Context Modeling and Reasoning Techniques

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***Abstract*—There exists many approaches for modeling context information and each model brings along some reasoning techniques. Many researchers work in the area of pervasive and context-aware computing has developed different kinds of context models and reasoning techniques. In this paper we describe the terms context and context-awareness, discuss the importance of pervasive computing, the need of context modelling and reasoning techniques. Furthermore, we discuss the requirements which context models should feature, describe some modeling approaches for context information types. In every chapter we give some examples to show how different context models could be used to solve problems in pervasive computing environments. Also we give a exemplaric overview about the combined use of context modeling approaches**

***Index Terms*—context, context modelling, reasoning techniques, hybrid context model, mobile computing, pervasive computing**

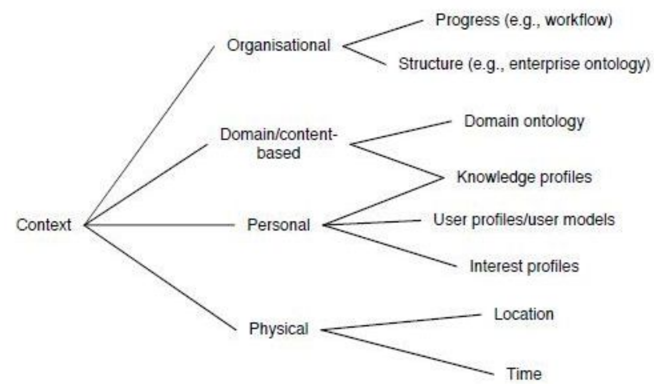

Fig. 1. Context Topology

I. INTRODUCTION

A. Motivation

In the last decade the introduction of newer smartphone operating systems and there success in the consumer space moves computing toward new fields known as pervasive or ubiquitous computing. The term ubiquitous computing was first articulated by Mark Weiser [1] and describes a world in which desktop computers disappear into the background of an environment. Ubiquitous or pervasive computing represents a powerful shift in computation, where people live, work and play in a seamless computer-enabled environment and people are surrounded by computing devices and a computing infrastructure that supports us in everything we do [2], [3], [4]. Pervasive environments are characterized by different kinds of elements, e.g. dynamicity, devices, sensors and so on. Two important tools to deal with these smart environments are context modeling and context awareness. Context modeling is an important instrument to deal with contexts and how they are collected, organized and represented whereas context awareness signifies for reasoning about the context [5].

Thus realizing applications which can be managed and used in pervasive environments is still a complex task. The paper introduces and explains the fundamental terms of context, context modeling and what requirements have to be taken into account when modeling context information. After that, we introduce three modeling approaches (spatial modeling, ontology-based modeling and a hybrid modeling attempt) and give some smart home environment examples.

B. What is Context?

In the pervasive environment context information is the basis for realizing adequate context-aware applications. There are different definitions of the term context in the research area because most researchers define context for their specific application scenario. Figure 1 shows up a context topology related to the work of Klemke [6]. It presents a generic classification about different context types and how they were represented.

A qualified definition to solve these definition problems is given by Dey et al. [7]. In this work the term context is defined as follow:

> *Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves.*

This definition of the term context makes it easier for a developer to specify the context for a given scenario. After defining context, we understand that context modelling is an assistant means to handle our context information for existing or defined entities. Another important aspect while developing a context modeling approach is the necessity of *context awareness*.

A context-aware system is described as a system which uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task [7].

In the next chapter we want to discuss the fundamentals of any context modeling approach in an pervasive environment.

II. Requirements for context modeling approaches

It is important for any modeling of context information that every way of proceeding is considered closely with several requirements. We want to give a short overview to the requirements defined by Strang and Linnhoff-Popien [8]:

- *distributed composition:* Strang and Linnhoff-Popien define ubiquitous or pervasive computing as a specialized area of distributed and mobile computing. Therefore any context modeling approach for pervasive environments has a lack of a central instance which is responsible for important core functionalities thus distributed composition describes the ability of a context modeling attempt to fit in into pervasive computing system.
- *partial validation:* An important ability of a context model is the possibility of partial validation of contextual knowledge. Partial validation is necessary because the complexity of contextual interrelationships makes modeling attempts error-prone[8].
- *richness and quality of information:* The information delivered by sensors varies over time, as well as the richness of information provided by different sensors which defines an entity in a pervasive environment [8].
- *incompleteness and ambiguity:* Due to quality and richness indication of context information, the existing context information at any time is usually incomplete and/or inexplicit (e.g. GPS-coordinates). Therefore a context modeling approach should be capable with this possibility.
- *level of formality:* Sharing of contextual information needs the realization of an adequate specification of the contextual information. This requirements describes the ability of an context model to define such a specification for cross-system knowledge sharing and reuse.
- *applicability to existing environments:* Finally every context modeling approach has to be realizable. The modeling approach should be implemented and realized within the existing infrastructure.

  The mentioned requirements are important for any context modeling approach which has to be realized in an pervasive computing environment [8].

Since the establishment of distributed, mobile environments gets a larger push in the consumer's space, some modelling approaches get more importance then other ones. We have picked up two modelling attempts of context information which were used in many research works to give a closer sight to the area of context modelling. In the next chapters we will discuss the spatial (location) based and ontology based context modelling with some generic scenarios. After that we will show a newer tendency in the research area of context modelling with introducing a combination of the location and ontology based context modelling - called hybrid context modelling.

III. Spatial models for context information

A. Spatial context modeling

As we mentioned in the previous chapter spatial context information are important for most context-aware applications. Places were used in different context definitions [7], [9] to show that spatial information are a core component of developing context-aware applications. Moreover most spatial context models are fact-based models that organises context information by physical location [10]. There are two different representation forms of spatial (location) based attempts; therefore spatial information are divided into symbolic and geometric coordinates.

Symbolic coordinates are often represented by an identifier such as a room number or the ID of a cell or access point in a wireless local network area [10]. Symbolic coordinates are used in applications where a explicit positioning of an object is not necessary for the context modelling. The negative aspect of using symbolic coordinates is the lack of spatial relations between pre-defined spatial coordinates, thus to avoid this lack we need to specify the relationship between pairs of the symbolic coordinates. Now we want to give some exemplary scenarios to show some possible scopes for applications.

Example 1: A good example to describe a scope for context-aware applications which uses symbolic coordinates would be a smart light system in a home environment. A light system in home environments only needs spatial information about the rooms such as a room number or room name (parlor, bath etc.) where one or more persons are moving between these rooms. The rooms would be equipped with cameras or sensors which recognizes a change of the room environment if one or more persons enter a room. A simple scenario would be a home environment with at least two persons (Alice and Bob) staying in there (Fig. 2). Alice is in Room2, the light system recognizes her and turns the light on. If a second person, e.g. Bob, enters another room the light system realizes it, too. Hence the system must be aware about a change of the number of people in a room the light system could count the persons which are staying in a room. Now, if Bob leaves Room1 and enters Room2 the light system recognizes a change and increments the counter for Room2 whereas Room1 decrements his counter. The light system realizes that there are two people in room Room2 and no one is in room Room1 so the light in room Room1 switched off.

Example 1 shows how a smart home environment only needs symbolic coordinates to realize a light system with a recognizing system. However many mobile context-aware applications are using geometric coordinates because most mobile applications need real world points or areas for their application realization, e.g. navigation systems or mobile

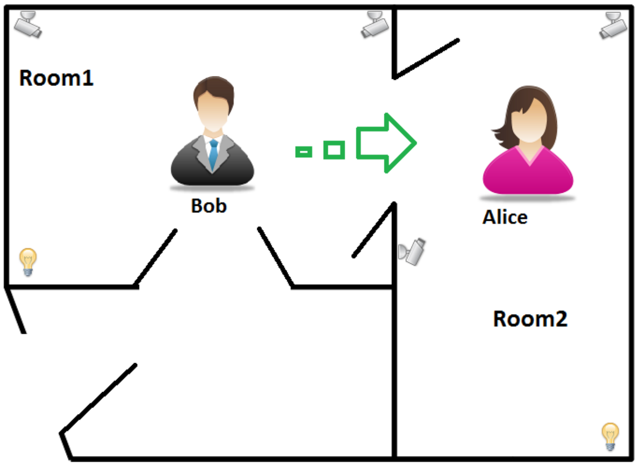

Fig. 2. Smart Light System

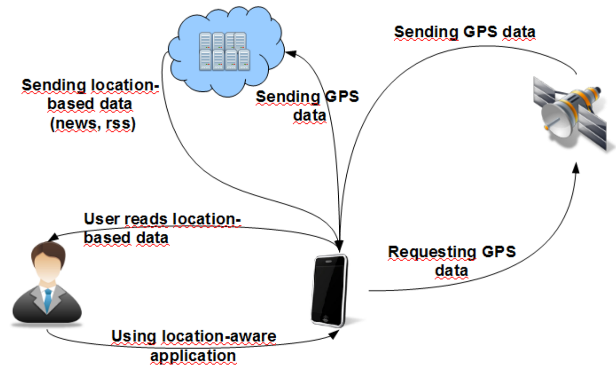

Fig. 3. Simple flow of a location-based News Aggregator Application

coupons.

Geometric coordinates represent points or areas in a metric space, such as GPS. Benefit of such use is the possibility of distance calculation or neareast neighbour queries. The use of this type of spatial information is commonly used in the area of location-based services / applications [11].

Example 2: An interesting context-aware application which is using geometric coordinates would be a location-based news aggregator for mobile devices like a mobile applications who serves location-based news to the user instead of global world news. The simple scenario how the mobile device and user gets the news information from the servers of the service is shown in figure 3. News information and their applications only deliver static information generally global news or region-based (Europe, USA etc.) but many people are also interested in news which gives them more information about there neighborhood or district. Using spatial contextual information allows the application to provide news based on the geometric coordinates from the GPS-sensors of the smartphone. The application is aware about the location of the user and provides a more personalized, location-based news center. The application scans important news pages and tags every information with a geometric coordinate or with a range of coordinates if the news is about a district. As shown in figure 3 the user starts the location-aware application, the application sents GPS coordinates to a server and the server sents the news information back to users' smartphone. The application could provide location-dependent news. Currently many news services provide a more country- or global-dependent news but it would produce more value like for people who are traveling and would like to read news about there currently traveling-place. A detailed explanation about this location-based news application is given in chapter V.

B. Support for Reasoning

Spatial context models allow reasoning about the location and the spatial relationships of objects. Such relations cause three different typcial queries on spatial context information: Position, Range and Nearest Neighbour. [10]. A much larger analysis of spatial context information and the management of them is given by [10], [12].

C. Evaluation

Spatial context models are well suited for context-aware applications that are mainly focused on location-based scenarios, like many mobile information systems [10]. We have tried to consider this mainly focus of spatial context models in our examples. Another possible advantage of using spatial context models is the use of spatial organisation for context information. For applications in mobile computing environment the use of spatial organisations would help to manage there large amount of context information where relevant context information can be easily preselected by using a spatial predicate [10].

IV. Ontology based modeling of context information

A. Ontology based context modeling

Most context modelling approaches are realized for a special application scenario and on that account many context information models are limited from the view of interoperability. Thus, the need for ontology based context modelling is given for many context-aware applications. Before we continue with the term of ontology we have to think again about the term context. Context, against our first definition, can also be considered as a specific kind of knowledge [10]. Therefore ontology based approaches represents knowledges, concepts and relationships about a domain and describes specific situations in a domain [13], [10], [14]. There are different areas where researchers are using ontologies to describe various types of applications for specific issues. These different attempts are helpful to classify the different ontology-based application approaches. Ye et al.[15] illustrate such a classification of ontologies in terms of the level of generality:

- *Generic ontologies:* Generic ontologies describe general concepts, independent of any task or particular domain (e.g. time, space, etc);

- *Domain ontologies:* It describes concepts for a specific domain (such as physics or biology);
- *Application ontologies:* They describe concepts which are necessary for a specific application. Application ontologies depend on both the domain and the generic ontologies;

The underlying goal of ontology development is to provide common terminologies and rich semantics to enable knowledge sharing and reuse between different systems[13], [15]. Such general vocabulary is an important feature to share information among different pervasive computing systems. Now, we understand that ontology based context modelling is a generally used attempt to provide knowledge over different domains (systems) in order to get a suitable infrastructure for complex context-aware systems.

Tier 0: Ontology of physical reality
Tier 1: Observation of the physical reality
Tier 2: Reality of objects with properties
Tier 3: Social reality
Tier 4: Subjective knowledge and cognitive agents

TABLE I
FIVE TIER OF ONTOLOGY CLASSIFICATION FROM FRANK [12]

Another classification of ontologies which is often cited in research papers, especially for spatial ontology representations, is the five tiers of ontology classification from Frank [12] (Tbl. I). The first tier of this classification (tier 0) is the ontology of physical reality. It assumes that there exists only one real world thus Frank describes this tier as a four-dimensional continuous field of attribute where every property has a single value for a given time [12], [16]. Tier 1 is the first level that can be accessed in context models [10]. Here, a value can be derived at a location with a given observation type [16]. Tier 2 describes how the single observations are formed to objects. At this tier objects or individuals [12] are used instead of the single observations. Frank mentioned that for realizing a more realistic model it is necessary to breakup the physical reality into objects because cognitive agents - persons or organizations - interact with objects [12]. After introducing objects the next tier, tier 4, inducts social reality. In this tier the constructed reality in tier 2 is represented as a social reality and it it includes all objects and relations that are created by social interactions [10]. Finally, in tier 4 the rules are modeled that are used by cognitive agents for deduction. Bettini et al. [10] remarks that this tier is generally built into applications or reasoning engines of knowledge based system.
The five tier of ontology could be marked as one of the first research works which describes a combined use of spatial and ontology based context models. We will go more into detail about this combination in the next chapter.

B. Technologies for implementing ontologies

The formalism of choice in ontology-based models is typically OWL-DL [17] or RDF [18]. The syntax of both base on XML with a focus on describing ontologies. OWL-DL is a sublanguage of OWL which was developed by the World Wide Web Consortium(W3C) Web Ontology Working Group. With OWL-DL it is possible to model domains by defining classes, individuals, datatype properties (characteristics of individuals) an object relations [10], [19]. OWL-DL is a well-defined language for description logic and therefore it supports reasoning techniques. This paper is not intended as a description of OWL or OWL-DL, a detailed description is given in different Guides [17], [18]. We want to discuss a example of how ontology based approaches may be used.

C. Ontologies in pervasive computing

There are several pervasive computing systems which use ontology models and we want to give a short overview about selected ones, including CoBrA [20] and SOCAM [21].

- *CoBrA:* The Content Broker Architecture (CoBrA) is a broker-centric, agent-based architecture for supporting context-aware computing in intelligent spaces like intelligent meeting rooms or smart homes [15]. The CoBrA architecture provides a set of functionalities like acquiring, maintaining and reasoning about context information. Also it is possible to share knowledge information, detect and resolve inconsistencies within knowledge [20]. CoBra uses OWL to define different ontologies (e.g. people, spaces, etc.). It realizes a general ontology attempt named SOUPA (Standard Ontology for Ubiquitous and Pervasive Applications) [22].
- *SOCAM:* The Service-Oriented Context-Aware Middleware (SOCAM) is an architecture that enables the building and rapid prototyping of context-aware services in pervasive computing environments [21]. The SOCAM architecture uses the ontology-based model CONON (CONtext ONtology) [5] for modeling context. This ontology-based context model defines a hierarchical approach for designing context ontologies. It provides ontology for general concepts in pervasive environments and domain-specific ontologies which applies to different subdomains [15]. The CONON approach allows two different reasoning types: reasoning with description logic and user-defined reasoning.

We describe these systems to show some of well-established and widely used architectures that are using ontology-based context models.

D. Example for using ontologies

Example 3: There are several ontology based approaches to realize a context-aware framework for smart home environments [23], [24]. Most of them have a very complex domain infrastructure, thus we want to show one possible scenario about a smart fridge system in a smart home environment for realizing a smart healthcare system in our daily life. Figure

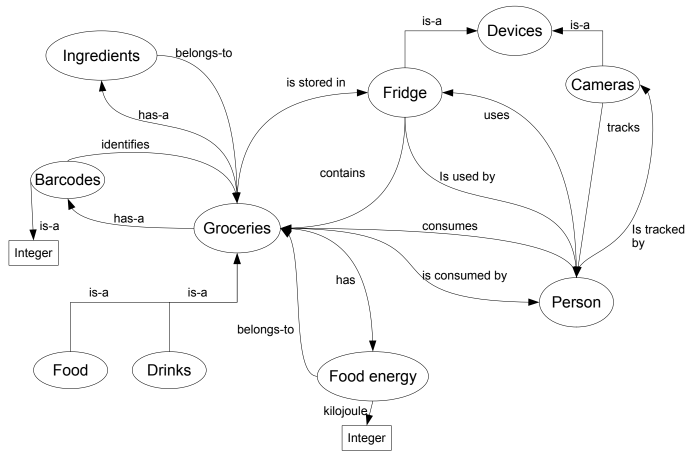

Fig. 4. Principles of an fridge system in a smart home environment

```
<owl:Class rdf:ID="Person">
    <rdfs:subClassOf rdf:resource="http://www.w3.org/2002/07/owl#Thing"/>
</owl:Class>

<owl:DatatypeProperty rdf:ID="age">
    <rdfs:domain rdf:resource="#Person"/>
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#nonNegativeInteger"/>
</owl:DatatypeProperty>

<owl:DatatypeProperty rdf:ID="gender">
    <rdfs:domain rdf:resource="#Person"/>
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
</owl:DatatypeProperty>

<owl:Class rdf:ID="Groceries">
    <rdfs:subClassOf rdf:resource="http://www.w3.org/2002/07/owl#Thing"/>
</owl:Class>

<owl:ObjectProperty rdf:ID="consumes">
    <rdfs:domain rdf:resource="#Person"/>
    <rdfs:range rdf:resource="#Groceries"/>
</owl:ObjectProperty>
```

Fig. 5. A owl-dl code sample for a smart fridge system

4 shows a simple graph notation of a possible ontology of a smart fridge system. The ellipses define the basic classes or individuals and every arrow defines a relation between these entities. The rectangles are added to show datatype values for completion. Now if a person, Bob, uses a fridge it would be an interesting approach if the fridge takes care about the groceries Bob consumes. In figure 4 we define that groceries are stored in the fridge and the inversive relation ”contains” gives the ontology some logic. Furthermore within this simple ontology we define more relations, such as the class ”Person” consumes this groceries or uses the fridge. In this application scenario the whole system gets data from different providers. Every groceries can be identified with an barcode, has a food energy value and ingredients. Another important data source is the use of the fridge or cameras which can track and analyze Bob when he is eating some groceries. The system must set up a content data repository to save the usage of groceries from Bob. After a while the smart fridge system can analyze the habits of Bob and gives Bob some advices to eat something else, like if Bob is eating a lot of frozen-meal then the system could give him some tipps to eat a fresh salad or to cook something instead of eating frozen-meals.

As mentioned before ontology based context models provide advantages in terms of expressiveness and interoperability. In our example the ontology model acts as a middleware to serve a good interoperability between the different data information (barcodes, cameras, sensors within the fridge). Also this approach allows us to realize simpler representations of the system and it supports reasoning tasks. It is possible to derive new knowledge about the current context and to detect possible inconsistencies in the context information[10]. For example, if the system knows that Bob consumes the groceries, the groceries are stored in the fridge, Bob uses the fridge then it is possible to know that Bob uses the fridge to consume his groceries.

The realization of such a system, if we expect our intelligent fridge system as a web connected system, would be realized with OWL-DL based on the graph in figure 4. With OWL-DL we define our classes, there properties and necessary ontologies. If we assume figure 4 as our starting point then the implementation of the classes, there properties and relationships are realized with OWL-DL. Figure 5 shows such a possible OWL-DL implementation of two classes, ”Person” and ”Device”. With the tag ”owl:Class” we define the classes which are necessary for our smart fridge. There are four possible tags to define properties of Classes and there relationships. In our sample OWL-DL code we set up two properties for the class Person with ”owl:DatatypeProperty” and it is possible to define relationships between these classes (figure 5 , owl:ObjectProperty).

However ontology based context modeling especially with OWL-DL has some limitations. OWL-DL is sometimes inadequate to define complex context descriptions, like modeling complex users’ activities and has performance issues during ontological reasoning [10].

E. Support for Reasoning

Several research papers [8], [10], [5] describe the benefit of ontologies. Ontology-based context models support reasoning tasks in a better way then many other modeling approaches [8]. Currently with semantic languages like OWL or RDF it is possible to implement predefined ontology-based context models and with such technologies it is possible to derive new knowledge about current context, and to detect possible inconsistencies [10].

F. Evaluation

Compared with simpler context modeling approaches, ontological context models offer a clear advantages in terms of expressiveness and interoperability [8], [10]. Ontology-based context modeling approaches are strong regarding the distributed composition, partial validation and formality. Strang and Linnhof-Popien [8] determine ontology-based context models as the best approach for our predefined requirements (chapter II). But the main problem with current ontology implementations is the expensive computational request for

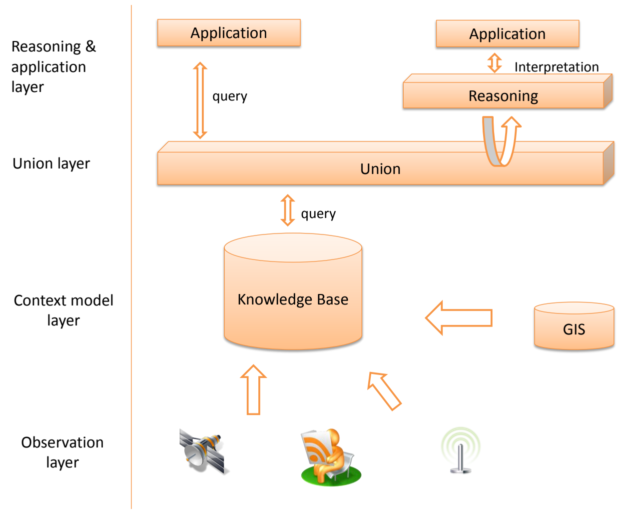

Fig. 6. A principle approach of the LociNews application [16]

reasoning especially with OWL-DL. Due to this limitation and other minor problems when using OWL-DL [10] recent works establish a new context modeling approach with hybrid context modeling. Now, we will discuss this newer approach in the next chapter.

V. Hybrid based approach of context modeling

An appropriate infrastructure for context aware system should support most of the tasks involved in dealing with contexts picking up context from different sources like physical sensors, databases and agents, context reasoning, sharing of context to interested domains in due time and in a distributed way [13]. As we described in Chapter IV using contextual ontologies has a lack of supporting periodically updated information in a scalable manner [16].

Recent research [16], [3] propose a new approach where different context modeling approaches are combined to a hybrid modeling scheme. Nicklas and Becker [16] postulate after analyzing spatial and ontology based context modeling two theses based on the tier classification of ontologies from Frank, A.[12]. First thesis describes the fact that ontologies provide conceived advantages for knowledge representation and reasoning. This is a tier 4 feature. The management of context information, tier levels 0-3, is not a key feature of contextual ontologies. This insight consequently ushers the second thesis. It repeats the ability of context models to allow a scalable context management rather than suitable reasoning or representation concepts.

This key idea introduces a combined use of context models and contextual ontologies. If we recall the second example of this paper about the location based news application then we should realize that the use of a hybrid context modeling approach would be a good opportunity for realizing the application. We call our application LociNews and we describe a closer look to this application scenario. Our proposed service architecture (fig. 6) base on the infrastructure from Becker and Nicklas [16] wants to combine the advantages of both modeling approaches while trying not to use the disadvantages. As mentioned before context models are responsible for the integration of received data from different sources such as sensors, user inputs and etc. into a context models, hence we need a Knowledge Base (KB) shown in figure 6 which collects all of this input information. The observation layer reflects the physical inputs. After that the context model layer has to overcome with challenging task. First, to provide a adequate knowledge sharing the context model layer has to provide a usable context representation and a well-established query languages. After that the union layer provide with the support of the layers below every necessary context information for reasoning tasks and reduce the complexity of the context information for the higher levels [16]. Currently the reasoning layer can make use of the context information for the application. The modeling approach in figure 6 is similar to the combined approach of Becker et al. [16].

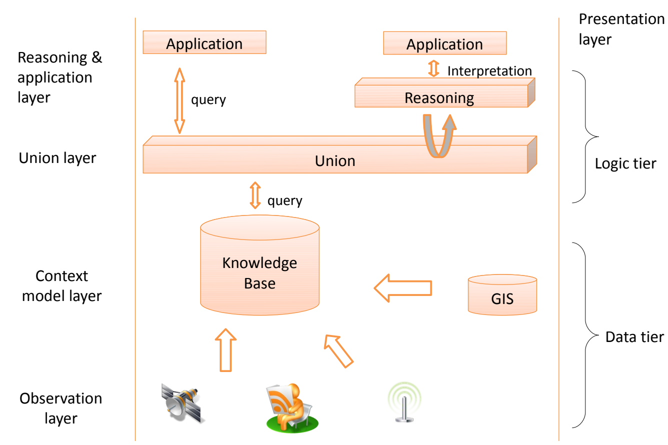

Fig. 7. Comparison of the combined modeling approach with the three-tier architecture

The proposed hybrid context architecture above could be realized as a web application with the widely used three-tier architecture[25], [26]. Due to the fact that we need different content repositories and a large-scaled calculation the most part of it should be done on web servers. If we compare the three-tier application architecture with the four-layer architecture such as in figure 7 shown we see some differences.

The data tier is described as the place where database server consists and where the information of our different sources can be stored and retrieved. Compared to our hybrid approach this tier level would fit with our first two layers because at these layers the main focus is to store the received data and realize a usable representation of the given context information. Our ontology based approach on the higher layers could be realized on the application / logic tier since this teir is used for logical decisions and evaluations, calculations and processes the data between the different tiers. The presentation tier is the frontend of our web application so this would not fit one-to-one to the four-tier approaches because the presentation of our location based news is realized within the application.

After discussing the basic architectural layout figure 8 shows a raw graph about possible individuals and classes which are interacting with each other. The represented ontology based approach for our news service ”LociNews” based on the COMANTO ontology [3] and we have tried to adapt this approach for our fictional ”LociNews”. The COMANTO ontology is another context management ontology which was introduced by Roussaki et al. for the use with location-based context models. It tries to establish a ontology design to support various stakeholders in sharing, and synchronizing their context knowledge [3]. Listed below is a short introduction about the possible classes used in our location-based news application.

- *Person:* The class ”Person” is one of the central entities. It offers various properties, interacts with different classes and the properties of the class ”Person” as a user of the offered service ”LociNews” are reflected by the class Users’s Pref.
- *Place:* This class is a abstract representation of the physical place where the person is located.
- *Preferences:* For representing user, service, network and device preferences. The three preference subclasses need to be disjoint with each other [3].
- *Service:* It saves the information relevant to the applications the user has subscribed to.
- *LegalEntity:* This class is mentioned as a representation of the corporate actors involved in the pervasive computing supply chain [3].
- *Device:* The class ”Device” is a abstract representation of our mobile handset.
- *Network:* The ”Network” class has all information related to the basis network.
- *Sensors:* ”Sensors” is another abstract class to get a realistic representation about the device. The subclass ”GPS” is added as an example.

The illustrated attempt describes a location based news application for use in pervasive environments. Currently it is not considered adequate but with this example we want to give a more practical introduction for using hybrid context models.

VI. Conclusion

Our study in this paper shows some context modeling approaches from different prospects and application scenarios. We want to give a overview about the commonly used context models in the area of pervasive and mobile computing environments. As we mentioned before many context models are limited and do not offer solutions for general problems except ontology-based context modeling. There are several architectures for solving different problems within pervasive environments but we think that a hybrid context modeling approach is an interesting new way for realizing systems for pervasive computing. With our example and study about

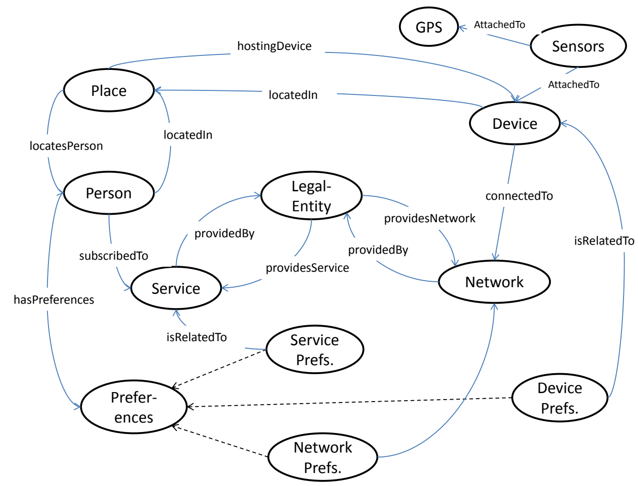

Fig. 8. A combined approach of the news application

hybrid context modeling we want to reveal the advantage in using a combined context modeling approach. Recent innovations like Near Field Communication, Location-based social communities (e.g. Foursquare) displays the fact that the future of computing is already present and the shift from personal desktop computers to mobile and pervasive computing is growing rapidly. This growth effect in an increase of the amount of context data, the multitude of context providers and sources involved, the requirement for real-time context retrieval, the need for seamless mobility across devices and the heterogeneity of devices used, lead to the conclusion that a combined approach should be adopted by pervasive computing systems [3]. We think that the use of hybrid context models will get a highly focus from researchers with respect to well-established approaches. With our exemplary location-based news application ”LociNews” we want to emphasis our proposal about hybrid context models.

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