Context-awareness of the IoT through the on-the-fly preference modeling

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Abstract. The context-awareness of things that belong to IoT networks have to be considered in a distributed computation paradigm. In the paper we suggest the use of graph transformations and temporal logic as a formal framework for a knowledge representation of user/inhabitant behaviors in multi-agent systems. IoT networks are considered as graph structures. Dynamic preference models, understood as a priority in the selecting, is also introduced. Preference models as a result of observed behaviors base on formal logic, and they are built on-the-fly by software agents. Software agents gather knowledge about user preferences expressed in terms of logical specifications as well as suggest on-the-fly future behavior basing on the logical inference process using the semantic tableaux method. The predictive processes are result of some new and important events in the context of IoT systems that should meet a response. Due to the ubiquitous availability of cyber systems that interact with physical environments, there is a great need to develop technologies that target the whole IoT system as a context-awareness system. Formal approach increases the trustworthy of a system. A simple yet illustrative example is provided.

Keywords: context-awareness; preference models; temporal logic; reasoning; semantic tableaux; agents; graph structure;

1 Introduction

The Internet of Things, or IoT, refers to uniquely identifiable objects enable automatic transfer data over a network and cooperation without any kind of intervention. There are some examples of the IoT successful implementations, e.g. smart bus stops and smart parking spots both in Barcelona (Spain), c.f. [19]. They not only improved the quality of live but also, in the case of parking spots, increased revenues of parking fees as well as allow to create new jobs. Success attracts success. The UK government is going to spend huge sums of money for the IoT technology [6]. IoT becomes increasingly ubiquitous and revolutionizes pervasive computing and its applications.

Pervasive computing is understood as existing or being everywhere at the same time, assuming the omni-presence of computing providing strong support for users/inhabitants. Ubiquitous computing is a post-desktop information processing organizing an environment in always unobtrusive and available devices
of any type, and communicating through easy available and effective networks of any kind. It means being and seeming to be everywhere spreading the computation into everything around us/user/inhabitant. Thus, computing is embedded everywhere in the environment providing freely available computations. Computing machines must sense user/inhabitant presence and act accordingly. This leads to the need for awareness of computational processes and applications. Context-awareness is a property of linking changes in the environment with computer systems which are otherwise static. Important aspects of context are: where you are, who you are with, and what resources are nearby [12]. Context-awareness is necessary to anticipate user/inhabitant’s needs and pro-actively offer functions and services. In software engineering, for software developers, context-awareness means sensing and reacting on environment, where remote sensors, devices and monitoring technology might allow the continuous capture and analysis of the incoming data. This constitutes significant challenge for developers. IoT should be environmentally safe, what is especially important in the case of safety-critical systems or functions, thus the reliability demand for such systems increases. Deployment of a formal approach during the development phase might be an appropriate response to such demand. Sophisticated sensors and algorithms require a special attention. Solid and reliable interactions of IoT systems entail technologies basing on a formal approach.

In this paper we suggest the use of formal logic and graph transformations which are formal background for a multi-agent system which operates in the IoT environment to provide context-aware and pro-active services. To the best of our knowledge, there is a lack of such deployment for both formalisms in the mentioned above domains/applications. The main issue addressed in the paper is to prepare a formal foundation of the hierarchical multi-agent structure supporting the IoT system that is verified by finding a workable and comprehensive solution and analyzing a simple yet illustrative example that discerns intent rather than mere inputs.

Broadly speaking, the proposed multi-agent system operates in such a way that gathers knowledge about users/inhabitants’ behaviors and preferences and guides further and possible comfortable behaviors in the IoT network which is considered as a graph structure. Dynamic preference models, understood as a priority in the selecting, is also introduced. Preference models as a result of observed behaviors base on formal logic, and they are built on-the-fly by software agents. Software agents gather knowledge about user preferences expressed in terms of logical specifications as well as suggest on-the-fly future behavior basing on the logical inference process using the semantic tableaux method.

The IoT environment should be formally modeled in order to allow the computational agents make some decisions. Graph seems to be intuitive formalism to represent the static structure of the IoT networks. Graph transformations model this network modification. Unfortunately, in most cases we have a problem with the synchronization of the parallel work of a few agents on the same structure. In this paper we suggest using the replicated complementary graph RCG concept [25] that allows to split the graph into set of complementary subgraphs that
represent part of knowledge maintained by an agent. The RCG concept introduces the explicit synchronization mechanism that guarantees correct application of the transformation rules designed for the centralized system in the distributed multi-agents environments.

Preferences understood as a priority in the selecting of something over another or others follows from observed users/inhabitant’s behaviours. However, preference models is built in a different way comparing works [21,23,20], where the introduced approach is static, i.e. not changed during the execution of a system. The goal of this approach is building preference models on-the-fly when the system operates. Preference models base on temporal logic, and they are built by software agents sensing and reacting users/inhabitants and preparing user-oriented preference decisions. Formal logic allows to register behavior in a precise way, i.e. without any ambiguity typical for natural languages, “Logic has simple, unambiguous syntax and semantics. It is thus ideally suited to the task of specifying information systems”. [9] Moreover, it also allows to perform automatic reasoning to obtain preference decisions for newly observed users/inhabitants. The semantic tableaux method for temporal logic, as a method of reasoning, is proposed. Logical inference allows to build truth trees, searching for satisfiability or contradictions with respect to logical specifications.

The parking space system is provided as an example. It is considered and understood as a graph structure, where everything/object is a graph node. The past behavior of users/inhabitants are registered in the form of logical specifications expressed in terms of temporal logic formulas. There is a hierarchy of software agents in the system. They gather basic information in nodes, identify users/inhabitants, observe their behaviours, and register behaviours in the form of logical specifications, preparing preference decisions, as a suggested behaviours, for users/inhabitants. Some agents exist permanently and some of them exist temporarily. The whole system constitutes a smart, context-aware and proactive software system. Some discussion that refers related works is in the next Section.

Let us focus our attention on some related works. In paper by Perera et al. [27] a wide range of problems which concern the IoT is discussed. An analysis and research that allow to understand challenges of context-aware computing are presented. A set of projects is evaluated, and some trends are discussed. In paper by Gubbi et al. [17] a proliferation of devices is in focus, and also a cloud based model for the IoT emerging technology is discussed. In paper by Ye et al. [30] situation identifications for data which come from a huge number of sensor are discussed. There are considered many different situation and specification techniques. Work by Atzori et al. [5] contains a detailed report on different aspects on the IoT. As pointed out, the US National Intelligence Council included the IoT in the list of six “Disruptive Civil Technologies” with potential impacts on US national power [10]. All these issues highlight the importance of IoT for everyday life. This paper is a continuation of the work [22].

Summing up, it seems that the proposed approach basing on this formal framework provides, hopes promising, improved methods to monitor the IoT
environment as a smart system, i.e. both sensing and reacting the environment. It allows continuous realtime data collection and reliable analysis via remote devices enriching user/inhabitant’s everyday situations.

2 Context models and preferences

Issues to the Internet of Things, context-awareness systems, preferences and their models as well temporal logic are discussed in the Section. Pervasive computing or ubiquitous computing can be understood as existing or being everywhere at the same time, assuming the omni-presence of computing providing strong support for users/inhabitants. Because of the pervasiveness of everyday technologies, one use them without thinking about them, making the technology effectively invisible to the user. Context-awareness and context modeling is one of the crucial aspect of pervasive systems. The Internet of Things (IoT) is another important subject that refers to pervasive computing and context-aware systems. It could be understood as a scenario in which objects, users, inhabitants (or even animals) are provided with unique identifiers to enable automatic transfer data over a network and cooperation without any kind of intervention. The aim is to give strong support for users or inhabitants.

Context-awareness is an important component of today’s most pervasive applications which behaviour is characterized by the interpretation logic that is embedded inside these applications. This type of computing assumes transfer of contextual information among pervasive applications in the IoT network. A context is conditions and circumstances that are relevant to the working system. A sample physical world which create a context which is interpreted by context-aware applications is shown in Fig. 1 c.f. also [7]. The physical world and the

![Fig. 1. A three-layer context model of an smart environment](image-url)

context-awareness software constitute the smart environment. Context model creates different types of sensors which are distributed in the whole considered physical area. For example, the smart street lighting could be controlled by intelligent software which is context-awareness and pro-active. Distributed sensors constitutes a kind of eyes for software systems. These ideas also refer to the
concept of Ambient Intelligence (AmI), i.e. electronic devices that are sensitive and responsive to the presence of humans/inhabitants. It follows that the smart application must both understand the context (tracking and sensing), that is context-aware, and characterized by pro-activity, that is acting in advance to deal with an expected occurrences or situations, especially negative or difficult ones (reacting and influencing). Context-aware system is able to adapt their operations to the current context without explicit user intervention. It follows that it requires special treatment when modeling software. Multi-agent systems seem to be a proper idea to support the issues of this work.

Issues to preferences and their models as well temporal logic and deductive reasoning are discussed in the Section. Preference modeling is a key step in many fields. It enables customization of software behavior to users needs. The construction of preference models is particularly important in systems of pervasive computing. Preference modeling needs formalization and it is discussed in some works, e.g. [26]. The model of preference might be constructed using fuzzy sets, classical logic and many-valued logics. Classical logic, and particular rule-based systems, are especially popular [16]. Non-classical logics, and especially temporal logic, are less popular. On the other hand, temporal logic is a well established formalism for describing reactivity, and meanwhile, the typical pervasive application should be characterized by reactivity and flexibility in adapting to changes on the user side. These changes may result from recognized and predefined preferences. The variability and change in valuation of logical statements are difficult to achieve in classical logic. “Certainly there are unchanging truths, but there are changing truths also, and it is a pity if logic ignores these” (A. Prior[28], p. 46). Further, one can continue reading: “and leaves it to existentialists and to comparatively informal ‘dialecticians’ to study the more ‘dynamic’ aspect of reality”. So it seems that it is encouraging enough to include temporal logic in the consideration of preference models. After building a preference model in temporal logic, one can analyze it using a deductive approach. The goal is searching, if any, for contradictions in a model or analyzing its satisfiability. It is also possible to inference about correctness of preference objectives. Thus, temporal logic creates new possibilities for analysis of preferences by going beyond the static world of classical logic. It also allows to illustrate the dynamic aspect of preferences which describe situations of preference valuations that vary over flows of time.

The issue of preference models based on temporal logic are discussed in some works [21,23,20]. For example, in work [21] some basic notions and definitions are introduced. The architecture of an inference system is proposed. It allows examining of satisfiability, contradiction or being a tautology of preference models. The methodology for gathering information about preferences in the requirements engineering process is proposed in work [20]. The quality of the require-
ments engineering process strongly influences in the positive way the quality of the entire developed system. Finally, in work [23], it is shown that preference modeling could reduce the state space of the agent-based world.

Let us present briefly temporal logic which constitutes important theoretical background of the approach presented in the work. Temporal Logic TL which is a branch of symbolic logic focusses on statements whose valuations depend on time flows, e.g. [29], which has strong application in the area of software engineering. It is used for the system analysis where behaviors of events are of interest. TL exists in many varieties, however, considerations in this paper are limited to the Linear Temporal Logic LTL, i.e. logic with the linear time structure.

The syntax of LTL logic is formulated over a countable set of atomic formulas \( AP = \{ p, q, r, \ldots \} \) and the set of temporal operators \( M = \{ \Diamond, \Box \} \).

**Definition 1.** A LTL formula is a formula which is build using the following rules:

- if \( p \in AP \) then \( p \) is a LTL formula,
- if \( p \) and \( q \) are formulas, then \( \neg p \), \( p \lor q \), \( p \land q \), \( p \Rightarrow q \) are LTL formulas,
- if \( p \) is a formula, then \( \Diamond p \), where \( \Diamond \in M \), is also a LTL formula.

Thus, the whole LTL alphabet consists of the following symbols: \( AP, M \) and classical logic symbols like \( \neg, \lor, \land \), etc. There is no difficulty to introduce other symbols, e.g. parenthesis, which are omitted here to simplify the presentation. The \( M \) set consists two fundamental and unary temporal logic operators, where \( \Diamond \) means “sometime (or eventually) in the future” and \( \Box \) means “always in the future”. Considerations in the work are focused on the LTL logic, and particularly on Propositional Linear Temporal Logic PLTL.

The semantics of the LTL logic is traditionally defined using the concept of Kripke structure which is considered as a graph, or path, whose nodes represent the reachable states \( w = s_0, s_1, s_2, \ldots \), or in other words the reachable worlds, and a labeling function which maps each node to a set of atomic formulas \( 2^{AP} \) that are satisfied in a state. A valuation function \( \nu(w(i)) : \longrightarrow 2^{AP} \), where \( i \geq 0 \), and \( w(i) \) means the \( i \)-th element of the path \( w \), allows to define the satisfaction \( w \models \) relation between a path and a LTL formula, e.g. \( w \models p \) iff \( p \in w(0) \), \( w \models \neg p \) iff it is not \( p \in w(0) \) and \( w \models \Diamond p \) iff \( p \in w(i) \), where \( i \geq 0 \), etc. Theorems and laws of the LTL logic can be found in many works, e.g. [14]. Considerations in this paper are limited to the smallest, or minimal, temporal logic, e.g. [8].

Logic and reasoning are cognitive skills. Logical reasoning is the process of using a sound mathematical procedures to given statements to arrive at conclusions. There are some techniques, or proof procedures, which are systematic methods producing proofs in some calculus, or provable, statements. Although the work is not based on any particular method of reasoning, the method of semantic tableaux is presented in a more detailed way. The method of semantic tableaux, or truth tree is well known in classical logic but it can be applied in modal logic [11]. The method is based on the formula decomposition using pre-defined decomposition rules. At each step of the well-defined procedure, formulas
become simpler as logical connectives are removed. At the end of the decomposition procedure, all branches of the received tree are searched for contradictions. When the branch of the truth tree contains a contradiction, it means that the branch is closed. When the branch of the truth tree does not contain a contradiction, it means that the branch is open. When all branches are closed, it means that the tree is closed. Simple examples of inference trees are shown in Fig. 4. The adopted decomposition procedure, as well as labelling, refers to the first-order predicate calculus and can be found in work [18].

The semantic tableaux method can be treated as a decision procedure, i.e. the algorithm that can produce the polar answer Yes-No as a response to some important questions. Let \( F \) be an examined formula and \( T \) is a truth tree build for a formula.

**Corollary 1.** The semantic tableaux method gives answers to the following questions related to the satisfiability problem:

- formula \( F \) is not satisfied iff the finished \( T(F) \) is closed;
- formula \( F \) is satisfiable iff the finished \( T(F) \) is open;
- formula \( F \) is always valid iff finished \( T(\neg F) \) is closed.

The semantic tableaux method is based on the systematic search for models that satisfy a formula. To show that a formula is unsatisfiable, it needs to show that all branches are closed. Hence, if the tree is closed, it means there is no model that satisfy a formula. To show that a formula is satisfiable, it needs to find one open branch. If the tree is open, it means there exist a model that satisfy a formula. If the tree for the negation of a formula is closed, it means there is no model that satisfy a formula, and as a result of the fact that this is a proving by contradiction, it leads to the conclusion that the initial formula is always valid.

### 3 Context-awareness of the IoT

A proposal to construct preference models that operate in the IoT basing on temporal logic, graph structures and the multi-agent cooperation is introduced in this Section. Preference models are expressed in terms of temporal logic formulas and can be changed on demand during the system operation.

Let us consider a sample parking space, c.f. Fig. 2. It consists of some entrance/exit gates, and a number of identified parking areas. The outline of the procedure used for the management of preference models could be described as a sequence of some steps that are performed concurrently, and are briefly discussed below. The world of things/objects is modeled using a graph structure, the definition of which is given in this Section. The procedure is based on the following ideas:

- The system records basic events of a smart parking space, and events are recorded in particular nodes of a graph structure;
Events are registered in nodes (of the IoT) and the time-stamp for every event is also registered. Identification of users/inhabitants is based on various possibilities, such as RFID, PDA devices, biometric data, image scanning and pattern recognition, and others. The issue of user/inhabitant identification is not discussed here;

The event information is collected permanently and allow to build logical specications expressed in terms of temporal logic formulas based on the corresponding algorithm. Specification provides knowledge about the user behavior and allows to prepare the preference decision for a newly observed user that appear in the smart parking space.

When a gate of the parking space is reached by a new user/inhabitant, then the logical specification is analyzed to prepare a preference decision, and pass this decision to the user/inhabitant. Generating preference decision is made on the highest level of the agent hierarchy, c.f. Fig. 3. Generating decisions take into account the knowledge about the past behaviour, which is logically analyzed using, for example, the semantic tableaux method, which allows to search for satisfiability (choice a preference decision based on past behaviours), or contradictions (new behaviors overriding the previous behaviors).

The goal mentioned above, we suggest to implement by the following multi-agent system. The world of things/objects is modeled using a graph structure, that glues the cooperation of three types of agents into one system. Fig. 3 shows the whole agent world, i.e. agents that operate in the smart environment. It is assumed the existence of the following types of agents:
A3 – agent also called decision agent, it exist permanently in the system and its primary aim is to prepare/compute preference-based decisions for a new user/inhabitant entering the parking space, these decisions are based on the gathered knowledge expressed in terms of graph representation structure and logical specifications which are prepared by agents A2, decision agents can also modify knowledge, what is their secondary aim, when they find that the newly observed behaviors include contradictions in regards to the old behaviors, i.e. knowledge expressed in (old) logical formulas, and the contradiction elimination might be a result of the formal analysis of logic formulas using, for example, the semantic tableaux method. Each of these agents marks some graph nodes and any graph transformation that use such a node cooperate with the pointed agent.

A2 – agents also called follower agents, they might exist temporary in the system and their aim is to observe objects that appear in the smart environments and built logical specifications considered as a set of temporal logic formulas that express behaviours of newly observed users/inhabitants, the logical specification constitutes knowledge about user preferences and is built based on information form agents A1. They are generated when some event occurs.

A1 – agents also called reactive agents, or node agents, they exist permanently in the system and their aim is to operate in an individual node gathering information about users/inhabitants which reach this node in the IoT’s network, information is obtained through sensors and combined with the identification of a user/inhabitant. The determination by such agent of some event causes the execution of some graph transformation.

The graph layer is defined as a labelled and attributed graph (abbrev. LA-graph) defined below.

**Definition 2.** An LA-graph is a labelled and attributed digraph of the following form \( G = (V, E, \{\text{lab}_X, \text{att}_X\}_X=V, E) \), such that:

- \( V \) is a finite and nonempty set of vertices;
- \( E \subset V \times V \) is a set of directed edges (arcs);
- \( \text{lab}_X : X \rightarrow L_X \) are labelling functions for nodes \( (X = V) \) and edges \( (X = E) \) respectively, where \( L_V, L_E \) are sets of node and edge labels;
- \( \text{att}_X : X \rightarrow 2^{A_X} \) are attributing functions for nodes \( (X = V) \) and edges \( (X = E) \) respectively, where \( A_V, A_E \) are sets of node and edge attributes.
The interpretation of labels and attributes in Definition 2 is following. A label \( l \in \mathcal{L} \) identifies unambiguously a given vertex/edge, e.g., by assigning an unique name to an object, an attribute \( a \in \mathcal{A} \) is some property of a vertex/edge, for example a power station transformer output voltage or time interval of a smart meter. As stated in Definition 2 one may assign a set of attributes to a given entity. It should be stressed that an attribute \( a \) must not be confused with its value. Thus the notion of LA-graph may be compared to a class definition. The graph analog of a class instance is an instantiated LA-graph defined below.

**Definition 3.** Let \( G = (V, E, \{ \text{lab}_X, \text{att}_X \}_{X=V,E}) \) be an LA-graph. An instantiation of \( G \) is a triple \( \hat{G} = (G, \text{val}_V, \text{val}_E) \), where \( \text{val}_X : X \times \mathcal{A}_X \rightarrow \Omega_X \) is an instantiating function for nodes \((X = V)\) and edges \((X = E)\) respectively. \( \hat{G} \) will be also referred to as an instantiated LA-graph (shortly, ILA-graph).

The mentioned idea we will explain on the idea of the parking system. The graph consist of only four types of nodes:

- node labelled by \( G \) – that describe a gateway to the parking,
- node labelled by \( R \) – that describe an road segment,
- node labelled by \( P \) – that describe a parking place,
- node labelled by \( C \) – that describe a car.

In the real solutions we have to considered also a few types od sensors, the area of their cooperation, but it will influence only to more complex behaviour of the agent of \( A1 \) type (so we will not consider them here). We assume that with each node labelled by \( G, R \) or \( P \) are associated agents of type \( A1 \) that discover the appearance of a car in the space described by it. The structure of the system is maintained inside the graph maintained by the \( A3 \). The more complex action is associated with appearance of a car in the gateway (coming for outside of the parking); it consist from the sequence of actions:

- a new node labelled by \( C \) is added to a graph – it is linked with node labeled by \( G \),
- a new agent of a type \( A2 \) is created, and it communicates with the agent of type \( A3 \) supervising this gateway – asking for the preference of the identified car. If the preferred place is empty – this information we can find from the graph structure (i.e. nor node labeled by \( C \) is linked with this parking place) – than the information is passed to the car, and it start to take a parking place. If the preferred place is occupied, that this agent try to find the solution the closed to this preference. This generated agents follows by the car, observing the driver behaviour both while it goes to the parking place and while it leaves the parking.
- when the car leaves the parking, agent of the \( A2 \) type sent its observation to agent of \( A3 \) type, and destroy itself.

The actions associated with the activities of agent of \( A1 \) (associated with nodes labeled by \( R \) and \( P \)) is simpler, agent notice movement of the car and:
– perform a graph transformation changing edge linking a node representing a car with the previous detected position to the edge linking the considered node with the node representing a car,
– informs agent of A2 type following the car about its behaviour.

We assume that each agent gathers some part of knowledge from other agents. Due to the large size of the maintained graph, representing the knowledge, in the real application it will be maintained by a set of agents cooperating over the replicated complementary graph structure. Formally it takes or replicates some part of the graph specifying this knowledge. Next agents modify its local representation in a parallel way. This leads a problem with synchronization of their work in the distributed system. Fortunately at least one solution Replicated Complementary Graph [25] allows to split the graph representation onto a few subgraphs, remembering border and replicated nodes in such a way that:

– it is possible gluing these subgraphs to the centralized form,
– explicit synchronization of the transformation rules applied in the parallel way,
– extend the current knowledge either by the replication of some information.

Let us consider a simple yet illustrative example for the approach. Let us present rules for the A1 agents, i.e. the node agents. These agents occupy the lowest level in the whole hierarchy of the agent activities. Agents are assigned to particular nodes of parking space/graph structure. The basic events that refer to the presence of users/inhabitants are recorded in nodes. Let \( O = \{o_1, o_2, \ldots\} \) is a set of users/inhabitants identified in the system. Individual users have unique identifiers. The problem of unambiguous identification is well known and is not be discussed widely here. Let \( D = \{d_1, d_2, \ldots\} \) is a set of events, where every \( d_i \) belongs to \( (O, V, T) \), where \( O \) is a set of identified users/inhabitants, \( V \) is a node of a network, and \( T \) is a set of time stamps. For example, \( d_i = (idKR55, p0018, t2014.01.28.09.30.15) \) means that the presence of the idKR55 object is observed at the physical point/area p0018 of the parking space, and the time stamp assigned to this event is t2014.01.28.09.30.15. Summing up, the primary task of every agent A1 is event logging in a particular node of a parking space.

Let us present rules for the A2 agents, i.e. the follower agents. These agents occupy the middle level in the whole hierarchy of the agent activities. Agents gather knowledge about preferences of users/inhabitants in the considered area. Preferences are expressed in terms of temporal logic formulas. To obtain such logical specifications, the information produced by agents A1, i.e. events registered in particular nodes, are processed. Informally speaking, the A2 agents translate physical events to logical specifications. The input for this translation are events \( d_i \) as defined above. The output are logical formulas understood as triples of the form \( l_i = (id, f, r) \), where \( id \) is an identifier/id of an object that operates in the parking space/IoT, \( f \) is a temporal logic formula, i.e. PLTL, and \( r \) is a number of occurrences of this formula as a result of a user behaviour. The algorithms for generating logical specification are to be a subject of future works,
c.f. also concluding remarks in the last Section. The entire logical specification is a set of these triples, i.e. \( S = \{ l_i : i \geq 0 \} \). The introduced notion requires some explanation. Many users can be identified in the entire system. The system stores information about different users and the id allows to differentiate formulas intended for a particular user. The meaning of \( f \) is obvious, i.e. it is a syntactically-correct temporal logic formula. The \( r \) element, where \( r > 0 \), is a kind of counter and it means multiple occurrences of a given formula as a result of multiple registrations of the same behaviour. For example, \( \langle idKR55, g2 \Rightarrow \Diamond p018, 7 \rangle \) and \( \langle idKR55, g2 \Rightarrow \Diamond p015, 2 \rangle \) means that user idKR55 enters gate g2 and sometime reaches the parking area p018 (seven times in the past), and sometime reaches the parking area p015 (two times in the past). When the preference decision is taken, and if p018 is free, then this parking area is suggested as the most preferred one, otherwise first p015 or second no suggestion is made.

Let us present rules for the A3 agent, i.e. the decision agent. This agent occupy the highest level in the whole hierarchy of the agent activities, and its purpose is to prepare preference decisions for a user/inhabitant. The agent analyze knowledge about preferences expressed in terms of logical formulas, which are produced by agents A2. The input for this analysis is a logical specification which is produced by the follower agents. The output are preference decisions prepared for a user/inhabitant.

Let us consider some cases to explain some ideas of the Algorithm. Say, the logical specification for a user \( o_i \) contains logical formula \( \square \neg (g3) \) which means that the user never entered gate g3. However, when at a certain time point user \( o_i \) appears at g3, then it provides the logical formula \( \square \neg (g3) \land g3 \) which might give the reasoning tree for the semantic tableaux method shown in Fig. 4.a, c.f. closed branch (\( \times \)). Of course, this tree could be a part of a greater truth tree, which is omitted here to simplify considerations, but it must contain at
least one closed branch, i.e. branch that contains a contradiction. It follows that the logical specification should be modified removing formula $\Box \neg(g3)$ from the initial specification, then new formula which results of a new event, entering gate $g3$, are to be added to specification. Another case could refer a situation when user enters gate $g2$ and the logical specification contains formula $g2 \Rightarrow \Diamond p010$, which means that when $g2$ is reached then sometime area $p010$ is reached. It leads to the following formulas and reasoning: $g2 \wedge (g2 \Rightarrow \Diamond p010) \Rightarrow \Diamond p010$, or using the truth tree Fig. 4.b, c.f. the open branch ($\circ$). The preference decision is the sample $p010$ parking area, if it is still free. The last case is the situation when a gate is reached and there exist two (or more) different (sub-)formulas, i.e. $g1 \wedge ((g1 \Rightarrow \Diamond p018) \lor (g1 \Rightarrow \Diamond p015)) \Rightarrow \Diamond p018 \lor \Diamond p015$, or using the truth tree Fig. 4.c, c.f. the open branches ($\circ$). It means that both $p018$ and $p015$ are areas of preference. It also means that the last element of the triple $l_i$ which is frequency $r$ of a particular formula determines which parking area is chosen as a preferred one, if it is still free.

4 Conclusions

In the paper we show an example of application of the IoT concept in the multi-agent environment where the external knowledge is represented by a graph and the preference model of behaviours is represented by the Linear Temporal Logic. Despite its exploratory nature, this work offers some formal foundations for future work. Although the current study is based on a relatively small sample, the findings suggest that it can be deployed in the case of more complex ones.

Temporal logic enables representing behaviours of objects in terms of temporal information within a logical framework. This allows to avoid many ambiguities typical for natural languages. This also allows to perform the reasoning process in a formal and reliable way. Logic modeling involves the development and application of formal logics to solve problem of interest in a field of the IoT. Temporal logic has strong application in the area of software engineering, and is used for the system analysis where behaviors of events are of interest. In work [13] the method of discovering behaviours considered as patterns is discussed. It provides logical specifications expressed in terms of temporal logic. In work [15] the temporalisation aspect of a plain system is discussed. It can be also used to analyze normal system events and behavior mining in smart environments. Both these works might provide strong support for algorithms generating logical specifications for users/inhabitants’ behaviours in the IoT network, considered as a context-aware and pro-active system.

The graph representing the parking consists of a few dozen of nodes, but in real systems such a graph representation consist of hundreds of thousands nodes. Thus, such a graph should be divided onto smaller parts that will cooperate themselves (with the explicit synchronization mechanism). Such an environment called Replicated Complementary graphs is supported by GRADIS [24] multi-agent framework where each agent controls one local graph $G_i$. Following the FIPA [2] specification [1] we assume a very simple functionality of a multi-agent
environment, reduced to a message transport and a broker system. This approach is similar to those applied in popular frameworks like JADE [3] or Retsina [4]. Summing up, it seems legitimate the statement that the deployment of these two formalisms, i.e. temporal logic as a branch of formal logic and graph representation and transformations, provide the synergistic effect, i.e. acting together the total effect is greater than if taken separately.

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