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A Framework for Proximity-Based Federation of Smart Objects
（スマート・オブジェクトの近接フェデレーションのためのフレイムワーク）

After the mainframe era in the 60s, the personal computer era in the 80s, and the mobility era in the 2000-2010s, the ubiquity era will certainly arrive in the 2020s. Mark Weiser was one of the first who introduced the concept of ubiquitous computing in a seminal paper of 1991. His vision of ubiquitous computing was the creation of physical environments saturated with computer devices. However, these devices are supposed to be gracefully integrated in the environment, and thus disappear from the eyes of the users. In other words, a ubiquitous computing system should provide services to the user seamlessly with a minimum of distraction.

Today, 24 years after the seminal of Mark Weiser, our real world environments are filled with many embedded intelligent devices with communication capabilities. We call these devices smart objects (SOs). They include smart phones, PDAs, tablet PCs, embedded computers, sensor devices, and RFID tags. Most ubiquitous computing applications are limited to the scope of two stereotyped scenarios, i.e., the location-transparent service continuation, and the context-aware service provision. Some researchers think that the potential of the ubiquitous and/or pervasive computing is limited because of the lack of formal models. They also think that any single layer model cannot handle all the concepts needed to understand ubiquitous and/or pervasive computing, and therefore, a hierarchy of models is necessary. Some studies focus on process calculi models. Other studies provide middleware frameworks to help developers to implement solutions.

These approaches are not sufficient to describe the interactions among SOs depending on SO location changes during the execution of an application scenario. Moreover, these solutions generally use a centralized control mechanism. It was already proposed that a decentralized solution is required to deal with spontaneous interoperation among mobile devices. Based on this, we believe that to realize the full potentiality of SOs, it is necessary to introduce a framework organised in a hierarchy of formal models. Each formal model in this hierarchy should focus on a specific concept of ubiquitous computing. This framework should allow the SOs to dynamically and autonomously reconstruct their federation configurations depending on location and context change. And it should not use a centralized control.

The first major contribution of this thesis is to provide a formal model that allows the smart objects to dynamically and autonomously reconstruct their federation configurations depending on location and context change. No centralized control is used to achieve this. This formal model deals with the following three different levels, where each level is built on top of its previous level:

- At the first level, or at the bottom level, the port-matching model describes the federation and interoperation mechanism between two SOs.
- At the second level, the graph-rewriting rules describe the dynamic change of federation structures among SOs.
- At the third level, the catalytic-reaction-network model describes complex application scenarios involving mutually related multiple federations.

A catalytic reaction network is a set of catalytic reactions. There are composition reactions and decompositions reactions. A composition reaction recombines a set of input materials into an output material. A decomposition reaction decomposes an input material into a set of output materials. An output material of a catalytic reaction may work as an input material of other reactions, or as a catalyst to enable or disable other reactions. If a material works as a catalyst to enable another reaction, it is called a promoter or a stimulus of this reaction. If it works as a catalyst to disable another reaction, it is called a repressor of this reaction. There is also contexts that can enable reactions. The main difference between a context and a stimulus is that a context is not mobile. Here we will consider only two types of catalytic reactions, i.e., reactions requiring both a context and a stimulus, and reactions requiring only a context. Reactions that can be disabled by a repressor, or reactions that do not require a context are not considered in this thesis.

We use this catalytic reaction network system to model scenarios involving complex federations of SOs where each material denotes an SO or a federation of SOs. These SOs are called application SOs. We present an implementation of our third level using the second level, and prove the validity of this model. This implementation is inspired by a biological RNA replication mechanism. In our framework, this replication mechanism is implemented using the graph-rewriting rules of our second level.

The second major contribution of this thesis is the proof of the validity of the implementation of catalytic-reactions using graph-rewriting rules. It has been shown that proving the properties such as confluence or termination of graph rewriting systems is not possible in general. However, our system only deals with a certain type of graphs. To prove the validity of our graph rewriting system, we needed to formally represent the class of graphs to which our graph rewriting rules are applied. These graphs all share the same type of structures that we called the double-strand structures. Proving the validity of our system for this type of graphs is possible, unlike proving it for the general case.

A system based on our theory has several advantages. It is robust and scalable. Since our system is decentralized, each scenario implemented by such a system is easy to modify. Even if there are several copies of the same context, each federation reaction uses only one of them. Multiple copies of the same context, however, may increase the robustness of the federation mechanism. Even if one of them may malfunction and get terminated, other contexts will continue to make federations. For scalability, whenever a certain context is overloaded, you may add more copies of this context to immediately increase the concurrent operation capacity. Each scenario is easy to modify because different contexts deal with different federation reactions, and each of them can be added or removed independently from the others.

With this new approach based on the RNA replication mechanism, and with the representation of the interactions among smart objects based on catalytic-reaction-networks, we can consider, describe, and implement new innovative scenarios beyond the current scope of stereotyped applications of ubiquitous, pervasive, and/or mobile computing.