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AN ONTOLOGY FOR SIGNAL STRENGTH ESTIMATION OF NOMADIC 5G NETWORKS ON CONSTRUCTION SITES

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Abstract

Network availability and quality is vital for using robotics, real-time digital twins or augmented reality in construction. This paper explores using semantic web models to perform radio propagation calculations for construction sites. We have created an ontology describing and linking data to calculate how building element installation affects attenuation losses. Our findings enable to predict network quality in the context of construction progress to ensure network performance and coverage for mobile construction robotics. Hereby, network optimisation tasks can be automated or planned in time for re-adjusting antenna positions and orientation.

Introduction

The construction sector faces major challenges in creating affordable housing and modernising infrastructure despite rising material prices and a shortage of skilled workers. To meet these challenges, it is necessary not only to optimise the design of buildings but also to dramatically increase the productivity of construction processes. In the methods commonly used in practice, team productivity is strongly influenced by effective communication in coordinating construction activities and fast access to information (Ahsan et al., 2009). Nowadays, this means that a stable network connection is of great benefit. Network availability and quality are crucial to further digitalising the sector and enabling the use of digital twins and robotics, which have increased productivity in other sectors.

Construction activities can be monitored by various sensors, including laser scanners, depth cameras, ground penetrating cameras, RGB cameras, radio frequency identification, inertial measurement units, global navigation satellite systems, and wireless sensor networks (Rao et al., 2022). These sensors are also needed for mobile robots to operate safely on construction sites - especially to provide situational awareness in human-machine collaboration. The success of construction robotics will depend not only on the capabilities of each machine but also on the ability to share observations and, thus, context. This is highly dependent on a robust and high-performance network infrastructure.

Common, widely used wireless network technologies, such as WLAN (e.g. IEEE 802.11), have range, throughput, jitter, latency and reliability limitations that significantly hinder construction automation. Additionally, a lot of devices do not back up Quality of Service (QoS) functionalities. A promising approach to overcome this is the introduction of 5G technologies in the form of campus networks for construction sites. For example, the reliability and low latency promised by 5G networks play an important role in autonomous and remote-controlled construction machinery (Lee et al., 2022). In general, high latency is detrimental to real-time robot control.

While the capabilities of 5G networks can potentially improve network quality and coverage on construction sites, these environments present specific challenges. Unlike fixed factory floor deployments, environmental factors on a construction site are permanently changing. Therefore, networks must be able to adapt and move as construction progresses. Otherwise, limited network performance and connectivity results (Din and Bernold, 2017). As with other wireless radio networks, the quality of 5G networks depends on the characteristics and design of the antenna and the propagation of radio waves. Factors such as propagation losses, including path loss, reflection, diffraction, refraction and scattering, can limit the effectiveness of radio networks (Erunkulu et al., 2020).

Predicting network quality at specific locations on a construction site by estimating the loss of signal strength, considering construction progress, building information, and antenna configuration could significantly contribute to digitalization and automation in construction. The knowledge gained could, for example, influence the navigation preferences of mobile robots to avoid areas with poor network quality.

More promisingly, it could be used to optimise a network setup, where antenna settings, position and orientation can be adjusted based on construction progress. Recent antenna technologies such as Massive Multiple Input Multiple Output (MIMO) allow software-optimised radio, such as beamforming optimizations. Concepts like O-RAN and SD-RAN enable applications to steer RAN so that fewer physical positioning adjustments are required. Still, such applications require exact information about site topology and progress.

To enable this, the proposed network quality prediction requires harmonising and linking data that do not originate from the same source system and cannot currently be put into a machine-readable context. Linked Data and Semantic Web technologies are ideal for linking such heterogeneous data from different knowledge domains. In addition, there are already approaches for Building Information Modeling (BIM) and construction process modelling in the form of Linked Building Data (LBD) ontologies, ifcOWL (Pauwels and Terkaj, 2016) and the results of the Internet of Construction (IoC) project (Brell-Cokcan and Schmitt, 2024). Therefore, the approach described in this paper investigates the development and use of a semantic data model using an ontology to represent the data required for the calculation of radio wave propagation.

State of the Art

Fundamentals in Radio Wave Propagation

Radio waves are electromagnetic waves. As such, they are affected by reflection, refraction and absorption phenomena when propagating through matter. Commonly, the propagation of an electromagnetic wave is described with the wave equation:

$$\begin{aligned} E\left(x,t\right) &= E_0 \cdot e^{-i\left(\omega t - \frac{\omega}{c} x n\right)} \mid \text{with } n = n' + i \cdot n'' \\ &= E_0 \, e^{-\frac{\omega n''}{c} \cdot x} \cdot e^{-i\left(\omega t - \frac{\omega n'}{c} \cdot x\right)} \end{aligned} \tag{1}$$

where the first term gives the exponential decay of the wave's amplitude with propagation for $n' > 0$. For the intensity $I\left(x\right)$ holds

$$\begin{aligned} I\left(x\right) &= \frac{1}{2} \varepsilon_0 c \cdot |n| \cdot |E\left(x\right)|^2 \\ &= \frac{1}{2} \varepsilon_0 c \cdot |n| \cdot {E_0}^2 \cdot e^{-\frac{2\omega n''}{c} \cdot x} = I_0 \cdot e^{-\alpha \cdot x} \end{aligned} \tag{2}$$

where α is the attenuation coefficient, and the last identity is known as Beer-Lambert's law. The intensity of the transmitted radio wave is related to its power by multiplication with the unit area $I \cdot 4\pi d^2 = P$. Typically, the transmit power of an antenna is given in the unit dBm. This is equivalent to the power ratio of the signal power in reference to $P_0 = 1\,\text{mW}$ on a $\log_{10}$-scale as in equation 3.

$$P\,[\text{dBm}] = 10 \cdot \log_{10}\left(\frac{P_{RX}\,[\text{mW}]}{1\,\text{mW}}\right) \tag{3}$$

On the same logarithmic scale, the received signal strength P_{RX} at the distance d can be expressed as the sum of the transmit power P_t of the transmitting antenna, its respective antenna gain G_{TX}, the propagation losses along the path between the transmitter and the receiver TL, and the gain of the receiving antenna G_{RX} on the logarithmic scale.

$$P_{RX}\,[\text{dBm}] = P_t\,[\text{dBm}] + G_{TX}\,[\text{dBi}] - TL\,[\text{dB}] + G_{RX}\,[\text{dBi}] \tag{4}$$

The antennas' gain and transmit power are adjustable properties, whereas, for propagation losses, the environment plays a crucial role. Propagation loss describes the reduction in signal strength when an electromagnetic wave traverses a medium capable of absorbing or dispersing a portion of the wave energy. In a simplified model, the total propagation losses can be considered as the sum of the free space path loss (FSPL), reflection loss (RL), and attenuation by penetrating building elements (PL).

$$\text{TL}\,[\text{dB}] = \text{FSPL}\,[\text{dB}] + \text{RL}\,[\text{dB}] + \text{PL}\,[\text{dB}] \tag{5}$$

FSPL refers to "the loss between two isotropic radiators in free space, expressed as a power ratio". The Friis transmission equation (Friis, 1946) can be written as

$$\text{FSPL}\,[\text{dB}] = 20 \log_{10}\left(\frac{4\pi d f}{c}\right) \tag{6}$$

where d denotes the distance between the transmitter and receiver and f the frequency.

Reflection losses describe the signal lost when an object's surface reflects a fraction of incoming radio waves. The reflectance is a material property and depends strongly on the frequency of the incident radio wave and the angle under which the wave hits the surface.

$$P_r = R\left(f\right) \cdot P_{in} \tag{7}$$

Lastly, and especially in the construction environment, penetration loss or attenuation occurs when radio waves penetrate building elements since most real-world materials are dielectric materials characterised by permittivity, permeability, and conductivity. To quantify the impact of material properties on wave propagation, we follow the calculations in ITU (2023) and consider the attenuation distance Δ where the amplitude of the electromagnetic field vector has fallen by a factor $\frac{1}{e}$:

$$\Delta = \frac{1}{k_0 \sqrt{\eta'}} \sqrt{\frac{2\cos\left(\delta\right)}{1 - \cos\left(\delta\right)}} \tag{8}$$

In equation 8 η' denotes the real part of the complex relative permittivity $\eta = \eta' + i \cdot \eta''$. The permittivity of the material is then $\varepsilon = \eta \varepsilon_0$. Since the angle of the loss tangent $\delta = \arctan\left(\frac{\sigma}{\varepsilon\omega}\right)$ relates the conductivity σ with the permittivity, the attenuation distance also depends on these properties of the material and the frequency of the wave. In the limit of a good conductor, the attenuation length simplifies to

$$\Delta_{conductor} = \lim_{\sigma \to \infty} \Delta = \frac{1}{k_0 \sqrt{\eta'}} \sqrt{\frac{2}{tan(\delta)}} \tag{9}$$

whereas for a nearly perfect dielectric, it becomes

$$\Delta_{dielectric} = \lim_{\sigma \to 0} \Delta = \frac{1}{k_0 \sqrt{\eta'}} \frac{2}{tan(\delta)} \tag{10}$$

The attenuation distance is related to the attenuation rate as shown in equation 11.

$$A\left[\text{dB}\,\text{m}^{-1}\right] = \frac{20 \log_{10}\left(e\right)}{\Delta} \tag{11}$$

As suggested by ITU (2023), we use equations 9 and 10, to express the attenuation rates for conductors and approximately ideal dielectric materials as functions of η' and σ resulting in

$$\begin{aligned} A_{conductor} &= 20 \log_{10}\left(e\right) \sqrt{\frac{\pi}{\varepsilon_0 {c_0}^2}} \cdot 10^9 \cdot \sqrt{\sigma f\,[\text{GHz}]} \\ A_{dielectric} &= \frac{20 \log_{10}\left(e\right)}{2 \varepsilon_0 c_0} \cdot \frac{\sigma}{\sqrt{\eta'}} \end{aligned} \tag{12}$$

Both σ and η' depend on the frequency and can be characterised as follows:

$$\eta' = af^b \quad \text{and} \quad \sigma = cf^d \tag{13}$$

To calculate the total amount of propagation losses, the derived attenuation rates have to be multiplied by the distance the wave travels within the material. Since building elements often consist of several layers of materials, these calculations need to be done for all layers. The thus found value for the expected signal strength can be compared to the RSSI value that can be found in the network statistics of each connected device that fulfils the IEEE standards 802.11 or 802.15.4.

Research on building materials affecting radio wave propagation

Current research on the electromagnetic behaviour of building materials is mainly conducted at the city scale or focuses on the finished building and how the choice of materials affects the signal quality. Exemplary approaches focus on the use of blueprints (Seidel and Rappaport, 1994) and the 3D geometry of the building (Ullah et al., 2020) for ray tracing simulations. Similarly, empirical studies of building penetration losses indicate the effect of façade material, structure and thickness, radio parameters such as frequency, signal strength, incidence angle and the incident field's polarisation. A study by García Sánchez et al. (2022) focused on the impact of building penetration losses at 3.5 GHz across various facade types, examining factors such as the incidence angle, polarization, and material effects within 5G systems. Their findings included an attenuation variation of up to 8 dB based on the incident angle. An example of a compilation of such studies can be found in (ITU, 2021). Like Yamamoto et al. (2019), we relate the received radio signal strength at a dedicated measurement point to the distance between the transmitting antenna and the receiver. Yet, in contrast, in construction, considerations about the propagation losses that affect the radio signal along its path through physical objects need to be included. While only applied studies are available for many phenomena such as scattering, and therefore no values exist that can be meaningfully transferred to individual components and their materials, the necessary characteristic values for permittivity and conductivity are collected in ITU-R P.2040 (ITU, 2023). Therefore, in this paper, we concentrate primarily on mapping these values.

Linked Building Data

Linked Building Data (LBD) leverages Linked Data principles (Heath and Bizer, 2011), connecting information relevant to applications in the Architecture, Engineering and Construction sectors. World Wide Web Consortium (W3C) standards such as the Resource Description Format (RDF) (Lassila et al., 1998) are used. LBD benefits interdisciplinary collaboration (Pauwels et al., 2017) and interoperability (Beetz, 2009). To promote data accessibility, the W3C Linked Building Data (LBD) Community Group has focused on developing modular approaches in recent years(Rasmussen et al., 2020). For material properties, the Digital Construction Building Material (DICBM) ontology, developed by Valluru et al. (2020), is a modular framework to improve the management of building material information within the BIM collaboration process. This ontology encompasses components such as MaterialDefinition, LayerSet, Layer and MaterialProperty. However, it does not include properties for describing the electromagnetic behaviour of construction materials. In contrast to materials, radio antennas and their properties have been completely absent and, therefore, cannot currently be modelled in the LBD context.

Methodology

Scope and competency questions

Calculating values to dynamically predict network quality and coverage on construction sites is mainly related to antennas, their properties, the site topology, and the building plan, including geometry and used materials. Moreover, the construction process, which involves scheduled and performed progress and auxiliary elements such as formwork or scaffolds, needs to be included as changing spatial conditions. As there is not yet the possibility to model and link all the needed data in RDF, an ontology is created to introduce the necessary classes and properties while connecting them to existing approaches from the linked building data domain, as the ontology complements and extends these when possible. The methodology deployed is described by Noy and McGuinness (2001). According to their guide, the first step is to clarify the focus and scope of the new ontology. Three questions regarding the scope (SQ) are defined and answered for that purpose.

SQ1: What domain is covered by the ontology?
The ontology covers radio network modelling and signal strength predictions for construction sites.

SQ2: What is the purpose of the ontology
The ontology should enable the calculation of the Received Signal Strength Indicator (RSSI) calculation to predict radio networks' relative signal strength at any spot on a construction site. Therefore, it is necessary to be able to save and link data relevant to radio propagation of the frequency used connected with the building information modelling and construction process data. It should enable the simulation of wireless communication networks with respect to changing spatial conditions of the construction site and propose possible adaptations to the nomadic network infrastructure.

SQ3: What questions should the ontology answer?
The ontology should be able to answer questions about the topology-related setup of the wireless network infrastructure and its current configuration. It should help assign and query values for building materials describing their type permittivity and conductivity to query and calculate propagation losses dynamically and independently of the deployed radio frequency.

Competency questions (CQ) were developed according to the scope specification. These competency questions are technical-functional, describing what queries should be able to be answered when data is instantiated using the ontology. These queries are not intended to directly answer questions about the expected network quality, as this requires complex calculations. Our goal is to prove that context-enriched values can be retrieved to calculate or simulate approximate values incorporating dynamic construction process information. The CQs are shown in Table 1.

Table 1: Defined competency questions (CQ).

No.	Questions
CQ1	What are the characteristics and position of the transmitting antenna?
CQ2	What are the characteristics and position of the receiving antenna?
CQ3	What building elements that interfere with radio wave propagation are expected to be realized at a given time?
CQ4	What is the material composition of the building elements in question?
CQ5	What are the materials' type, permittivity and conductivity properties concerning radio waves?

Reusing existing ontologies is one of the core principles of Linked Data. Our investigation into existing ontologies that predict radio propagation within construction sites reveals a lack of developed approaches. Therefore, the competency questions cannot be answered with any existing solution known to us. However, for concepts that describe the building elements and the construction process, there are ontologies that we consider to be applicable and mature. These can be built upon and incorporated to achieve greater interoperability. Table 2 gives an overview of the reused or linked ontologies.

Table 2: Overview of the connected ontologies.

Name	Main classes and purpose
bot	*bot:Zone*, *bot:Element*, *bot:Interface* Ontology describing topological concepts of a building (Rasmussen et al., 2018)
ifc	*Ifc:Root* Web Ontology Language (OWL) representation of the IFC schema (Pauwels and Terkaj, 2016)
ioc	*ioc:process* Ontology developed within IoC to describe processes (Kirner et al., 2024)
opm	*opm:PropertyState* An ontology for describing properties that change over time (Rasmussen et al., 2020)
qudt	*qudt:Quantity*, *qudt:Unit* A unified model of measurable quantities and units (QUDT.org, 2015)

The Construction Site Network Ontology (CNO)

The **CNO** ontology is designed as an application-level ontology. It is intended to be used in combination with the LBD ontologies (Oraskari et al., 2021) and *ifcOWL* (Pauwels and Terkaj, 2016) to add construction context, as well as the Internet of Construction Process Ontology (ioc) (Kirner et al., 2024), which enables dynamic scheduling and status information of construction processes. The main classes of the **CNO** ontology describe the missing dynamic data needed to calculate the expected signal strength according to the radio propagation fundamentals. Specifically, these are *cno:Antenna*,*cno:Obstacle* and *cno:Material*. Most proposed additions are object and data properties that extend or link existing classes like *ifc:IfcMaterial* to add metadata relevant to radio propagation.

cno:Antenna

The major new concept to add is the *cno:Antenna*. Simplified, the antennas are subdivided into *cno:Transmitter*, which describes the main antenna and *cno:Receiver*, in this case, the antennas of the devices in the network. Antennas must have object properties that describe the relevant properties. In this first draft, these are limited to position and direction, power, gain, and frequency. As antennas for wireless communication are quite complex, these properties will be extended in future iterations.

cno:Obstacle

An object that leads to reflection and propagation losses caused by its dielectric properties is described with the class *cno:Obstacle*. Although the focus is clearly on the building elements, obstacles, such as formwork, can also be auxiliary or temporary objects of the construction process. In addition, cars or construction machinery are relevant. For building elements, position and rotation can be queried via LBD geometry descriptions or data from the *ifcOWL* instances. Geometry information in conjunction with antenna position and properties can be used to calculate FSPL or coarse reflection effects (see equation 6).

cno:Material

For the object propagation loss, the material composition of the building elements is decisive. Real-life building elements rarely consist of a single material. The *ifc:IfcMaterialLayer* instances can provide material, layerthickness, and direction. Therefore, we propose extending *ifc:IfcMaterial* via *rdfs:subclassOf* with *cno:Material* to add metadata regarding the relevant material type (*cno:Conductor* or *cno:Dielectric*). The values needed to calculate the attenuation rate according to equation 11 are linked as *cno:hasRelativePermittivityFrequencyCoefficient*, and *Exponenet* as well as *cno:hasConductivityFrequencyCoefficient* and *Exponent*. They can be retrieved from Table 3 of ITU-R P.2040-3 (ITU, 2023). The model from which these equations were deduced is only valid in a certain frequency spectrum, so a *cno:FrequencyRange* must also be attached to each material.

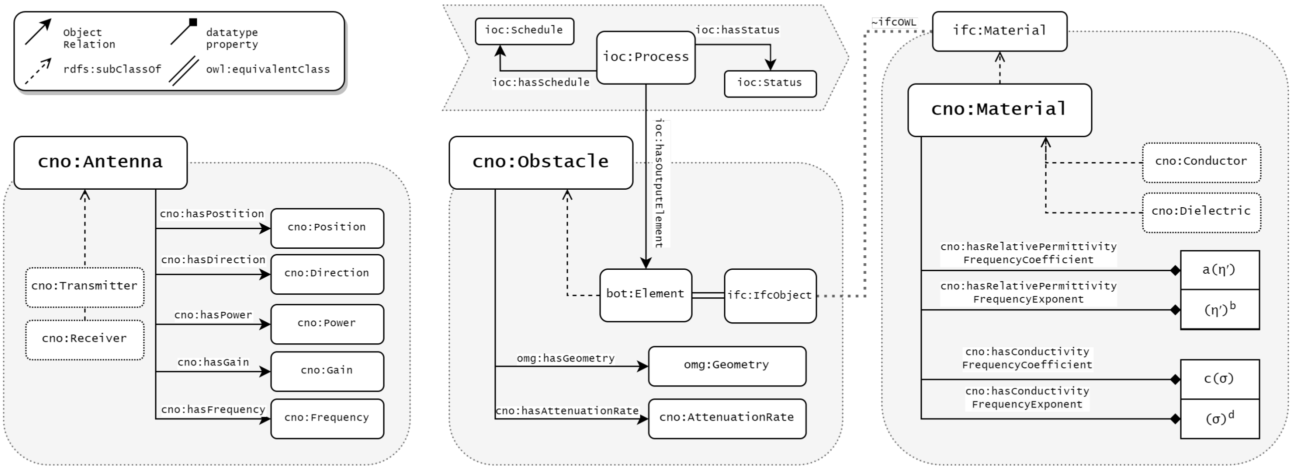

*Figure 1: Main concepts and properties of the **CNO** ontology.*

All classes and properties presented aim to enable the calculation of attenuation rates in a construction site context. For object propagation losses, they can be added to a *cno:Obstacle* with the help of *cno:hasAttenuationRate*. This should be a dynamic, time-stamped value enabled using the OPM ontology's *opm:CurrentDataState* class. This is considered a main improvement over static material bound values found throughout the state-of-the-art. On the one hand, depending on the composite material, the number of layers is due to changes in the course of the construction process. On the other hand, as shown in equations 8, attenuation rates also depend on frequency, which is not necessarily static, depending on the network setup deployed.

Properties of the ontology

The ontology described here represents a first draft of an OWL-based ontology describing radio networks on construction sites. In its current state, the ontology consists of twelve classes, six object properties, and six data-type properties. Figure 1 shows the basic concepts, as well as object and datatype properties proposed.

Evaluation and use-case

A dataset derived from the operational 5G network on the reference site Aachen Melaten was created to evaluate the ontology presented. This does not aim to validate whether the calculated values are precise but to prove that the established competency questions can be answered. Therefore, a dataset created with the help of the CNO ontology provides the data required to predict signal strengths in a dynamic construction site environment.

Due to scientific comparability, a known BIM model, the duplex[1], is used as a source of building information. It is converted to RDF and extended by *ioc:processes*, which describes, using *ioc:Schedule* that a certain building element is expected to be erected at a given time.

The modelled scenario consists of the transmitting antenna, an AW3374-T0-F (1) mounted on a Liebherr L1-24 tower crane, and a Milesight UR75 5G Router (2). The Router is mounted on a Heros 224 mobile AGV from Innok Robotics. A multilayer outside wall of the BIM model is chosen as the element of interest (3). Figure 2 shows the scenario and its components.

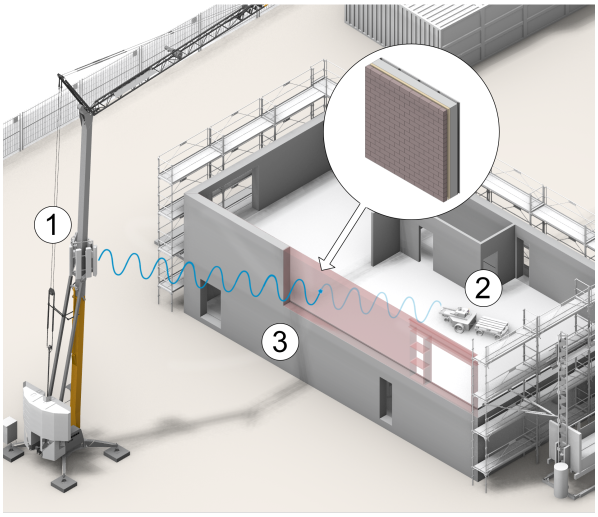

Figure 2: Scenario on the reference construction site in Aachen.

The Antenna and its properties were modelled manually. While values like gain or direction are among the characteristics provided by the antenna's manufacturer, power and frequency are subject to the network setup. It is to be noted that these values are linked to the antenna to simplify the data model and queries. Practically, the radio in use determines these values. The antenna position is designed as a dynamic feature to enable nomadic network setups in reaction to progressing construction processes. The resulting triples added to the graph are shown in figure 3.

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[1] https://portal.nibs.org/files/wl/?id=O9inoVWDytV4P3UTS7iIdqhVKcTyVlcs

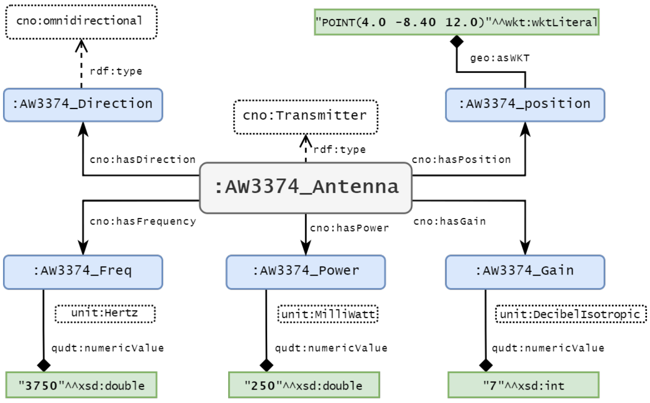

Figure 3: Example for an instantiated cno:Antenna including metadata.

CQ1-2 can be answered by querying the depicted instances in addition to a receiver that is modelled accordingly. Listing 1 presents a query retrieving the transmitter, frequency, and receiver positions. Querying for *opm:CurrentDataState* ensures that the currently valid value is retrieved, which implies the dynamic characteristics of the proposed approach.

Listing 1: SPARQL Query for CQ1

```
PREFIX cno: <http://w3id.org/cno#>
PREFIX qudt: <http://qudt.org/schema/qudt#>
PREFIX unit: <http://qudt.org/vocab/unit#>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX opm: <http://www.w3id.org/opm#>

SELECT ?f ?posTX ?posRX WHERE
   {?Transmitter a cno:Transmitter;
      cno:hasPosition ?posTXState;
      cno:hasFrequency ?fstate.
   ?fstate a opm:CurrentDataState;
      qudt:numericValue ?f;
      qudt:unit unit:Hertz.
   ?posTXState a opm:CurrentDataState;
      geo:asWKT ?posTX.
   ?Receiver a cno:Receiver;
      cno:hasPosition ?posRXState.
   ?posRXState a opm:CurrentDataState;
      geo:asWKT ?posRX.}
```

Retrieving the cartesian coordinates of the transmitter and receiver and the transmitter frequency enables us to calculate the free space path loss as in equation 6.

$$\mathrm{FSPL} = 20\log_{10}\left(\frac{4\pi \cdot 21\,\mathrm{m} \cdot 3.75\,\mathrm{GHz}}{c_{air}}\right) = 70.37\,\mathrm{dB} \qquad (14)$$

To answer CQ3, the process model linked to the building model must be queried. The structure of the query depends on how detailed the process model was created. In its most simplistic form, a *ioc:Process* is created for each *bot:Element*, which describes the "finalization" of said element. The object property *ioc:hasOutputElement* describes that the instantiated Process creates the linked element. Finally, a schedule is added to that process via *ioc:hasSchedule*. To keep it simple, the schedule is only connected to *xsd:datetime*, which expresses the scheduled end time of the process with the help of *prov:endedAtTime*. Querying elements that are the output of processes with this schedule metadata and using a SPARQL Filter for the timestamp will retrieve the necessary building element IRIs.

All values from Table 3 of ITU-R P.2040-3 are collected in a JSON file to include the relevant material properties for radio wave propagation to the data model. Hereafter, material aliases are added to map the materials from the Table to materials in the IFC. Depending on which authoring software is used, these can differ slightly. The Duplex was modelled with Revit, so exemplarily, "Brick" needs to be mapped to "Masonry - Brick". Finally, a Python script queries the data model for IFC materials, locates the materials via the aliases in the JSON file, and updates the graph with the needed material properties. An excerpt of the resulting database is depicted in figure 4. It shows the process logic on the top, LBD element and *ifcOWL* structure, and two of the material layers on the bottom. For enhanced readability, we refrained from labelling *ifcOWL* object properties.

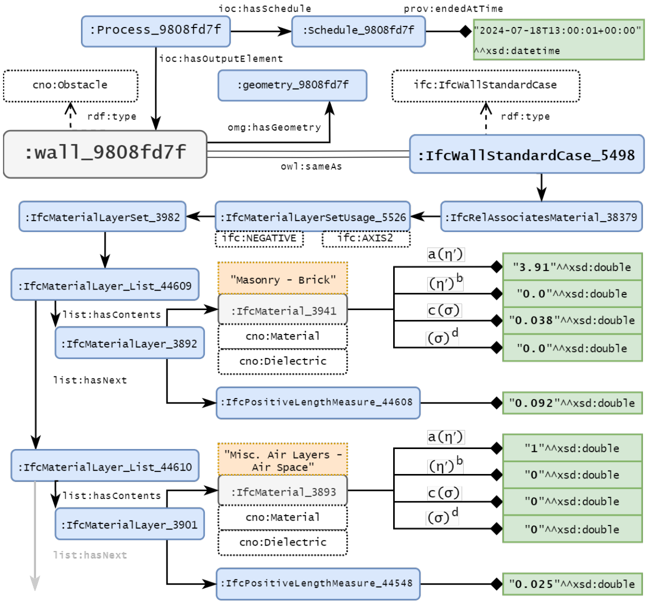

Figure 4: Excerpt of the data model extended with the help of the cno classes and properties.

Querying the database to answer QC4-5 mainly involves traversing the *ifcOWL* structure, which is complex. While for many use cases, the LBD ontologies and, most specifically, *props* in combination with geometry is more than sufficient, we need the full expressiveness of the IFC data model here. RDF lists need to be processed when navigating via *relAssociates* to the material layers. This is best done by using the SPARQL 1.1 property path features. Listing 2 shows a query realising this. The asterisk in *list:hasNext** shows that we follow this property to the end of the list via a path of "zero or more occurrences".

Listing 2: SPARQL Query for CQ5-7

```
PREFIX cno: <http://w3id.org/cno#>
PREFIX qudt: <http://qudt.org/schema/qudt#>
PREFIX unit: <http://qudt.org/vocab/unit#>
PREFIX list: <https://w3id.org/list#>
PREFIX express: <https://w3id.org/express#>
PREFIX ifc: <https://standards.buildingsmart.org/IFC/DEV/
    ↪ IFC2x3/TC1/OWL#>

SELECT ?Axis ?Dir ?dLayer ?MatType ?a ?b ?c ?d WHERE
   { BIND (<Element-IRI> as ?Element)
   ?IfcRelAdMat ifc:relatedObjects_IfcRelAssociates ?Element;
   ifc:relatingMaterial_IfcRelAssociatesMaterial ?IfcMat.
   ?IfcMat a ifc:IfcMaterialLayerSetUsage;
       ifc:forLayerSet_IfcMaterialLayerSetUsage ?
           ↪ IfcMatLayerSet;
       ifc:layerSetDirection_IfcMaterialLayerSetUsage ?Axis;
       ifc:directionSense_IfcMaterialLayerSetUsage ?Dir.

   ?IfcMatLayerSet ifc:materialLayers_IfcMaterialLayerSet ?
       ↪ IfcMatLayer_List.
   ?IfcMatLayer_List list:hasNext* ?IfcMatLayer_List_Elem.
   ?IfcMatLayer_List_Elem list:hasContents ?IfcMatLayer.
   ?IfcMatLayer ifc:material_IfcMaterialLayer ?IfcMatLayered;
      ifc:layerThickness_IfcMaterialLayer ?IfcMatLayered_d.
   ?IfcMatLayered_d express:hasDouble ?dLayer.

   ?IfcMatLayer ifc:material_IfcMaterialLayer ?Mat.
   ?Mat rdf:type ?MatType;
      cno:hasRelativePermittivityFrequencyCoefficient ?a;
      cno:hasRelativePermittivityFrequencyExponenet ?b;
      cno:hasConductivityFrequencyCoefficient ?c;
      cno:hasConductivityFrequencyExponent ?d.}
```

This query returns the sequence of materials in the layered element. The direction, axis and thickness of each layer describe the geometric properties. The material properties introduced in the cno ontology contain the values to be inserted into the required propagation loss equations. These depend on the type of material, either a *cno:Conductor* or a *cno:Dielectric*. For the first layer queried, "Masonry - Brick" (see figure 4), we calculate:

$$\begin{aligned} \eta' &= 3.91 \cdot 3.75\,\mathrm{GHz}^{0.0} = 3.91 \\ \sigma &= 0.0238 \cdot 3.75\,\mathrm{GHz}^{0.16} = 0.81\,\mathrm{S\,m^{-1}} \\ A_{dielectric} &= 1636 \cdot \frac{0.03}{\sqrt{3.91}} = 24.33\,\mathrm{dB\,m^{-1}} \end{aligned} \tag{15}$$

Multiplying the calculated attenuation rate by the layer thickness of 0.092 m gives an attenuation of about 2.23 dB. This process must be repeated for all 6 layers of the component, resulting in a calculated propagation loss of 20.61 dB and an average attenuation rate of 49.4 $\mathrm{dB\,m^{-1}}$. While this value is consistent with the approximate values found in the literature, it should be noted that this calculation is highly simplified. On the one hand, the layered wall has a stud metal layer, which can significantly affect propagation due to its conductive behaviour. On the other hand, we do not consider other effects, such as Snell's law or additional reflections that are relevant here.

To complete this proof of concept, the transmitting and receiving antenna gain is taken from listing 1. Focusing on the FSPL and the element propagation loss, combining the values to get the total propagation loss and inserting it into equation 4, we can calculate the received power in dBm and thus the expected RSSI (see equation 16).

$$36.98\,(\mathrm{dBm}) + 9\,(\mathrm{dBi}) - 90.97\,(\mathrm{dB}) + 5\,(\mathrm{dBi}) = -39.99\,(\mathrm{dBm}) \tag{16}$$

Conclusions and Outlook

Construction sites differ from other production environments due to the ever-changing site topology, leading to restricted radio network connectivity and performance. To address this, an ontology is designed and developed that introduces and links concepts relevant to radio wave propagation with existing building and construction process modelling approaches. These concepts have been developed with respect to both the scientific fundamentals and the material properties available in official reports. To test the usability of the approach, a sample data set describing the 5G installations of the reference construction site in Aachen and a BIM model enriched with scheduling was generated and queried. The values obtained could be used in simplified, basic equations to determine the network quality, thus demonstrating that the approach makes it possible to link the necessary variables with the construction process context.

The described use case can prove that the necessary data can be retrieved to perform basic estimations. For this, the developed ontology as open and extensible data standard the facilitates access to information independent of software vendors, ensuring accessibility and interoperability. However, the ultimate goal is to feed more complex simulation environments to enable accurate network quality estimation for network optimization. To achieve the required accuracy, the ontology will need to be extended to include material properties such as albedo, roughness, or refractive index to allow for the calculation of effects such as reflection, refraction, and scattering, which were beyond the scope of this work. Future research will aim to validate more complex, construction context-dependent simulations with precise measurements in real-world scenarios. In this way, further insights will be gathered to create a network infrastructure that can adapt to the evolving construction environment by predicting network coverage and quality, thus driving innovation in the construction industry, such as digital twins and construction robotics.

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