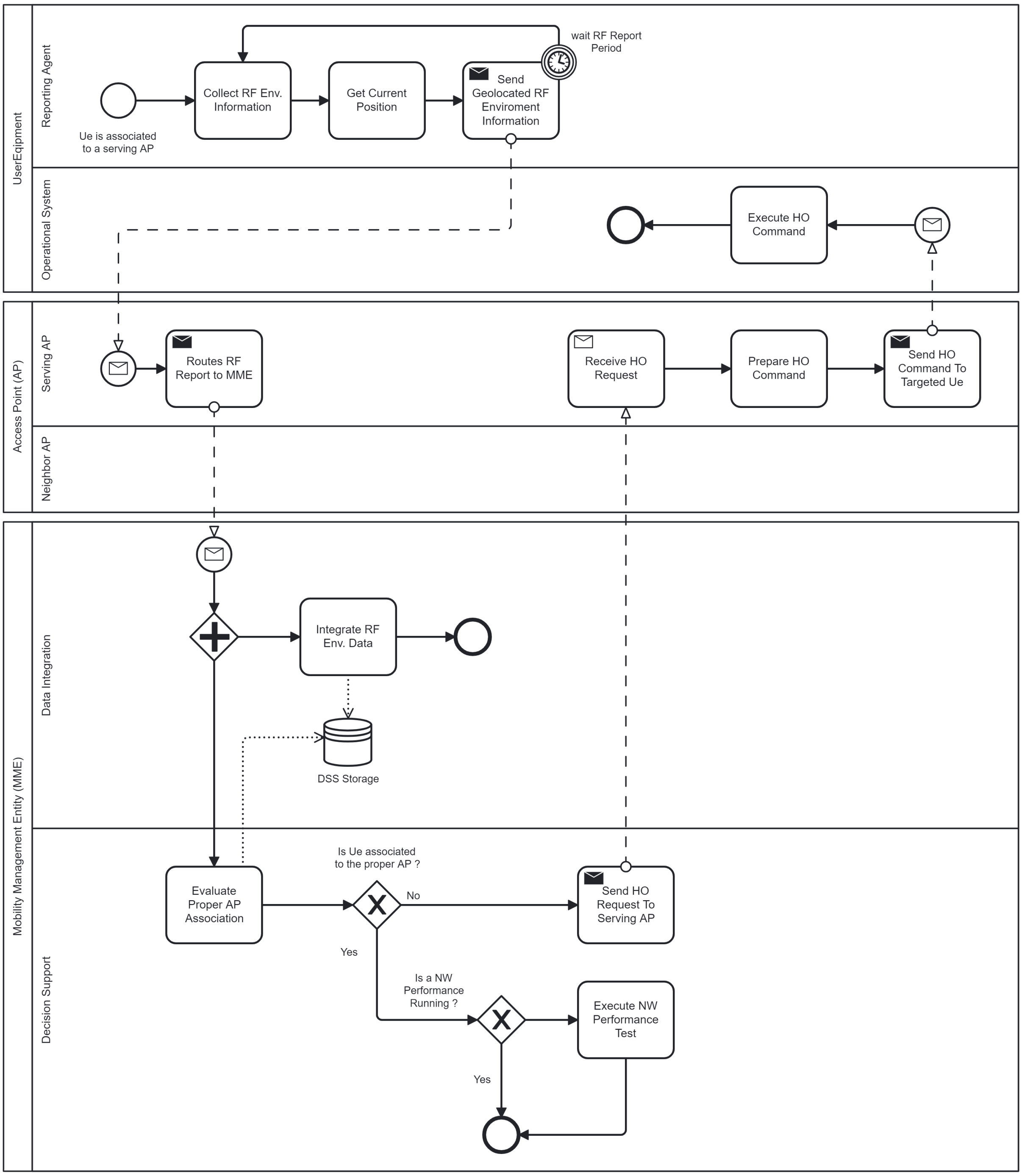


Source: Prepared by author.

Using the BPMN business modeling notation, Figure 50 shows the expected behavior and information flow between the wireless network elements, access points, and user equipment. The process begins whenever a user's equipment (Ue) is already attached to a serving AP. Once attached, the Ue begins collecting information about the RF environment, such as the received signals properties (e.g., power strength, frequency, bandwidth, among others) coming from the serving AP and its neighbor APs. Then, the Ue adds its current position to the previous RF environment collection and sends it to the mobility management entity (MME) of the network through its serving AP. Once sent, the Ue waits for the configured reporting period to repeat the task.

The serving AP receives the Ue's RF environment report and routes it to the network mobility management entity (MME). Once the Ue's RF environment report is received, the MME processes it and loads it into the decision support repository according to the provided network ontology. Simultaneously, the MME starts the evaluation of the current association between Ue and its serving AP. This evaluation uses the current RF report information and historical data, if available, to decide if the current association between the Ue and the serving AP is the most appropriate to guarantee ubiquitous coverage for the network user. The result of the evaluation determines whether the MME will request the Ue to change its association to a new serving AP to keep continuous coverage or whether it will just perform a network performance test. In the first case, the MME sends a message to the current serving AP to handle the HO request to Ue, informing the new serving AP. Once the message reaches the Ue's serving AP, it sends the HO command instruction to the Ue. Then, when the Ue recognizes the HO command from the serving AP, it initiates the HO execution to attach itself to the new serving AP selected by the MME. Alternatively, when the MME decides that the Ue is still associated with the most appropriate AP, it uses the opportunity to evaluate if a network performance test (TCP/UDP throughput, latency) can be executed.

Figure 50 – Process flow of the emulation scenario



Source: Prepared by author.

6.2 Building The Emulation Environment

The cornerstone of developing the wireless network emulation described in Section 6.1 is the Mininet-WiFi network emulator. It is a Python-based open-source network emulator that extends the capabilities of the well-known Mininet emulator by enabling the creation of software-defined wireless networks (SDWN) composed of virtual WiFi-based stations and access points [FONTES et al., 2015]. Moreover, it allows researchers and developers to simulate WiFi-based networks in different scenarios involving user mobility, wireless security, and quality of service (QoS). Looking at our proposed emulation scenario in Section 6.1, the Mininet-WiFi allows us to create all the network elements (ue1, ap1, ap2, ap3, gw1, pm1, and mme1) and their respective wireless or wired associations according to the proposed topology in Figure 49. However, the Mininet-Wifi features alone do not cover all the functionalities described in Figure 50. Thus, the emulation script relies on other supporting Python packages (owlready2 and mqtt) and operational system applications to perform network performance tests (ping and iPerf3).

The **owlready2** is a Python package for ontology-oriented programming able to load, modify, and save OWL 2.0 ontologies as Python objects [LAMY, 2017]. Also, it provides semantic reasoning features through SWRL rules and built-in semantic reasoners such as HermiT or Pellet. In our scenario, it supports the emulation script by representing the proposed wireless network using *hint* and *qvas* ontologies along with the proposed OWL Axioms and SWRL rules, becoming able to reason about forbidden associations and infer knowledge using the Pellet reasoner.

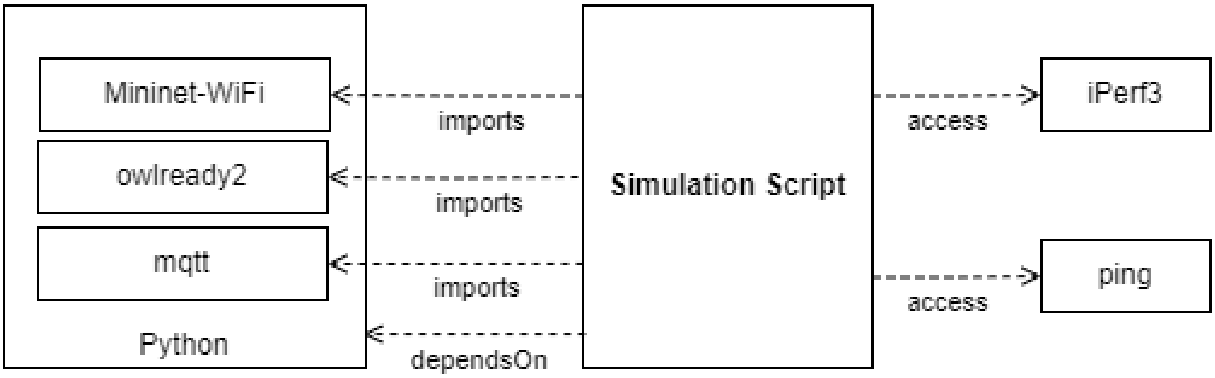
The **mqtt** Python package is a library that interacts with the Message Queue Telemetry Transport (MQTT) messaging protocol, a publish-subscribe protocol designed for communication in resource-constrained environments. This package allows network elements to act as servers (brokers) or clients. In server mode, the program becomes a central message broker responsible for receiving messages published by clients and delivering them to subscribed clients based on topics. In client mode, the program can publish messages on specific topics and subscribe to receive messages published by other clients. In our proposed emulation scenario, `ue1` plays the client role, and `mme1` plays the broker role, integrating RF environment information and network performance results.

Finally, while **ping** evaluates the round trip time between two network elements, giving us latency measurements, **iPerf3** executes TCP/UDP throughput tests. In our emulation scenario, the script calls both programs to perform the network performance tests between `ue1` and `pm1`. Figure 51 shows the emulation script dependency on Python, importing Mininet-WiFi, owlready2, and mqtt packages, among others, and the access of ping and iPerf3 programs.

6.3 Developing The Emulation Script

Our emulation script has three major functional blocks: network topology configuration, environment and performance report, and handover evaluation. The following sections detail each block.

Figure 51 – Dependencies of the emulation script functionalities dependencies



Source: Prepared by author.

6.3.1 Network Topology Configuration

In this block, we configure the network topology as portrayed in Figure 49 using two methods: `buildTopo` and `buildOnto`. The `buildTopo` method is responsible for building the network topology for the Mininet-Wifi engine. It uses `buildOnto` to create an instance of the emulation ontology representing the same network built for Mininet-Wifi. Listing 6.1 shows the main instructions to build our simulated wireless network scenario, as follows:

Line 3: creates the network, establishing the type of controllers it will use and some wireless environmental parameters;

Lines 5-12: creates the wireless user(`ue1`) and the wireless nodes(`ap1`,`ap2`,`ap3`) of the network, setting some attributes such as channel, bandwidth, mode, MAC and IP addresses, among others. It also sets the propagation model that will simulate the WiFi signal strength at each space-time snapshot;

Lines 13-15: creates the wired nodes (`mme1`,`gw1`,`pm1`), setting only the attributes we need to run the emulation;

Lines 17-21: sets the links between the wired nodes and between the network gateway (`gw1`) and the wireless access points;

Lines 23-26: set the mobility behavior of the user equipment (e.g. `ue1`). In this case, we set a simple straight movement from a point next to `ap1` to a point next to `ap3`;

Line 28: calls the `buildOnto` method to mirror the configured network in an ontology supported by **hint** and **qvas** ontologies;

Lines 30-35: starts the configured network.

Listing 6.1 – Mininet-WiFi network configuration

```
def buildTopo():

    net = Mininet_wifi(controller=Controller,
        link=wmediumd,wmediumd_mode=interference, noise_th=-91, fading_cof=3)

    ap1 = net.addAccessPoint('ap1', ssid='hoSim', mode='a', channel='36',
        position='25,50,0', ip='10.0.0.11/8',range=15)
    ap2 = net.addAccessPoint('ap2', ssid='hoSim', mode='b', channel='6',
        position='50,50,0', ip='10.0.0.12/8',range=15)
    ap3 = net.addAccessPoint('ap3', ssid='hoSim', mode='a', channel='40',
        position='75,50,0', ip='10.0.0.13/8',range=15)
    ue1 = net.addStation('ue1', mac='00:00:00:00:00:02', ip='10.0.0.20/8', min_x=7,
        max_x=53, min_y=22, max_y=38, min_v=5, max_v=10,range=1)

    net.setPropagationModel(model="logDistance", exp=4)
    net.configureWifiNodes()

    mme1 = net.addController('mme1',ip='10.0.0.1/8')
    gw1 = net.addHost('gw1',ip='10.0.0.2/8')
    pm1 = net.addHost('pm1',ip='10.0.0.3/8')

    net.addLink(ap1, gw1)
    net.addLink(ap2, gw1)
    net.addLink(ap3, gw1)
    net.addLink(gw1, pm1)
    net.addLink(gw1, mme1)

    net.startMobility(time=0)
    net.mobility(ue1, 'start', time=1, position='7,35,0')
    net.mobility(ue1, 'stop', time=10, position='50,35,0')
    net.stopMobility(time=60)

    buildOnto(net)

    info("*** Starting network\n")
    net.build()
    mme1.start()
    ap1.start([mme1])
    ap2.start([mme1])
    ap3.start([mme1])
```

The `buildOnto` method relies on the owlready2 package to create our decision-support system enriched with semantic reasoning capabilities. This method transforms the configured network in Mininet-WiFi into an emulation ontology (e.g., `eonto`), which stores the network's element configuration and performance measurement results and allows the execution of SPARQL queries and semantic reasoning assertions. Listing 6.2 shows a fragment of `buildOnto` instructions to load he Mininet-WiFi configuration, as follows:

Lines 3-8: create the `eOnto` ontologies importing local versions of **hint** and **qvas** exported in RDF/XML, since owlready2 is unable to parse ttl format;

Lines 10-11: retrieve the network nodes created in Mininet-WiFi and establishes a unique loading time reference for all values assignment;

Lines 13-21: start loading the Mininet-Wifi nodes as **hint**'s `CommDevices`, associating with their initial positions through the *isPositionOf* object property. The `Position` attribute is then associated with a **qvas** value assignment entity through the *holdsValueFor* object property. Finally, the node's position and the assignment's timestamp are associated with the *holdsValueFor* and *hasResultTime* data properties.

Listing 6.2 – Emulation ontology loading

```
1  def buildOnto(nw):
2
3      nwOnto = get_ontology("file:///home/workdir/hint/obase/hint-r.owl").load()
4      msOnto = get_ontology("file:///home/workdir/hint/obase/qvas-r.owl").load()
5      eOnto = get_ontology("file:///home/workdir/hint/obase/eonto.owl")
6
7      eOnto.imported_ontologies.append(nwOnto)
8      eOnto.imported_ontologies.append(msOnto)
9
10     nodes = nw.stations()
11     base_time = time.time()
12
13     with eOnto:
14         for eachNode in nodes:
15             cd = nwOnto.CommDevice(eachNode.name)
16             cd_pos = nwOnto.CommDevice(eachNode.name + "_pos")
17             cd_pos.isPositionOf.append(cd)
18             cd_pos_vasgmt = msOnto.ValueAsgmt(eachNode.name + "_pos_" + base_time)
19             cd_pos_vasgmt.holdsValueFor.append(cd_pos)
20             cd_pos_vasgmt.hasAssignedValue(eachNode.position)
21             cd_pos_vasgmt.hasResultTime(base_time)
22     # code continues
```

6.3.2 Environment and Performance Report

In this block, we set the reporting procedures described in Section 6.2. They were developed considering the user equipment as the monitor of the RF environment and the network's performance. There are three methods to accomplish this: `nwMonPS`, `nwPingPS`, and `nwIperfPS`. They use the **mqtt** and Python's thread packages to publish the collected data over predefined topics. The `nwMonPS` method collects data using the Mininet-Wifi methods to extract RF environment attributes. In contrast, `nwPingPS` and `nwIperfPS` use Linux **ping** and **iPerf3** commands to retrieve performance data. The published data is collected by another method (`rtvData`) by subscribing to the same predefined topics. Listing 6.3 shows a fragment of the code exemplifying the report methods as follows:

Lines 1-8: create the auxiliary methods to use the thread approach for RF environment and network performance monitoring (`createThread`) and to invoke a publish and subscribe broker (`mqtt_conn`) ;

Lines 9-26: define the `nwMonPS` method responsible for the RF Environment monitoring. It takes the monitoring network node (e.g., `ue1`), the reporting period, and the list of RF attributes to be collected. Then, it sets the mqtt client to publish the collected data and uses Mininet-WiFi methods to retrieve the RF attributes as seen by the monitoring network node. If no RF attribute is set to be reported, the method collects all RF attributes defined for the monitoring network node type in Mininet-WiFi. Finally, it publishes the collection result in the *rfmon* topic and executes the handover evaluation (`evalHO`) as a thread.

Lines 27-41: define `nwPingPS` method responsible for the round trip time performance monitoring. It works like the `nwMonPS` method. Still, instead of using Mininet-WiFi methods to execute the performance test, the Linux ping command from Linux is used to evaluate the network latency. Although not presented in Listing 6.2, `nwIperfPS` works similarly but uses the Linux iPerf3 command to retrieve TCP and UDP performance tests.

Listing 6.3 – RF environment and performance report

```
1 def createThread(fc, argList):
2     t = threading.Thread(target=fc, args=(argList))
3     t.daemon = True
4     t.start()
5 def mqtt_conn(broker_address,pnode):
6     client = mqtt.Client(pnode)
7     client.connect(broker_address)
8     return client
```

```python
def nwMonPS(nwnode, period=1, list=None):
    node_name = nwnode.wintfs[0].name
    p = mqtt_conn("localhost",node_name)
    measDict = {}
    while True:
        measDict.clear()
        measDict.update({'node': nwnode.wintfs[0].name})
        measDict.update({'timestamp': time.ctime(time.time())})
        measDict.update({'position': nwnode.position})
        if list == None:
            measDict.update({'nwmeas': nwnode.wintfs[0].__dict__})
        else:
            for eachAttr in list:
                measDict.update(
                    {eachAttr: getattr(nwnode.wintfs[0], eachAttr)})
        p.publish("rfmon/" + node_name,json.dumps(measDict))
        createTread(evalHO,nwnode)
        time.sleep(period)
def nwPingPS(src, dst, period=5):
    node_name = src.wintfs[0].name
    pping = mqtt_conn("localhost",node_name)
    time.sleep(5)
    perfDict = {}
    while True:
        pingResult = src.cmd('ping', '-c 10 -q', dst.wintfs[0].ip)
        perfDict.clear()
        perfDict.update({'timestamp': time.ctime(time.time())})
        perfDict.update({'source': src.wintfs[0].name})
        perfDict.update({'destination': dst.wintfs[0].name})
        perfDict.update({'pingResult': pingResult.split('\r\n')[3]})
        perfDict.update({'rttResult': pingResult.split('\r\n')[4]})
        pping.publish("ping/" + node_name,json.dumps(perfDict))
        time.sleep(period)
```

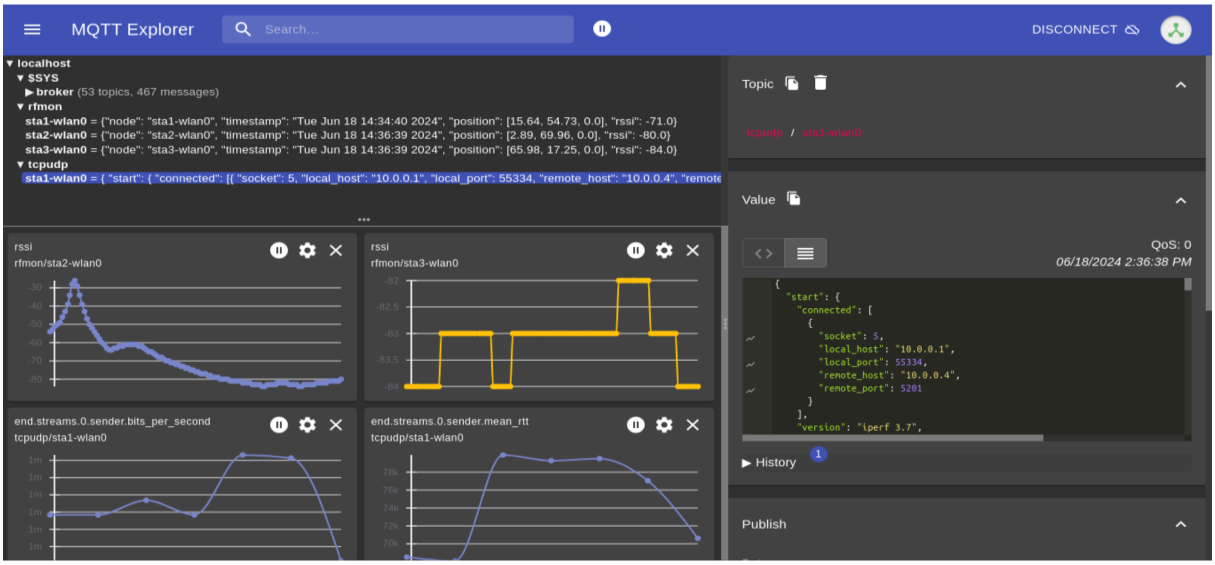
Figure 52 shows a running example using the MQTT explorer[1] to show the published RF environment and network performance topics.

6.3.3 Handover Evaluation

The functionalities of the handover evaluation based on semantic reasoning were limited by two factors: (i) **hint** ontology still does not cover the concept of prediction as described in Table 4. (ii) the Mininet-WiFi emulator does not represent multiple radio access technologies, only IEEE 802.X protocols. Nevertheless, the implemented competence questions can still provide semantic reasoning to support the handover process. For instance,

[1] available at <https://mqtt-explorer.com/>

Figure 52 – A running example of the RF environment and performance monitoring



Source: Prepared by author.

to overcome the incapacity of the emulator to represent multiple RATs, we treat the ***a*** and ***a*** modes of the WiFi signal as if they were two different RATs. With this approach, we could implement a set of competence questions of the ubiquitous coverage case to evaluate the strength of server and neighbor signals and the types of `CommBoards` the `CommDevice` bear. Listing 6.4 show SPARQL query for CQ14 (current server received signal power) used by *evalHO* method to assess the need to start the handover process:

Listing 6.4 – Handover evaluation

```
def exSparql(onto,spquery):
    return list(onto.sparql(spquery))
def evalHO(nwnode):
    cq14 = f"
    PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
    PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
    PREFIX qvas: <https://purl.org/s2c2/qvas#>
    PREFIX hint: <https://purl.org/s2c2/hint#>
    PREFIX : <http://www.example.com/exho/>
    SELECT (MIN(?avalue) as ?lavalue) (MAX(?rtime) as ?lrtime) WHERE
    { ?dbnd hint:bindsReceiver :ue1-cb1.
        ?dbnd rdf:type hint:SelectedBond.
        ?dbnd hint:bindsSSignal ?ssgn.
        ?ssgnpwr rdf:type :Power.
        ?ssgnpwr qvas:describes ?ssgn.
        ?msrslt qvas:holdsValueFor ?ssgnpwr.
        ?msrslt qvas:isAssignedBy :ue1-cb1.
        ?msrslt qvas:resultTime ?rtime.
        ?msrslt qvas:assignedValue ?value. }
```

```
    ?msrslt qvas:assignedValue ?value. }
"

eOnto = get_ontology("file:///home/workdir/hint/obase/eonto.owl").load
exSparql(eOnto,cq14)
```

6.4 Handover Execution Experiment

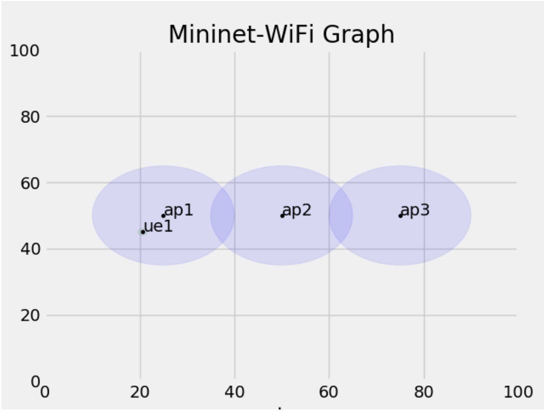
To evaluate the semantic reasoning capabilities of the developed operational ontologies so far, an inter-radio access technology (IRAT) handover situation was used as a use case for ensuring ubiquitous coverage (as described in Section 6.1). Unfortunately, to the best of the author's knowledge, there is no wireless emulator capable of dealing with IRAT handovers. To overcome this limitation, we configured the access points in the Mininet-WiFi emulator with incompatible WiFi modes as a proxy for IRAT handover situation. Therefore, in the proposed scenario,`ap1` and `ap3` were set to transmit a WiFi Signal in mode ***a***, while `ap2` was set to transmit in mode ***b***. Also, `ue1` is forced to start working only with mode ***a***, and the auto-association feature that allows the automatic WiFi mode selection by the user equipment is disabled. With this configuration, the handover process would not be executed without changing the WiFi mode of the user through a decision-making request using the `evalHO` method. Listing 6.5 shows these settings.

Listing 6.5 – Emulation setting for handover execution without auto-association

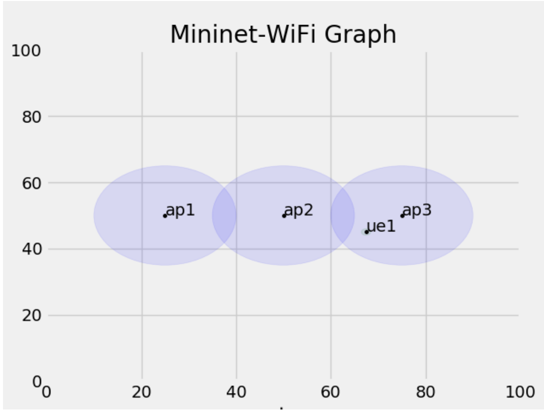
```
net = Mininet_wifi(controller=Controller, link=wmediumd,wmediumd_mode=interference,
    noise_th=-91, fading_cof=3, allAutoAssociation = False)

info("*** Creating wireless nodes\n")
ap1 = net.addAccessPoint('ap1', ssid='hoSim', mode='a', channel='36',
    position='25,50,0', ip='10.0.0.11/8',range=15)
ap2 = net.addAccessPoint('ap2', ssid='hoSim', mode='b', channel='6',
    position='50,50,0', ip='10.0.0.12/8',range=15)
ap3 = net.addAccessPoint('ap3', ssid='hoSim', mode='a', channel='40',
    position='75,50,0', ip='10.0.0.13/8',range=15)
ue1 = net.addStation('ue1', mac='00:00:00:00:00:02', ip='10.0.0.20/8', min_x=7,
    max_x=53, min_y=22, max_y=38, min_v=5, max_v=10, range=1, mode='a')
```

Three distinct tests were executed to evaluate the effectiveness of the semantic-based handover using the same coverage scenario but changing some settings. In all three tests, `ue1` starts close to `ap1` and stops near `ap3` at the same running speed (Figure 53). First, the Mininet-WiFi standard handover behavior was executed by using the automatic auto-association with access points set to mode ***a***. This first test is used as a reference for comparison. In the second test, the auto-association feature is disabled, and the WiFi

Figure 53 – Starting and ending points of the emulation



(a) Emulation starting point



(b) Emulation end point

Source: Prepared by author.

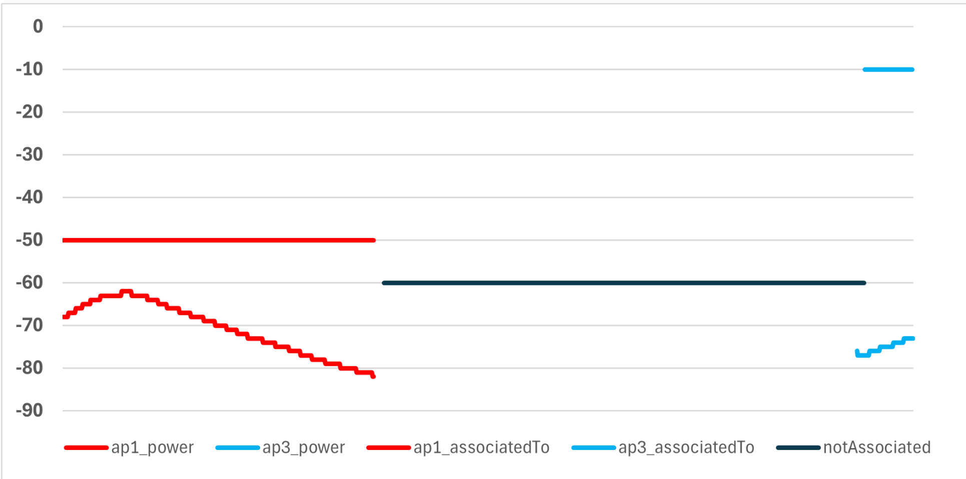
mode of `ap2` is set to ***b***. In this case, a failure is expected between `ap1` and `ap2` since both WiFi modes are incompatible. In the last test, the settings of the second test remain the same, but the proposed semantic-based handover method (`evalhO`) is enabled.

Figure 54a shows the first test result when enabling auto-association. As the `ue1` moves towards `ap3`, the received signal strength coming from (ap1) decreases. When this strength reaches the HO threshold, it starts the HO process (or association according to IEEE specification) and moves to `ap2`, even though they have different modes of operation (Listing 6.5). This process repeats until it reaches close to `ap3`. The second run is portrayed in Figure 54b, where auto-association is disabled. The `ue1` remains associated with `ap1` until it can not decode any other access point. It will remain unassociated with any other access point until it reaches any other with the same RAT, in this case, the same operation mode. In this test, `ue1` will restore an association with a serving AP when it reaches close to `ap3`

The last test is shown in Figure 54c, where auto-association is still disabled, but the semantic-based HO is running. Since the HO method runs every second together with the RF environment report, it evaluates the server's and neighbor's signal strength by running a SPARQL query in the knowledge base to answer the competence questions for the ubiquitous coverage scenario (**CQ14**, **CQ16** and their dependents CQs in Appendix B). Tables 9 and 10 show the SPARQL queries result at the point where the signal strength of the neighbor AP became greater than the signal strength of the serving AP. Figure 55 presents a log snippet from this last test showing the exact moment portrayed in the previous tables. The result is the same as with 54a, which shows that our semantic evaluation could execute the HO process even without the auto-association feature enabled.

Figure 54 – HO Experiment Results

(a) HO experiment - auto-association enabled



(b) HO experiment - auto-association disabled

(c) HO experiment - auto-association disabled, semantic reasoning evaluation enabled

Source: Prepared by author.

Table 9 – SPARQL query retrieving the signal strength of the serving AP (CQ14)

<table>
<tr><th>Query</th><th>Answer</th></tr>
<tr><td><pre>
SELECT (MIN(?avalue) as ?lavalue) (MAX(?rtime) as ?lrtime) WHERE
{
    ?dbnd hint:bindsReceiver :ue1-wlan0;
        rdf:type hint:SelectedBond;
        hint:bindsSSignal ?ssgn.
    ?ssgnpwr rdf:type :Power;
        qvas:describes ?ssgn.
    ?msrslt qvas:holdsValueFor ?ssgnpwr;
        qvas:isAssignedBy :ue1-wlan0;
        qvas:resultTime ?rtime;
        qvas:assignedValue ?avalue.
}
</pre></td><td>-81</td></tr>
</table>

Table 10 – SPARQL query retrieving the signal strength of the neighbor AP (CQ16)

<table>
<tr><th>Query</th><th>Answer</th></tr>
<tr><td><pre>
SELECT (MIN(?avalue) as ?lavalue) (MAX(?rtime) as ?lrtime) WHERE
{
    ?dbnd hint:bindsReceiver :ue1-wlan0;
        rdf:type hint:MonitoredBond;
        hint:bindsMSignal ?ssgn.
    ?ssgnpwr rdf:type :Power;
        qvas:describes ?ssgn.
        qvas:holdsValueFor ?ssgnpwr;
    ?msrslt qvas:isAssignedBy :ue1-wlan0;
        qvas:assignedValue ?avalue.
}
</pre></td><td>-72</td></tr>
</table>

Figure 55 – Log snippet of the third HO evaluation test

tick	node	timestamp	position	freq	mode	rssi	associatedTo	apsInRange	apsInRangeRSSI
22	ue1-wlan0	2024-06-20T19:07:47Z	(34.16, 45.0, 0.0)	5.180	a	-75	ap1-wlan1		
23	ue1-wlan0	2024-06-20T19:07:48Z	(34.88, 45.0, 0.0)	5.180	a	-76	ap1-wlan1		
24	ue1-wlan0	2024-06-20T19:07:49Z	(35.44, 45.0, 0.0)	5.180	a	-77	ap1-wlan1		
25	ue1-wlan0	2024-06-20T19:07:50Z	(36.0, 45.0, 0.0)	5.180	a	-78	ap1-wlan1	ap2-wlan1	-81
26	ue1-wlan0	2024-06-20T19:07:51Z	(36.64, 45.0, 0.0)	5.180	a	-79	ap1-wlan1	ap2-wlan1	-81
27	ue1-wlan0	2024-06-20T19:07:52Z	(37.28, 45.0, 0.0)	5.180	a	-79	ap1-wlan1	ap2-wlan1	-80
28	ue1-wlan0	2024-06-20T19:07:53Z	(37.92, 45.0, 0.0)	5.180	a	-80	ap1-wlan1	ap2-wlan1	-79
29	**ue1-wlan0**	**2024-06-20T19:07:54Z**	**(38.56, 45.0, 0.0)**	**5.180**	**a**	**-81**	**ap1-wlan1**	**ap2-wlan1**	**-72**
30	ue1-wlan0	2024-06-20T19:07:55Z	(39.2, 45.0, 0.0)	2.437	b	-72	ap2-wlan1		
31	ue1-wlan0	2024-06-20T19:07:56Z	(39.92, 45.0, 0.0)	2.437	b	-71	ap2-wlan1		
32	ue1-wlan0	2024-06-20T19:07:57Z	(40.64, 45.0, 0.0)	2.437	b	-70	ap2-wlan1		

Source: Prepared by author.

7 CONCLUSION

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 been defying researchers and developers over the years. The Always Best Connected and Served (ABCS) scenario represents the current research efforts to provide ubiquitous mobile coverage with a seamless connection. Multi-operator heterogeneous wireless networks (HetNet) are emerging as a combination of various mobile operators integrating different radio access technologies (RATs) like cellular (e.g., 4G, 5G) and Wi-Fi, creating a complex yet adaptable network ecosystem.

This thesis focused on the challenging problem of HetNets mobility management, especially enriching the decision support mechanisms with context understanding. An approach to handle this situation is to utilize semantic reasoning, a field of artificial intelligence (AI) that unlocks the potential for machines to reason, infer new knowledge, and solve problems based on their understanding of the context. Nevertheless, before reasoning about context, a decision support system assisting HetNets mobility management needs to reason over the elements of the heterogeneous wireless network and their relationships. Hence, our goal in this work was to show the potential of using semantic reasoning as part of the mechanisms of decision-making in HetNets mobility management.

Following our research methodology (Section 1.5), we reviewed the literature searching for ontologies that describe communication network elements and their relationships. After evaluating all possible ontologies describing certain aspects of a communication network, we concluded that none could properly represent the necessary elements to describe the mobility management process. Concepts such as `Link` and `Connection` were not properly described, leading to possible misinterpretations as they were the same entity. In the same sense, the concept of neighborhood, which is important to support the handover process, was not represented. Moreover, none of the researched network ontologies dealt with the task of measuring the attributes of the network elements, which is also important to allow any handover process to begin. Thus, our first specific goal was to derive an ontology able to represent the main elements of a mobile wireless network and how to represent the needed measurements to analyze the handover decision-making (SG1).

We started analyzing the focal network element of the handover process: the `Link`. Using the ontology-driven conceptual modeling approach and UFO foundational ontology to represent the elements of a mobile wireless network, we could describe the associations created between network elements due to signal detection and decoding. During this analysis, we could also find collapsed concepts, such as the propagation medium, and represent the necessary entities to describe the neighborhood concept. After we had our conceptual model based on the physical communication between network elements, we extended it to represent other communication abstractions that the layered network architectures proposed. We were able to represent the communication between layer entities and describe how entities categorized in upper layers depend on the integrity of the lower layer associations to maintain their peer communications.

As soon as our conceptual model for representing the main elements of a mobile wireless network was ready, we started to look at how to represent the measurements of network elements attributes. Although some measurement ontologies were considered reused, we verified that the mapping of the measurement result (quality value) was not directly related to the attribute (quality) of the network element. Instead, this direct mapping was between the measurement result and action. Based on recent studies of reification patterns, we proposed that the measurement action, the measured quality, and the measurement result should be represented separately and that their natural mapping should be maintained throughout the ontology development process. Consequently, we proposed a quality value assignment reference ontology that maintains the mapping between the quality and its result. At this point, we accomplished the first specific goal (SG1).

Having both reference ontologies ready and syntactically checked, we transformed them into operational ontologies using the Visual Paradigm Modeling Tool plugin, especially designing for OntoUML models. Moreover, we enrich them with inference rules derived from the restrictions conceived during the conceptual modeling phase. Finally, we documented both operational ontologies to comply with the FAIR principles. After this accomplishment, we concluded our second specific goal (SG2). Right after, we used these operational ontologies to support a handover process in a wireless network simulation environment, testing their reasoning capabilities in a ubiquitous coverage scenario. Our test revealed that semantic reasoning could provide a successful inter-RAT handover in a condition not handled by the standard HO process, accomplishing our last specific goal (SG3). Therefore, we concluded that semantic reasoning has the potential to be part of the solutions to improve decision-making in mobility management whenever the handover process needs to be fed with information that is not part of the standard radio frequency measured data.

7.1 Contributions

Throughout our research, we have made significant and novel contributions to representing entities and relationships in wireless mobile communication networks. Our approach, using an ontology-driven conceptual modeling approach combined with the UFO foundation ontology, has not only provided robust conceptual models of the domain but also clarified concepts that were previously ambiguous in the vocabulary recommendations of the standardization bodies. We have also brought to light concepts that were previously collapsed in the form of categorization of other concepts. Our specific contributions are as follows:

1. delivering solid reference ontologies describing mobile wireless networks, clarifying concepts in the domain, such as the distinct nature of `Link` and `Connection`, avoiding dubiousness in the vocabulary recommendations. The standardization bodies could benefit from this analysis to improve the description of these fundamental communication elements;

2. exposing the concept of propagation `Medium` as an essential entity for `Signal` detection, a concept collapsed in the vocabularies recommendations as `Link`s categorization and that is not described in other ontologies in the domain;

3. representing not only the physical communication between communication boards but also the communication between entities represented in a network architecture defined by layers, something also not seen in other ontologies in the domain;

4. creating operational ontologies (**hint** and **qvas**) based on the developed reference ontologies, respectively available to the scientific community via <https://www.purl.org/s2c2/hint> and <https://www.purl.org/s2c2/qvas>

5. using **hint** and **qvas** ontologies at Brazilian Army's Systems of Command and Control Systems Project (S2C2 Project) as a proof of concept;

6. publishing a short paper at the Ontobras 2020 conference entitled *Critical Communications Scenarios Description Based on Ontological Analysis*[TESOLIN et al., 2020], where we presented our first attempt to model a wireless network conceptually;

7. publishing a full paper in Future Generation Computer Systems Journal (FGCS) entitled *Enhancing Heterogeneous Mobile Network Management Based On A Well-Founded Reference Ontology*[TESOLIN et al., 2023], where we presented our reference ontology describing the physical communication between communion boards.

7.2 Future Works

Further studies can be carried out to identify new possibilities for using the **hint** ontology and expand its scope and representation capacity. Among the research opportunities that can be developed from this thesis, we foresee some potential directions :

- The SABiO approach to ontology development was chosen as the guideline for building the artifacts for representing and implementing the elements of the mobile wireless network that take part in the mobile management process. In addition to its pragmatism, SABiO distinguishes itself from other ontology development frameworks and approaches by proposing a clear separation between the conceptual model (the reference ontology) and its implementation (the operational ontology). However, it provides few details on how to start the *Identification of purpose and requirements elicitation* phase. To overcome this limitation, we used the first scenario described in the NeOn methodology as a guide for searching for knowledge resources. We envision a possible improvement to SABiO by adding or merging some NeOn scenarios that should maintain the pragmatism of the former and improve some parts with the latter;

- The **hint** ontology was initially designed to describe communication between communication boards belonging to an infrastructure mobile wireless networks. However, the conceptual model describing the detection and decoding of a signal between entities playing the role of `Sender` and `Receiver` seems to fit as a pattern in other communication types. For instance, while participating in the Systems of Command and Control Systems (S2C2 Project), we realized we could reuse this pattern to describe communications between communication boards belonging to an ad-hoc wireless communication network. Moreover, in our conceptual model, `Signal` is an electromagnetic wave. Nevertheless, it could be an acoustic wave generated by an entity playing the role of a `Sender` (e.g., a speaker) and detected by an entity playing the role of a `Receiver` (e.g., a microphone). Although it looks like straightforward reusing **hint** ontology to describe communication systems with this pattern, some effort to redesign has to be considered since not all communications systems share the same concepts with the mobile wireless communication systems. For instance, the neighborhood concept is a concept that is not present in wired communication networks. Hence, an effort to redesign **hint** ontology should be taken to separate what is common to all communication systems and what is not, creating new **hint**-dependent ontologies (sub-ontologies).

- Communication boards in **hint** ontology are a category that generalizes entities such as `TRx`, `Tx`, and `RX` and can simultaneously play the roles of `Sender` and `Receiver`. However, other taxonomies can be derived from the same entity. For instance, boards assume certain functions in infrastructure communication networks to allow users to exchange information. They can be user equipment (Ue), access points (AP), serving gateways (SGW), packet gateways (PGW), among others. In this sense, we could model another communication board specialization based on the functions it assumes in an infrastructure network that is orthogonal to the existing ones. Moreover, due to advances in network softwarization, communication boards could also be categorized as hardware and software-defined boards. In this sense, the network functions described previously as **kinds** of communications boards may now be described as a **phase** a board can have depending on if they are hardware or software-defined. This multitude of communication board categories can be difficult to handle. We foresee using multi-level modeling along with UFO as a possible solution to better handle these categorizations.

- The general representation of protocol stacks in layered network architectures has been a modeling challenge. Although standard bodies provide solid network reference models, such as OSI/ISO and TCP/IP, network designers use them only to communicate that a particular layer in their network architecture provides a network function described in the reference model. In other words, they do not need to comply with any reference network model. So, each network designer creates an architecture with layers and functions as many they need to solve their problems. So, instead of modeling a generic conceptual model, we foresee modeling sets of common layers as protocol subgraphs or direct acyclic graphs (DAG) that may be dependent on other protocol subgraphs, as Figure 56 suggests

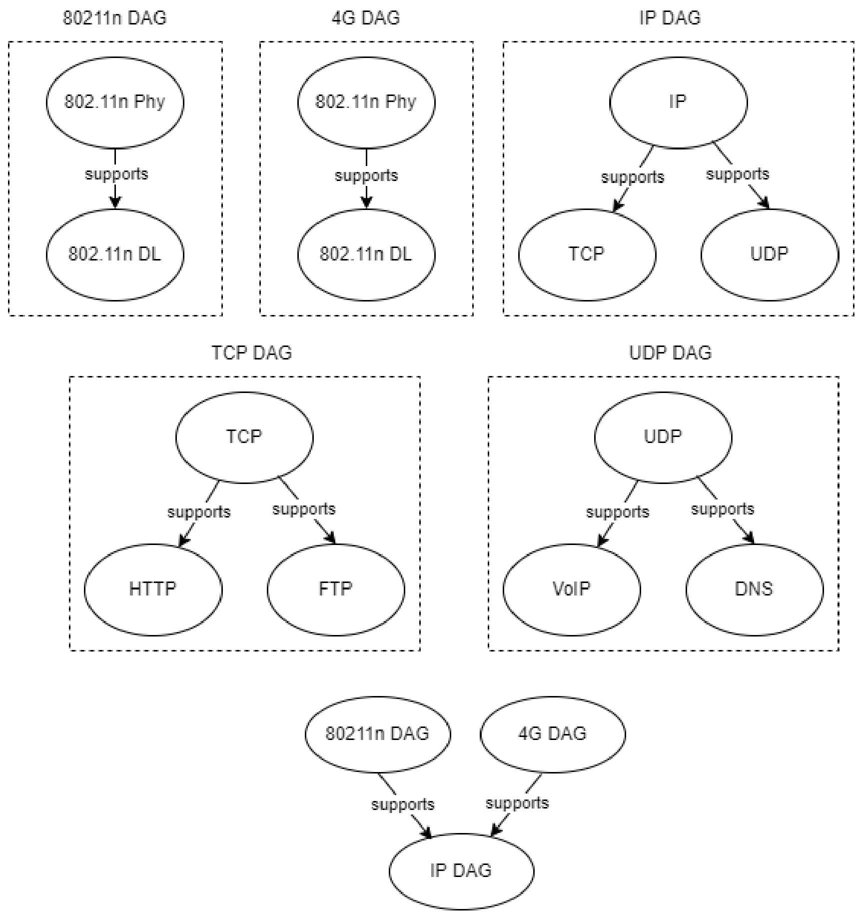


Figure 56 – Future work on representing network protocol’s DAG

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APPENDIX A – DOMAIN MAIN VOCABULARY

The following list presents the main concepts used while developing the conceptual model to represent mobile wireless networks: Communication, Connection, Interference, Link, Medium, Noise, Receiver, Signal,Transceiver and Transmitter

COMMUNICATION	
Source	**Definition**
ITU-R V.662-3, IEC 60050-701:1988	Information transfer according to agreed conventions. Note - In French and Spanish the corresponding terms "communication" and "comunicación" have additional specific meanings in telecommunications (see 3.05 and 3.02).
ITU-T G.800	A body of information produced by a sender and intended, in its entirety, to reach a particular receiver or set of receivers.
TIA Telecom Glossary	"1. Information transfer, among users or processes, according to agreed conventions. 2. The branch of technology concerned with the representation, transfer, interpretation, and processing of data among persons, places, and machines. Note: The meaning assigned to the data must be preserved during these operations."

CONNECTION	
Source	**Definition**
Collins Dictionary	an emotional or logical relationship between people or things
Webster Dictionary	the fact or state of having something in common ; a place where two or more things are united
Cambridge Dictionary	the state of being related to someone or something else
ITU-R V.662-3, IEC 60050-701:1988	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.
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Source	Definition
ITU-T G.8081	A connection is a concatenation of link connections and subnetwork connections (as described in ITU-T G.805) that allows the transport of user information between the ingress and egress points of a subnetwork.
ITU-T Q.1741	A communication channel between two or more end-points (e.g., terminal, server, etc.).
ITU-T G.9961	"A flow between a node and one or more other nodes uniquely identified by the following parameters carried in the PHY-frame header -Source ID (SID); -Destination ID (DID); -Multicast indication (MI); andConnection identifier (CONNECTION_ID). and the following parameter carried in the LPH of the associated LPDUs-Management queue flag (MQF)."
ITU-T G.993	An association of transmission channels or circuits, switching and other functional units set up to provide a means for a transfer of user, control and management information between two or more end points (blocks) in a telecommunication network.
3GPP TR 21.905 V16.0.0	"Connection: A communication channel between two or more end-points (e.g. terminal, server etc.). Connection mode: The type of association between two points as required by the bearer service for the transfer of information. A bearer service is either connection-oriented or connectionless. In a connection oriented mode, a logical association called connection needs to be established between the source and the destination entities before information can be exchanged between them. Connection oriented bearer services lifetime is the period of time between the establishment and the release of the connection. In a connectionless mode, no connection is established beforehand between the source and the destination entities; the source and destination network addresses need to be specified in each message. Transferred information cannot be guaranteed of ordered delivery. Connectionless bearer services lifetime is reduced to the transport of one message."

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Source	Definition
TIA Telecom Glossary	"1. A provision for a signal to propagate from one point to another, such as from one circuit, line, subassembly, or component to another. 2. An association established between functional units for conveying information."

INTERFERENCE	
Source	**Definition**
Radio Regulations (2004) - Art. 1 § 1.166	The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.
ITU-R V.662	Disturbance of the reception of a wanted signal caused by interfering signals, noise or electromagnetic disturbance. Note - The term "radio-frequency interference" is defined in Recommendation ITU-R V.573.
ITU-T K.123, ITU-T K.114, ITU-T K.137	Degradation of the performance of an equipment, transmission channel or system caused by an electromagnetic disturbance.
ITU-T K.79	Any electromagnetic phenomenon that may degrade the performance of a device, equipment or system, or adversely affect living or inert matter.
ISO/IEC 702-08-31	"interference (to a wanted signal) disturbance of the reception of a wanted signal caused by interfering signals, noise or electromagnetic disturbance"

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Source	**Definition**
TIA Telecom Glossary	"1. In general, extraneous energy, from natural or man-made sources, that impedes the reception of desired signals. 2. A coherent emission having a relatively narrow spectral content, e.g., a radio emission from another transmitter at approximately the same frequency, or having a harmonic frequency approximately the same as, another emission of interest to a given recipient, and which impedes reception of the desired signal by the intended recipient. Note: In the context of this definition, interference is distinguished from noise in that the latter is an incoherent emission from a natural source (e.g., lightning) or a man-made source, of a character unlike that of the desired signal (e.g., commutator noise from rotating machinery) and which usually has a broad spectral content. 3. The effect of unwanted energy due to one or a combination of emissions, radiation, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy. [NTIA] [RR] (188) 4. The interaction of two or more coherent or partially coherent waves, which interaction produces a resultant wave that differs from the original waves in phase, amplitude, or both. Note: Interference may be constructive or destructive, i.e., it may result in increased amplitude or decreased amplitude, respectively. Two waves equal in frequency and amplitude, and out of phase by 180°, will completely cancel one another. In phase, they create a resultant wave having twice the amplitude of either interfering beam. (188)"

LINK	
Source	**Definition**
Collins Dictionary	an emotional or logical relationship between people or things
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Source	Definition
Webster Dictionary	a uniting or binding force or influence
Cambridge Dictionary	a connection between two people, things, or ideas
ITU-R V.662-3, IEC 60050-701:1988	A means of telecommunication with specified characteristics between two points. Note - The type of the transmission path or the capacity is normally indicated, e.g. radio link, coaxial link, broadband link.
ITU-T G.9711	A combination of a path in the MTU-O and its corresponding path in the MTU-R connected to the MTU-O.
ITU-T G.9905	A link between two nodes exists if either can receive control messages from the other, according to this specification.
ITU-T G.997	The pair of a path in the MGfast transceiver unit–central office end and its corresponding path in the MGfast transceiver unit–remote side.).
3GPP TR 21.905 V16.0.0	"Radio link: A ""radio link"" is a logical association between single User Equipment and a single UTRAN access point. Its physical realisation comprises one or more radio bearer transmissions. Radio Bearer: The service provided by the Layer 2 for transfer of user data between User Equipment and UTRAN. Downlink: Unidirectional radio link for the transmission of signals from a UTRAN access point to a UE. Also in general the direction from Network to UE. Uplink: An ""uplink"" is a unidirectional radio link for the transmission of signals from a UE to a base station, from a Mobile Station to a mobile base station or from a mobile base station to a base station."

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Source	Definition
TIA Telecom Glossary	1. The communications facilities between adjacent nodes of a network. (188) 2. A portion of a circuit connected in tandem with, i.e. , in series with, other portions. 3. A radio path between two points, called a radio link. (188) 4. In communications, a general term used to indicate the existence of communications facilities between two points. [JP1] 5. A conceptual circuit, i.e. , logical circuit, between two users of a network, that enables the users to communicate, even when different physical paths are used. Note 1: In all cases, the type of link, such as data link, downlink, duplex link, fiber optic link, line-of-sight link, point-to-point link, radio link and satellite link, should be identified. Note 2: A link may be simplex, half-duplex, or duplex. 6. In a computer program, a part, such as a single instruction or address, that passes control and parameters between separate portions of the program. 7. In hypertext, the logical connection between discrete units of data."

MEDIUM

Source	Definition
ITU-R F.1499	The material on which information signals may be carried; e.g. wireless, optical fibre, coaxial cable, and twisted wire pairs.
ITU-T G.9959	The radio waves carrying the signals. Walls and other building components may affect the quality of the medium. Nodes communicating via the same medium may interfere with each other.
ITU-T G.9960, ITU-T G.9961, ITU-T G.9964	A wireline facility, of a single wire class, allowing physical connection between nodes. Nodes connected to the same medium may communicate on the physical layer, and may interfere with each other unless they use orthogonal signals (e.g., different frequency bands, different time periods).

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Source	Definition
IEC 60050-704-02-01	" natural medium or manufactured structure through or over which a signal is conveyed"
TIA Telecom Glossary	Any material substance, such as fiber-optic cable, twisted-wire pair, coaxial cable, dielectric-slab waveguide, water, and air, that can be used for the propagation of signals, usually in the form of modulated radio, light, or acoustic waves, from one point to another. Note: By extension, free space can also be considered a transmission medium for electromagnetic waves, although it is not a material medium.

NOISE

Source	Definition
ITU-R V.662-3, ISO/IEC 702-08-03	Any variable physical phenomenon apparently not conveying information and which may be superimposed on, or combined with, a wanted signal. Note - The term "radio-frequency noise" is defined in Recommendation ITU-R V.573.
ITU-T G.160	For the purposes of Recommendation ITU-T G.160, noise is defined as a slowly varying stochastic process appearing additive to the desired speech signal. Specifically, the variations in the characteristics of the noise process are such that it can be considered approximately stationary over much longer time intervals than a typical speech signal.

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Source	Definition
TIA Telecom Glossary	"1. An undesired disturbance within the frequency band of interest; the summation of unwanted or disturbing energy introduced into a communications system from man-made and natural sources. (188) 2. A disturbance that affects a signal and that may distort the information carried by the signal. 3. Random variations of one or more characteristics of any entity such as voltage, current, or data. 4. A random signal of known statistical properties of amplitude, distribution, and spectral density. 5. Loosely, any disturbance tending to interfere with the normal operation of a device or system."

RECEIVER	
Source	**Definition**
IEC 60050-701:1988	radio) receiver: 1 – a device for detecting radio-frequency radiation and extracting certain characteristics; 2 – in radiocommunication, a device with associated antenna or including an antenna, used to select the desired radio-frequency signals from the incident radio-frequency radiation, to amplify them, demodulate them and if necessary convert the recovered signals into a directly usable form such as sounds or pictures

SIGNAL	
Source	**Definition**
ITU-R V.662-3, ISO/IEC 702-08-03	A physical phenomenon one or more of whose characteristics may vary to represent information. Note - The physical phenomenon may be for instance an electromagnetic wave or acoustic wave and the characteristic may be an electric field, a voltage or a sound pressure.

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Source	**Definition**
ITU-T Z.100	The primary means of communication is by signals that are output by the sending agent and input by the receiving agent.
ITU-T H.248	For the purposes of descriptions in ITU-T H.248.68, "signal" comprises "tone" and (MF or DTMF) "digit".
TIA Telecom Glossary	"1. Detectable transmitted energy that can be used to carry information. 2. A time-dependent variation of a characteristic of a physical phenomenon, used to convey information. 3. As applied to electronics, any transmitted electrical impulse. [JP1] 4. Operationally, a type of message, the text of which consists of one or more letters, words, characters, signal flags, visual displays, or special sounds, with prearranged meaning and which is conveyed or transmitted by visual, acoustical, or electrical means. [JP1]"

TRANSCEIVER	
Source	**Definition**
IEC 60050-701:1988	combination in a single unit of a radio transmitter and a radio receiver employing common circuit components and usually the same antenna for both transmitting and receiving (Note – A transceiver is often used as a portable or mobile station.)
TIA Telecom Vocabulary	A device that performs, within one chassis, both transmitting and receiving functions. 2. In military communications, the combination of transmitting and receiving equipment that (a) is in a common housing, (b) usually is designed for portable or mobile use, (c) uses common circuit components for both transmitting and receiving, and (d) provides half-duplex operation.

TRANSMITTER	
Source	**Definition**
ITU-T K.70 (12/2020)	A transmitter is an electronic device to generate the radio-frequency electromagnetic field for the purpose of communication. Transmitter output is connected via a feeding line to the transmitting antenna which is the real source of the intentional electromagnetic radiation
ITU-T K.91	An electronic device used to intentionally generate radio frequency electromagnetic energy for the purpose of communication (in contrast to the definition for intentional emitter in clause 3.1.19). The transmitter output is connected via a feeding line to the transmitting antenna, which is the real source of intentional electromagnetic radiation.

APPENDIX B – COMPETENCY QUESTIONS

UBIQUITOUS COVERAGE SCENARIO		
CQ	**Question**	**CQD**
1	Is the Ue attached to best serving AP for ubiquitous coverage ?	2, 3, 4
2	Is the strength of serving received signal lower than the handover threshold ?	14, 15
3	Is the strength of the received signals coming from the serving AP neighbors greater than the strength of serving received signal ?	16
4	Is the predicted strength of the received signals coming from nearby APs that do not share the same RAT with active communication board would be greater that the strength of serving received signal where Ue is haeding to ?	5, 14, 10
5	what would the predicted strength of the received signals comming from the nearby APs that shares the same RAT with the inactive comm boards ?	6
6	what are the nearby APs that shares the same RAT with the inactive comm boards ?	7, 12
7	what radio access technologies do the inactive comm. boards use or able to use ?	9
8	which comm board is active ?	9
9	which comm boards are available for this Ue's IMEI ?	11
10	where is the Ue heading to ?	12, 13
11	what is Ue's IMEI ?	
12	what is the current Ue's position ?	
13	what is the last Ue's position?	
14	what is the current strength of serving received signal ?	
15	what is the configured handover threshold ?	
16	what are the received signals strength coming from the serving AP neighbors ?	

SERVICE LEVEL SCENARIO		
CQ	**Question**	**CQD**
1	Is the Ue attached to the best-serving AP for the best service level scenario?	2,3,5
2	Is the average downlink throughput of the serving AP greater than all of its neighbors?	5,8, 11,14
3	Is the average uplink throughput of the serving AP greater than all of its neighbors?	6,9, 12,15
4	Is the average latency of the serving AP greater than all of its neighbors?	7,10, 13,16
5	Is the average downlink throughput of the serving AP at the position Ue heading to be greater than the one at the current position?	8,13,23
6	Is the average uplink throughput of the serving AP at the position Ue heading to be greater than the one at the current position?	9,13,23
7	the average latency of the serving AP at the position Ue heading to be greater than the one at the current position?	10,13,23
8	What is the average downlink throughput when attached to the current serving AP at the Ue's current position?	20,23,25
9	What is the average uplink throughput when attached to the current serving AP at the Ue's current position?	21,23,25
10	What is the average latency when attached to the current serving AP at the Ue's current position?	22,23,25
11	What is the average downlink throughput when attached to the current serving AP at the position Ue is heading?	20,23, 25,26
12	What is the average uplink throughput when attached to the current serving AP at the position Ue is heading?	21,23, 25,26
13	What is the average latency when attached to the current serving AP at the position Ue is heading?	22,23, 25,26
14	What are the average downlink throughputs of each serving AP's neighbor at the Ue's current position?	20,23, 24,25
15	What are the average uplink throughputs of each serving AP's neighbor at the Ue's current position?	21,23, 24,25
16	What are the average latencies of each serving AP's neighbor at the Ue's current position?	22,23, 24,25
17	What are the average downlink throughputs of each serving AP's neighbor at the position Ue is heading?	20,24, 25,26
18	What are the average uplink throughputs of each serving AP's neighbor at the position Ue is heading?	21,24, 25,26

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CQ	Question	CQD
19	What are the average latencies of each serving AP's neighbor at the position Ue is heading?	22,24, 25,26
20	Does downlink throughput impact the Ue's running applications?	27
21	Does uplink throughput impact the Ue's running applications?	27
22	Does latency impact the Ue's running applications?	27
23	Who is the serving AP?	
24	Who are the serving AP's negihbors?	
25	What is the current Ue's position?	
26	What is the last Ue's position?	
27	What are the Ue's running applications?	

BATTERY CONSUMPTION SAVING SCENARIO

CQ	Question	CQD
1	Is the Ue attached to the best-serving AP for the battery consumption saving scenario?	2,3
2	Is the serving AP received signal strength lower than any of its neighbor's ?	10,11
3	Would there be any received signal strength that is higher than that currently received and would be generated by an AP that shares the same RAT as an inactive communication board in the Ue?	4,10,12
4	Which access points share the same RAT as the inactive communication cards in the Ue that would generate signals whose received power would be higher than that currently received?	5
5	What nearby APs share the same RAT as the inactive comm boards?	6,12
6	What RATs do the inactive communication boards in the Ue use ?	8
7	Which communication board is active ?	8
8	Which communications boards are available for this Ue's IMEI ?	9
9 10	What is Ue's IMEI?	
10 11	What is the current strength of the received serving signal?	
11 12	What is the strength of the received signals from the serving AP neighbors?	
12 13	Where is the Ue heading?	13,14
13 14	What is the current Ue's position?	

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CQ	**Question**	**CQD**
14 15	What is the last Ue's position?	

APPENDIX C – OPERATIONAL ONTOLOGY VOCABULARIES

hint: Heterogeneous Telecommunication Network Ontology

Metadata

IRI

`https://purl.org/s2c2/hint`

Title

hint: Heterogeneous Telecommunication Network Ontology

Creator

https://orcid.org/0000-0002-0240-4506
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Date Created

2024-06-07

License

Version Info

"1.0.0"@en

Preferred Namespace Prefix

hint

http://purl.org/s2c2/hint#

Description

"Heterogeneous Telecommunication Network Ontology (hint) aims to provide an operational ontology that allows the representation of the main mobility management concepts and relationships. It is supported by UFO Foundational Ontology and is based on the conceptual model proposed in the article entitled 'Enhancing heterogeneous mobile network management based on a well-founded reference ontology' (https://doi.org/10.1016/j.future.2023.08.008)"

Classes

Atmosphere c

IRI	`https://purl.org/s2c2/hint#Atmosphere`
Sub Class Of	PropagationEnabler c

CoaxialCable c

IRI	`https://purl.org/s2c2/hint#CoaxialCable`
Sub Class Of	PropagationEnabler c

CommBoard c

IRI	`https://purl.org/s2c2/hint#CommBoard`
Description	in this context, represents the category of hardware able to transmit and/or receive electromagnetic waves.
Sub Class Of	LayerNode c
In Range Of	hasCB op

CommDevice c

IRI	https://purl.org/s2c2/hint#CommDevice
Description	An entity comprising at least one CommBoard and some CommSW. For instance, it can be a cell phone, a modem, or a GPS receiver, among others.
Sub Class Of	gufo:FunctionalComplex
In Domain Of	hasCB op hasCS op
In Range Of	isPositionOf op
Restriction	n0c0d5419d21f4b90a59f65901415c418b2 *exactly* 1

CommSW c

IRI	https://purl.org/s2c2/hint#CommSW
Description	in this context, represents the category of software able to establish communication with other software or hardware
Sub Class Of	LayerNode c
In Range Of	hasCS op

DecodedBond c

IRI	https://purl.org/s2c2/hint#DecodedBond
Description	is a specialization of the DetectedBond EDM, representing the Signal's detection and decodification. According to several telecommunications vocabularies, it is the Link entity, such as the ITU V.662-3 recommendation.
Sub Class Of	DetectedBond c
Equivalentclass	MonitoredBond c *or* SelectedBond c
In Domain Of	bindsWSender op bindsWSignal op
Super Class Of	MonitoredBond c SelectedBond c

DetectedBond c

IRI	https://purl.org/s2c2/hint#DetectedBond
Description	is the truthmaker that binds Signal, Medium, and Receiver and supports the relation detectsSignal. It is the composition of the asymmetrical commitments between Receiver-Signal, Signal-Medium, and receiver-Medium, all representing external dependent modes (EDMs). It is also the truthmaker of the material relation between a Receiver and a Sender
Sub Class Of	gufo:ExtrinsicMode
In Domain Of	bindsMedium op bindsReceiver op bindsSender op bindsSignal op
Restriction	bindsMedium op *min* 1 bindsReceiver op *min* 1 bindsSender op *min* 1 bindsSignal op *min* 1

Super Class Of	DecodedBond ^{c}

FiberCable ^{c}

IRI	`https://purl.org/s2c2/hint#FiberCable`
Sub Class Of	PropagationEnabler ^{c}

HandShakeBond ^{c}

IRI	`https://purl.org/s2c2/hint#HandShakeBond`
Description	is the truthmaker of the material relationship that binds two distincts TRxs represeting their mutual commitements and obligations.
Sub Class Of	gufo:Relator
Restriction	gufo:mediates *min* 2

LLMedium ^{c}

IRI	`https://purl.org/s2c2/hint#LLMedium`
Sub Class Of	LogMedium ^{c}

LLNode ^{c}

IRI	`https://purl.org/s2c2/hint#LLNode`
Description	is a role category whenever a LayerNode "vertically" provides a service for another LayerNode
Sub Class Of	ServiceNode ^{c}
In Range Of	providedBy ^{op}

LayerNode ^{c}

IRI	`https://purl.org/s2c2/hint#LayerNode`
Description	represents an entity in a layered network architecture that is grouped in a layer and generalizes two distinct categories of entities: CommBoards and CommSWs.
Sub Class Of	gufo:FunctionalComplex
Equivalentclass	CommBoard ^{c} *or* CommSW ^{c} ServiceNode ^{c} *or* PeerNode ^{c}
Super Class Of	CommBoard ^{c} CommSW ^{c} PeerNode ^{c} ServiceNode ^{c}

LogMedium ^{c}

IRI	`https://purl.org/s2c2/hint#LogMedium`
Description	a logical structure through or over which a logical Signal is conveyed

Sub Class Of	Medium [c]
Equivalentclass	LLMedium [c] *or* ULMedium [c]
Super Class Of	LLMedium [c] ULMedium [c]

Medium [c]

IRI	`https://purl.org/s2c2/hint#Medium`
Description	a structure through or over which a Signal is conveyed
Sub Class Of	gufo:FunctionalComplex
Equivalentclass	PhyMedium [c] *or* LogMedium [c]
In Range Of	bindsMedium [op]
Super Class Of	LogMedium [c] PhyMedium [c]

MonitoredBond [c]

IRI	`https://purl.org/s2c2/hint#MonitoredBond`
Description	in mobile networks, the Receiver has to deal with several WantedSenders simultaneously. There are Signals that are not elected to be the ServingSignal, but need to be monitored to allow the execution of the handover process. In this sense, MonitoredSenders generates MonitoredSignals, which allows the bonding to a Receiver. The MonitoredBond represents such bonding, and it is a role played by the DecodedBond. According to 3GPP's recommendations, the MonitoredSender is also known as Neighbor and, therefore, the MonitoredBond is also known as the Neighbor Link.
Sub Class Of	DecodedBond [c]
In Domain Of	bindsMSignal [op]

MonitoredSender [c]

IRI	`https://purl.org/s2c2/hint#MonitoredSender`
Description	a role played by a WantedSender whenever its generates a Signal which is only monitored by the Receiver.
Sub Class Of	WantedSender [c]
In Range Of	dependsOnMSender [op]

MonitoredSignal [c]

IRI	`https://purl.org/s2c2/hint#MonitoredSignal`
Description	a role WantedSignal plays whenever it is only monitored by the Receiver, becoming a SelectedSignal whenever necessary.
Sub Class Of	WantedSignal [c]
In Range Of	bindsMSignal [op] caracterizesMSignal [op]

PeerNode [c]

IRI	https://purl.org/s2c2/hint#PeerNode
Description	a role category that a Layer Node plays when it "horizontally" communicates with another distinct Layer Node that shares the same communication Protocol.
Sub Class Of	LayerNode c
Equivalentclass	Sender c *or* Receiver c Tx c *or* Rx c *or* TRx c
In Range Of	hasProtocol op
Restriction	n0c0d5419d21f4b90a59f65901415c418b31 *exactly* 1
Super Class Of	Receiver c Rx c Sender c TRx c Tx c

PhyMedium c

IRI	https://purl.org/s2c2/hint#PhyMedium
Description	natural or manufactured structure through or over which a physical Signal is conveyed. A role category that generalizes entities in the physical world able to propagate electromagnetic waves.
Sub Class Of	Medium c PropagationEnabler c

Position c

IRI	https://purl.org/s2c2/hint#Position
Description	it is the location of an entity according to a coordinate system
Sub Class Of	gufo:Quality
In Domain Of	isPositionOf op

PropagationEnabler c

IRI	https://purl.org/s2c2/hint#PropagationEnabler
Sub Class Of	gufo:FunctionalComplex
Super Class Of	Atmosphere c CoaxialCable c FiberCable c PhyMedium c

Protocol c

IRI	https://purl.org/s2c2/hint#Protocol
Description	a set of communication rules that allows information exchange between distinct PeerNodes
Sub Class Of	gufo:IntrinsicMode
In Domain Of	hasProtocol op

Restriction	gufo:inheresIn *min* 1

Receiver c

IRI	`https://purl.org/s2c2/hint#Receiver`
Description	an abstract entity that detects Signals
Sub Class Of	PeerNode c
In Range Of	bindsReceiver op
Restriction	n0c0d5419d21f4b90a59f65901415c418b34 *exactly* 1

Rx c

IRI	`https://purl.org/s2c2/hint#Rx`
Description	hardware or software that can play, among others, the role of Receiver but not of Sender
Sub Class Of	PeerNode c

SelectedBond c

IRI	`https://purl.org/s2c2/hint#SelectedBond`
Description	in mobile networks, the Receiver has to deal with several WantedSenders simultaneously. Among them, one is selected to be the SelectedSender. Therefore, the SelectedBond, a role of the DecodedBond, represents the bonding of a SelectedSender and Receiver, where the user's information is actually exchanged. According to 3GPP's recommendations, the SelectedSender is also known as Server and , therefore, the SelectedBond is also known as the Server Link.
Sub Class Of	DecodedBond c
In Domain Of	bindsSSender op bindsSSignal op
Restriction	bindsSSender op *min* 1

SelectedSender c

IRI	`https://purl.org/s2c2/hint#SelectedSender`
Description	a role played by a WantedSender whenever it generates a Signal that is selected for information exchange.
Sub Class Of	WantedSender c
In Range Of	bindsSSender op dependsOnSSender op

SelectedSignal c

IRI	`https://purl.org/s2c2/hint#SelectedSignal`
Description	a role WantedSignal plays whenever it is selected for information exchange between the WantedSender, now playing the role of SelectedSignal, and the Receiver.
Sub Class Of	WantedSignal c
In Range Of	bindsSSignal op

caracterizesSSignal op

Sender c

IRI `https://purl.org/s2c2/hint#Sender`

Description an abstract entity that generates and transmits Signals

Sub Class Of PeerNode c

In Range Of bindsSender op
dependsOnSender op

Restriction n0c0d5419d21f4b90a59f65901415c418b37 *exactly* 1

Super Class Of WantedSender c

ServiceNode c

IRI `https://purl.org/s2c2/hint#ServiceNode`

Description a role category played by a LayerNode when it ServiceNode whenever it "vertically" requests and/or provides network services to another LayerNode in the same host.

Sub Class Of LayerNode c

Equivalentclass ULNode c *or* LLNode c

Super Class Of LLNode c
ULNode c

Signal c

IRI `https://purl.org/s2c2/hint#Signal`

Description a detectable transmitted energy that can be used to carry information

Sub Class Of gufo:FunctionalComplex

In Range Of bindsSignal op
caracterizesSignal op

Restriction n0c0d5419d21f4b90a59f65901415c418b42some

Super Class Of WantedSignal c

SignalGeneration c

IRI `https://purl.org/s2c2/hint#SignalGeneration`

Description is the truthmaker of the material relation between a Sender and a Signal, which characterizes the latter and is externally dependent on the former. It bears signal properties such as frequency, power, and bandwidth, among others.

Sub Class Of gufo:ExtrinsicMode

In Domain Of caracterizesMSignal op
caracterizesSSignal op
caracterizesSignal op
caracterizesWSignal op
dependsOnMSender op
dependsOnSSender op

dependsOnSender op
dependsOnWSender op
bandwidth dp
frequency dp
power dp

Restriction dependsOnSender op some
caracterizesSignal op *min* 1

SrvRequest c

IRI `https://purl.org/s2c2/hint#SrvRequest`

Description is the truthmaker of the material relation between a ULNode and a LLNode, which characterizes the latter and is externally dependent on the former.

Sub Class Of gufo:ExtrinsicMode

In Domain Of providedBy op
requestedBy op

Restriction providedBy op *min* 1
requestedBy op *min* 1

TRx c

IRI `https://purl.org/s2c2/hint#TRx`

Description hardware or software that can play, among others, the role of Sender and Receiver

Sub Class Of PeerNode c

Tx c

IRI `https://purl.org/s2c2/hint#Tx`

Description hardware or software that can play, among others, the role of Sender but not of Receiver

Sub Class Of PeerNode c

ULMedium c

IRI `https://purl.org/s2c2/hint#ULMedium`

Sub Class Of LogMedium c

ULNode c

IRI `https://purl.org/s2c2/hint#ULNode`

Description is a role category whenever a LayerNode "vertically" requests a service for another LayerNode

Sub Class Of ServiceNode c

In Range Of requestedBy op

WantedSender c

IRI `https://purl.org/s2c2/hint#WantedSender`

Description a role played by a Sender whenever it generates a Signal that is decoded by the Receiver

Sub Class Of Sender c

Equivalentclass SelectedSender c *or* MonitoredSender c

In Range Of bindsWSender op
dependsOnWSender op

Super Class Of MonitoredSender c
SelectedSender c

WantedSignal c

IRI `https://purl.org/s2c2/hint#WantedSignal`

Description a Signal conveying Information that is not only detected but also understood (or decoded) by the Receiver. In other words, it is a Signal role whenever it is decoded by the Receiver

Sub Class Of Signal c

Equivalentclass MonitoredSignal c *or* SelectedSignal c

In Range Of bindsWSignal op
caracterizesWSignal op

Super Class Of MonitoredSignal c
SelectedSignal c

MonitoredBond c SelectedBond c CommBoard c CommSW c PeerNode c ServiceNode c LLMedium c ULMedium c LogMedium c PhyMedium c Receiver c Se

Object Properties

bindsMSignal op

IRI `https://purl.org/s2c2/hint#bindsMSignal`

Sub Property Of bindsWSignal op

Domain MonitoredBond c

Range MonitoredSignal c

bindsMedium op

IRI `https://purl.org/s2c2/hint#bindsMedium`

Sub Property Of gufo:externallyDependsOn

Domain DetectedBond c

Range Medium c

bindsReceiver op

IRI `https://purl.org/s2c2/hint#bindsReceiver`

Sub Property Of gufo:inheresIn

Domain DetectedBond c

Range Receiver c

bindsSSender op

IRI `https://purl.org/s2c2/hint#bindsSSender`

Sub Property Of bindsWSender op

Domain SelectedBond c

Range SelectedSender c

bindsSSignal op

IRI `https://purl.org/s2c2/hint#bindsSSignal`

Sub Property Of bindsWSignal op

Domain SelectedBond c

Range SelectedSignal c

bindsSender op

IRI `https://purl.org/s2c2/hint#bindsSender`

Sub Property Of gufo:externallyDependsOn

Super Property Of bindsWSender op

Domain DetectedBond c

Range Sender c

bindsSignal op

IRI `https://purl.org/s2c2/hint#bindsSignal`

Sub Property Of gufo:externallyDependsOn

Super Property Of bindsWSignal op

Domain DetectedBond c

Range Signal c

bindsWSender op

IRI `https://purl.org/s2c2/hint#bindsWSender`

Sub Property Of	bindsSender op
Super Property Of	bindsSSender op
Domain	DecodedBond c
Range	WantedSender c

bindsWSignal op

IRI	`https://purl.org/s2c2/hint#bindsWSignal`
Sub Property Of	bindsSignal op
Super Property Of	• bindsMSignal op • bindsSSignal op
Domain	DecodedBond c
Range	WantedSignal c

caracterizesMSignal op

IRI	`https://purl.org/s2c2/hint#caracterizesMSignal`
Sub Property Of	caracterizesWSignal op
Domain	SignalGeneration c
Range	MonitoredSignal c

caracterizesSSignal op

IRI	`https://purl.org/s2c2/hint#caracterizesSSignal`
Sub Property Of	caracterizesWSignal op
Domain	SignalGeneration c
Range	SelectedSignal c

caracterizesSignal op

IRI	`https://purl.org/s2c2/hint#caracterizesSignal`
Sub Property Of	gufo:inheresIn
Super Property Of	caracterizesWSignal op
Domain	SignalGeneration c
Range	Signal c

caracterizesWSignal op

IRI	`https://purl.org/s2c2/hint#caracterizesWSignal`
Sub Property Of	caracterizesSignal op

Super Property Of

- caracterizesMSignal op
- caracterizesSSignal op

Domain SignalGeneration c

Range WantedSignal c

dependsOnMSender op

IRI `https://purl.org/s2c2/hint#dependsOnMSender`

Sub Property Of dependsOnWSender op

Domain SignalGeneration c

Range MonitoredSender c

dependsOnSSender op

IRI `https://purl.org/s2c2/hint#dependsOnSSender`

Sub Property Of dependsOnWSender op

Domain SignalGeneration c

Range SelectedSender c

dependsOnSender op

IRI `https://purl.org/s2c2/hint#dependsOnSender`

Sub Property Of gufo:externallyDependsOn

Super Property Of dependsOnWSender op

Domain SignalGeneration c

Range Sender c

dependsOnWSender op

IRI `https://purl.org/s2c2/hint#dependsOnWSender`

Sub Property Of dependsOnSender op

Super Property Of

- dependsOnMSender op
- dependsOnSSender op

Domain SignalGeneration c

Range WantedSender c

has cb op

IRI `https://purl.org/s2c2/hint#hasCB`

Sub Property Of gufo:isComponentOf

Domain	CommDevice [c]
Range	CommBoard [c]

has cs [op]

IRI	https://purl.org/s2c2/hint#hasCS
Sub Property Of	gufo:isComponentOf
Domain	CommDevice [c]
Range	CommSW [c]

has protocol [op]

IRI	https://purl.org/s2c2/hint#hasProtocol
Sub Property Of	gufo:inheresIn
Domain	Protocol [c]
Range	PeerNode [c]

is position of [op]

IRI	https://purl.org/s2c2/hint#isPositionOf
Sub Property Of	gufo:inheresIn
Domain	Position [c]
Range	CommDevice [c]

providedBy [op]

IRI	https://purl.org/s2c2/hint#providedBy
Sub Property Of	gufo:inheresIn
Domain	SrvRequest [c]
Range	LLNode [c]

requestedBy [op]

IRI	https://purl.org/s2c2/hint#requestedBy
Sub Property Of	gufo:externallyDependsOn
Domain	SrvRequest [c]
Range	ULNode [c]

Datatype Properties

bandwidth [dp]

IRI	`signalGeneration:bandwidth`
Sub Property Of	gufo:hasQualityValue
Domain	SignalGeneration c

frequency dp

IRI	`signalGeneration:frequency`
Sub Property Of	gufo:hasQualityValue
Domain	SignalGeneration c

power dp

IRI	`signalGeneration:power`
Sub Property Of	gufo:hasQualityValue
Domain	SignalGeneration c

Namespaces

:
: `https://purl.org/s2c2/hint#`

dc
: `http://purl.org/dc/elements/1.1/`

dcterms
: `http://purl.org/dc/terms/`

gufo
: `http://purl.org/nemo/gufo#`

ns1
: `https://purl.org/s2c2/`

owl
: `http://www.w3.org/2002/07/owl#`

prov
: `http://www.w3.org/ns/prov#`

rdf
: `http://www.w3.org/1999/02/22-rdf-syntax-ns#`

rdfs
: `http://www.w3.org/2000/01/rdf-schema#`

vann
: `http://purl.org/vocab/vann/`

Legend

c	Classes
op	Object Properties
dp	Datatype Properties

qvas: The Quality Value Assignment Ontology

Metadata

IRI

`https://purl.org/s2c2/qvas`

Title

qvas: The Quality Value Assignment Ontology

Creator

https://orcid.org/0000-0002-0240-4506
https://orcid.org/0000-0002-1153-3879
https://orcid.org/0000-0003-4965-9941

Date Created

2024-06-07

License

Version Info

"1.0.0"@en

Preferred Namespace Prefix

qvas

Preferred Namespace Uri

http://purl.org/s2c2/qvas#

Description

The Quality Value Assignment ontology (qvas) aims to provide an operational ontology that allows value assignment over time for qualities defined by the UFO foundational ontology. An assigning event can be further specialized as a measurement or a configuration, while a value assignment can be specialized as a measurement result or configuration setting.

Classes

AAsgnEvent c

IRI	`https://purl.org/s2c2/qvas#AAsgnEvent`
Description	is a specialization of AsgnEvent, representing atomic events of value assignment, which may result in value assignments
Sub Class Of	AsgnEvent c

AValueAsgmt c

IRI	`https://purl.org/s2c2/qvas#AValueAsgmt`
Description	is a specialization of ValueAsgmt, representing atomic value assignments holding a value for MQuality at a specific time.
Sub Class Of	ValueAsgmt c

AsgnEvent c

IRI	`https://purl.org/s2c2/qvas#AsgnEvent`
Description	is the category of events that assigns values to MQuality in which an MQBearer and a ValueAssigner participate and possibly lead to a value assignment.
Sub Class Of	gufo:Event

Equivalentclass	AAsgnEvent [c] *or* CAsgnEvent [c]
In Domain Of	endTime [dp] startTime [dp]
In Range Of	hasAEvent [op] isResultOf [op] participateAsMQB [op] participateAsVA [op]
Super Class Of	AAsgnEvent [c] CAsgnEvent [c]

CAsgnEvent [c]

IRI	`https://purl.org/s2c2/qvas#CAsgnEvent`
Description	is a specialization of AsgnEvent, representing complex events of value assignment as AsgnEvent aggregations
Sub Class Of	AsgnEvent [c]
In Domain Of	hasAEvent [op]

CValueAsgmt [c]

IRI	`https://purl.org/s2c2/qvas#CValueAsgmt`
Description	is a specialization of ValueAsgmt, representing complex value assignments as aggregations of ValueAsgmt.
Sub Class Of	ValueAsgmt [c]
In Domain Of	hasVAsgmt [op] sresultTime [dp]

DomainEntity [c]

IRI	`https://purl.org/s2c2/qvas#DomainEntity`
Description	an entity in a domain that can be identified as a UFO Object.
Sub Class Of	gufo:FunctionalComplex
Super Class Of	MQBearer [c] ValueAssigner [c]

DomainQuality [c]

IRI	`https://purl.org/s2c2/qvas#DomainQuality`
Description	an entity representing an aspect of the domain that can be defined as a UFO Quality.
Sub Class Of	gufo:Quality
Super Class Of	MQuality [c]

MQBearer [c]

IRI	https://purl.org/s2c2/qvas#MQBearer
Description	is the role an endurant plays whenever it bears an MQuality while participating in a value assignment event (AsgEvent)
Sub Class Of	DomainEntity c
In Domain Of	participateAsMQB op
In Range Of	describes op

MQuality c

IRI	https://purl.org/s2c2/qvas#MQuality
Description	is the role a quality plays whenever its value changes over time, and it is necessary to keep track of it.
Sub Class Of	DomainQuality c
In Domain Of	describes op
In Range Of	holdsValueFor op

ValueAsgmt c

IRI	https://purl.org/s2c2/qvas#ValueAsgmt
Description	is the truthmaker of the material relationship between MQuality and ValueAssigner. It is a category of external dependent modes responsible for holding the assigned value for an MQuality, which a ValueAssigner assigns, and it is the result of a value assignment event in a certain period.
Sub Class Of	gufo:ExtrinsicMode
Equivalentclass	AValueAsgmt c *or* CValueAsgmt c
In Domain Of	holdsValueFor op isAssignedBy op isResultOf op assignedValue dp resultTime dp
In Range Of	hasVAsgmt op
Super Class Of	AValueAsgmt c CValueAsgmt c

ValueAssigner c

IRI	https://purl.org/s2c2/qvas#ValueAssigner
Description	is the role an endurant plays whenever it is responsible for assigning a value to an MQuality while participating in a value assignment event (AsgEvent)
Sub Class Of	DomainEntity c
In Domain Of	participateAsVA op
In Range Of	isAssignedBy op

AAsgnEvent c CAsgnEvent c AValueAsgmt c CValueAsgmt c

Object Properties

describes [op]

IRI	`https://purl.org/s2c2/qvas#describes`
Description	identifies a MQuality which inheres in a MQBearer
Sub Property Of	gufo:inheresIn
Domain	MQuality [c]
Range	MQBearer [c]

hasAEvent [op]

IRI	`https://purl.org/s2c2/qvas#hasAEvent`
Sub Property Of	gufo:isEventProperPartOf
Domain	CAsgnEvent [c]
Range	AsgnEvent [c]

hasVAsgmt [op]

IRI	`https://purl.org/s2c2/qvas#hasVAsgmt`
Sub Property Of	gufo:isAspectProperPartOf
Domain	CValueAsgmt [c]
Range	ValueAsgmt [c]

holdsValueFor [op]

IRI	`https://purl.org/s2c2/qvas#holdsValueFor`
Description	identifies a ValueAsgmt which inheres in a MQuality
Sub Property Of	gufo:inheresIn
Domain	ValueAsgmt [c]
Range	MQuality [c]

isAssignedBy [op]

IRI	`https://purl.org/s2c2/qvas#isAssignedBy`
Description	identifies a ValueAsgmt which is externally dependent on a ValueAssigner
Sub Property Of	gufo:externallyDependsOn
Domain	ValueAsgmt [c]
Range	ValueAssigner [c]

isResultOf [op]

IRI https://purl.org/s2c2/qvas#isResultOf

Description identifies a ValueAsgmt that is the result of a value-assigning event

Sub Property Of gufo:wasCreatedIn

Domain ValueAsgmt c

Range AsgnEvent c

participateAsMQB op

IRI https://purl.org/s2c2/qvas#participateAsMQB

Description identifies a MQBearer participating on a value-assigning event

Sub Property Of gufo:participatedIn

Domain MQBearer c

Range AsgnEvent c

participateAsVA op

IRI https://purl.org/s2c2/qvas#participateAsVA

Description identifies a ValuseAssigner participating on a value-assigning event

Sub Property Of gufo:participatedIn

Domain ValueAssigner c

Range AsgnEvent c

Datatype Properties

assignedValue dp

IRI https://purl.org/s2c2/qvas#assignedValue

Description maps a ValueAsgmt to MQuality's domain (quality structure)

Sub Property Of gufo:hasQualityValue

Domain ValueAsgmt c

endTime dp

IRI https://purl.org/s2c2/qvas#endTime

Description maps a AsgnEvent to the ending time of a value-assigning event

Sub Property Of gufo:hasQualityValue

Domain AsgnEvent c

resultTime dp

IRI	`https://purl.org/s2c2/qvas#resultTime`
Description	maps a ValueAsgmt to the instant of time when a value was assigned to a MQuality
Sub Property Of	gufo:hasQualityValue
Domain	ValueAsgmt c

sresultTime dp

IRI	`https://purl.org/s2c2/qvas#sresultTime`
Description	maps a CValueAsgmt to the starting instant of the ValueAsgmt aggregation
Sub Property Of	gufo:hasQualityValue
Domain	CValueAsgmt c

startTime dp

IRI	`https://purl.org/s2c2/qvas#startTime`
Description	maps a AsgnEvent to the starting time of a value-assigning event
Sub Property Of	gufo:hasQualityValue
Domain	AsgnEvent c

Annotation Properties

is rule enabled ap

IRI	`http://swrl.stanford.edu/ontologies/3.3/swrla.owl#isRuleEnabled`

Namespaces

:
: `https://purl.org/s2c2/qvas#`

dc
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: `http://purl.org/dc/terms/`

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: `http://www.w3.org/2002/07/owl#`

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: `http://www.w3.org/2000/01/rdf-schema#`

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Legend

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op	Object Properties
dp	Datatype Properties
ap	Annotation Properties