A Taxonomy of Agent Technologies for Ubiquitous Computing Environments

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Abstract

The design, development and deployment of Mobile Agent (MA) systems for high-level inference and surveillance in wireless sensor networks and RFID systems have drawn increasing attention in the past decade. To answer how the state-of-the-art of MA in a wide range of ubiquitous and sensor environments is, this paper investigates the current progress of MA. It proposes a taxonomy, by which MA systems in ubiquitous computing environments are decomposed and discussed. Then, this paper provides insights into the strengths and weaknesses of existing efforts. Finally, it presents a series of solutions from the viewpoint of various roles of MA in ubiquitous environments and situations.

Keywords: Mobile Agents, RFID, smart grid, M2M, ubiquitous computing

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1. Introduction

The application-specific nature of Wireless Sensor Networks (WSNs) requires that sensor nodes have various capabilities for applications. It would be impractical to store all of the programs needed in the local memory of embedded sensors to run every possible application, due to the tight memory constraints and computation limitation. A Mobile Agent (MA) is a combined unit of code and data that migrates among sensor nodes to carry out tasks autonomously adapting to changeable contexts in the network environments, so as to achieve the objectives of the agent dispatcher, e.g., the sink nodes. The use of MAs to dynamically deploy new applications in WSNs has been proven to be an effective method to address this challenge [1].

Recently, there are several efforts regarding the use of agent technologies in WSNs. In order to what are missing, we review them one by one.

- In [2], the MAs fall into three categories --- *mobile software agents*, *mobile hardware agents* and *sensor nodes as agents*. The crucial issues for mobile software agents are middleware design and itinerary planning. In contrast, most previous efforts upon mobile hardware agents emphasize on localization, energy harvesting and agent communication. As for the sensor nodes as agents, existing research mainly leverages nodes as mobile relays in mobile sensor networks. The main issues consist of coverage, task assignment, topology control, and re-location algorithm [3].
- In [4], the agent design in WSNs is decomposed into four components: *architecture*, *itinerary planning*, *middleware system design* and *agent cooperation*. Among the four components, itinerary planning determines the order of source nodes to be visited during agent migration, which has a significant impact on energy performance of the MA systems.
- In [5], a survey on sensor networks is conducted from multi-agent perspective. Typically, sensors in WSNs must coordinate their actions to address system-wide design issues, e.g., physical distribution, resource boundness, information uncertainty, large scale, decentralized control and adaptiveness. Such challenges have been in the heart of MA systems research from its inception. Therefore, MA systems appear as a promising enabling technology for WSNs.
- In [6], various techniques for agent-assisted surveillance have been exploited. With technology advances, current surveillance systems are noted more and more for the use of several devices, heterogeneity in many instances, and distribution along the observed scenarios. Basic agent characteristics (autonomy, reactivity, pro-activeness and social ability), together with the distributed data management, low coupling, robustness, communication and coordination between autonomous entities of MA systems, bring us to the conclusion that the agency is an excellent alternative for solving the mind-boggling problems in surveillance systems.
- MAs may facilitate energy efficient data aggregation and sensor fusion by its intelligence. In [7], this kind of intelligence is investigated in a comprehensive manner. MA-based update is one of the major approaching for updating software in WSNs. The migration feature of MAs naturally suits the insertion of new code or upgrading the existing code [9].

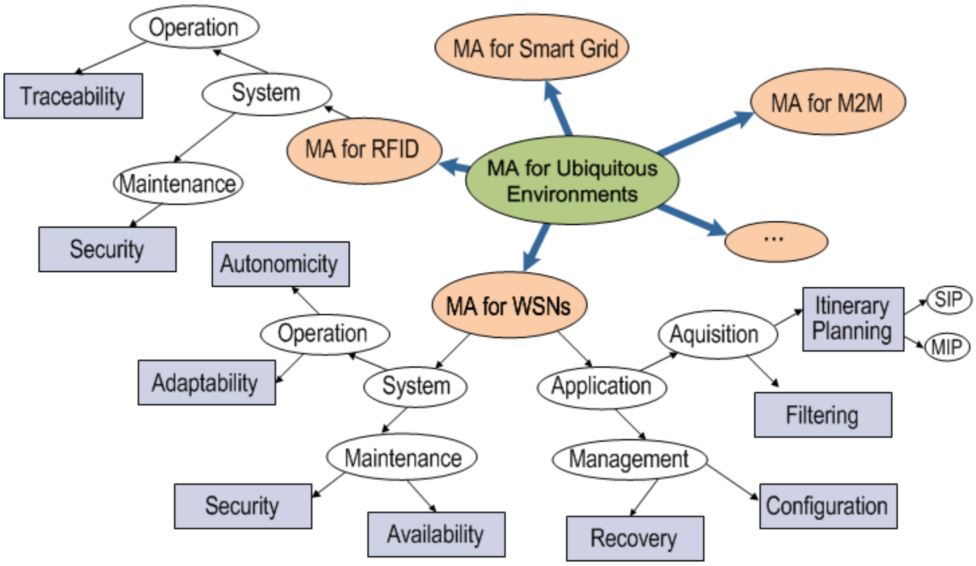

Fig 1. The proposed taxonomy tree of mobile agents in ubiquitous computing environments, involving agents in WSNs, RFID, M2M, smart grid, as well as other ubiquitous fields.

What is lacking in the previous literature is the taxonomy which covers a wide range of ubiquitous and sensor environments. Even for the agent technologies in WSNs, due to the large number of proposals, only three categories (i.e., *mobile software agents*, *mobile hardware agents*, *sensor nodes as agents*) are still not enough. Correspondingly, a more detailed classification for various proposals is beneficial to distinguish the broad usage of MAs. In this extensive survey, we address these shortcomings by: (a) in addition to WSNs, the ubiquitous environments are also extended to Radio Frequency Identification (RFID) networks, smart grid, Machine-to-Machine (M2M) networks, as well as any other ubiquitous networks in Internet of Things (IoT), and (b) we propose a three-level-based taxonomy of MAs, as shown below:

- In the first level of classification, we review the previous work by two main categories: *system-oriented* and *application-oriented*. In the former category, the design of proposals enhances specific functionalities of WSNs from the system point of view. While the literatures in the latter category, most of them are targeted to specific applications.
- In the second level of classification, we further divide system-oriented papers into two sub-categories: -- *improvement of operational functionalities, which extends functionality of WSNs with new characteristics, and improved maintenance methods, which approaches to improve the maintenance of WSNs*. Moreover, we also look into application-oriented papers by acquisition and management subcategories: 1) acquisition ones present a way of gathering data from or within the WSN, and 2) management ones report approaches to handle the nodes in WSNs. Take WSNs for example, in the third level, the previous schemes are categorized by *the following* roles:

  1. Automaticity: ability to work autonomously.
  2. Security: upgrading security for WSNs.
  3. Adaptability: ability to adapt to new circumstances.
  4. Availability: improving availability to the user.
  5. Routing: routing in WSN during data acquisition.

6. Filtering: excluding junk data during acquisition.
7. Configuration: setting specific configurations.
8. Traceability: tracking objects all the time or on demand.

According to the aforementioned classification criteria, the taxonomy tree is introduced in Figure 1, which has four main branches where each branch stemming from "MA for Ubiquitous Environments" corresponds to the MA applications in a specific area. The branch of WSNs is the largest one, which has eight leaves.

The rest of this paper is organized as follows. Section 2 briefly investigates the MA efforts in WSNs. Section 3 holistically overviews the work in RFID. Section 4 concisely reviews the latest progress of MAs in smart grid. Section 5 summarizes the research of MAs on machine-to-machine field. Note that in each section of existing work overview, we also discuss the strengths and weaknesses of existing work, together with our solutions to open problems. Section 6 concludes the paper.

2. The Use of Mobile Agents in Wireless Sensor Networks

2.1 Automaticity

2.1.1 Constructing Locally Centralized Applications by Mobile Agents in Wireless Sensor Networks

This research was done by [13] at the Nihon Unisys University and the University of Tokyo on the subject of enabling locally centralized applications in WSNs, which aggregated MAs to perform specific centralized functions for mobile targets tracking and monitoring applications. Strong point of this approach is the idea of grouping MAs to form a central monitoring function. Each group operates independently, whereas multiple groups that have miscellaneous functions can coincide in the same WSN simultaneously, shown in Figure 2.

Groups consist of three types of MAs: *master*, *slave-T (tracker)*, and *slave-S (sensor)*. Master carries the code of its slave MAs and can reproduce them at will, thereby making group migration possible. While lost slaves who lose their masters are deprecated. The approach promises to resolve the issues at hand, such as loosing track of the monitored objects, non-reliable message passing in WSNs, and trying to discover the new location of the monitored objects, energy consumption by decreasing network communication with the base station, and the life cycle of monitoring applications. However, there might be several concerns when objects would be highly mobile. In that case, master MA would spend more time on tracking the objects and setting up to monitor it, than actually monitoring them, in which some mechanisms like "time waiting" for the objects to be stationary before starting to monitor the objects should be re-visited.

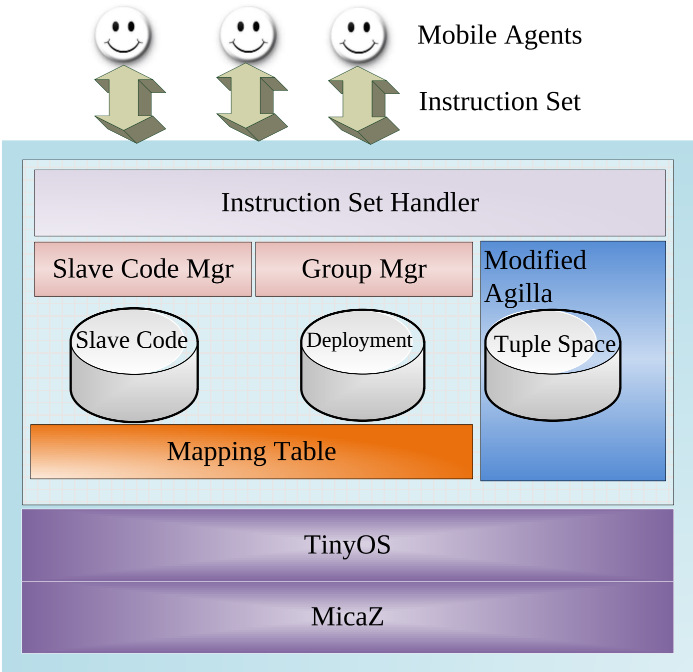

Fig. 2. The architecture of locally centralized applications by MAs in wireless sensor networks, which is built on top of MicaZ sensors and TinyOS.

2.2 Adaptability

2.2.1 Dynamic Macro-programming of Wireless Sensor Networks with Mobile Agents

The research on the subject of dynamic macro-programming of WSNs [15], partially funded in the framework of the ambiance project at the University of Luxemburg, aimed to enable diverse functionality of WSNs by MA technology. The use of uQueries is the main advantage of Macro-programming and by enabling the same in WSNs, it also benefits from its diverse functionality.

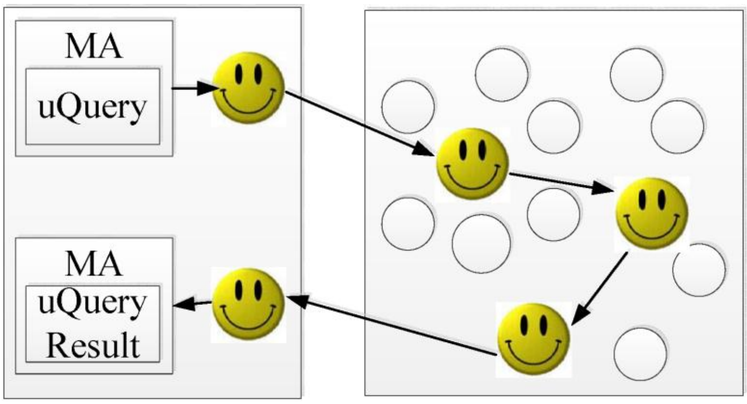

Fig. 3. Macro-programming with MAs, which provides uQuery – a high-level language that supports WSN macro programming.

The working principle of this approach is illustrated in **Fig. 3**. Enabling of uQueries is done by representing them with mobile agents or actors, as they are called in this paper, which are generated by a meta-agent, a stationary agent, and then sent over Internet to a desired sensor node to do its task. This research proves that mobile agents can enable macro-programming in WSN's and increase their work dynamics and diversity in ambient intelligence use. The solution proposed is salient for the operational part. The mobile code is transported via Internet, which could demise the security level of MA code. Therefore, strict security checks must be implemented on MA system itself to assure that its code is genuine and that it is not compromised with malicious code.

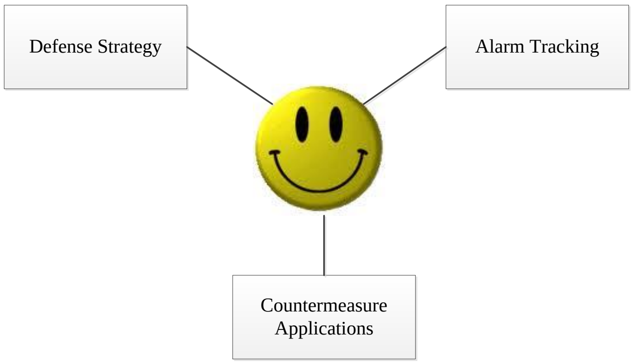

Fig. 4. A cross-layer security framework by MAs, where MAs can detect intrusion by defense strategy and notify applications by alarm tracking.

2.2.2 Mobile agent based event discovery in wireless sensor networks

Research was carried out at Basaveshwar Engineering College [17], on the subject of increasing the responsiveness of WSNs, with upgrading query distribution and event responsiveness by employing event paths generated by MAs. The chief goal of this research is to give better response time so as to trigger events by optimal paths from the user interface to the sensors that detected the event.

The information of optimal paths is generated and maintained by local node MAs on the basis of their autonomicity and mobility they hop through the network updating for message routing. Simulation results demonstrated that the approach was satisfactory for detecting real-time events. This proves its idea strength, but there might be a drawback in case that lots of MAs were employed to find an optimal path, particularly for MAs that are far away from the event, thereby negatively depleting the MAs' power.

2.3 Security

2.3.1 Agent-based Scalable Design of a Cross-Layer Security Framework for Wireless Sensor Networks Monitoring Applications

This work was studied at the Center of Excellence DEWS in 2009 [21], on the subject of designing a framework for WSNs, which would maintain the needed security level in WSNs by multiple agents. The objective of this research is devising a security framework for the WSNs, which is achieved by devising a cross-layer platform with components that allows use of multiple agents, amongst which are stationary and mobile agents, with integrated code for developing intrusion detection as well as intrusion detected reaction. Essence of this approach is shown in **Fig. 4**.

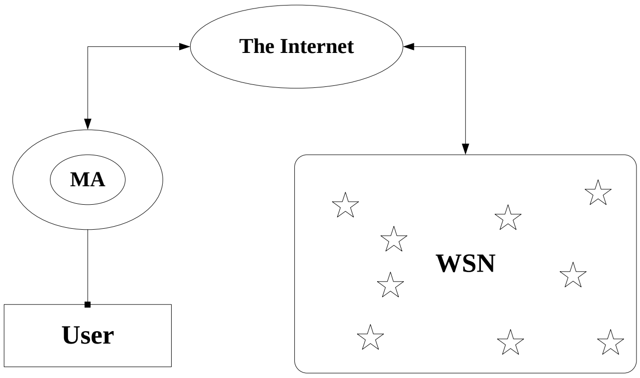

Fig. 5. A MA-based real-time mechanism of accessing Internet. This leverages mobile software agent paradigm to design a dynamic infrastructure for WSNs access on the Internet. This mechanism significantly reduces the consumption of network bandwidth and node energy.

In the example shown in the surveyed paper, only three types of agents are exploited-a stationary agent to detect anomalies in radio traffic and trigger anomalies alarm which is run on each node; a mobile agent which traverses the whole WSN looking for anomaly alarms, and report to the third agent; the last agent is also a stationary agent, but only run on the base station of the WSN, it manages alarmed nodes. This approach proposes a cross-layer framework to provide security for WSNs, which is a good solution that allows mobile and stationary agents to offer security in WSNs. Note that special attention must be given to MA authenticity and protection from being compromised by malicious code.

2.4 Availability

2.4.1 A Mobile Agents-Based Real-Time Mechanism for Wireless Sensor Network Access on the Internet

The research on the subject of WSNs access over the Internet was carried out at the Shengyang Institution of Automation so as to integrate WSN's and the Internet by using mobile agents which sent over the Internet through a gateway node [11]. The solution at hand provides advantage in power consumption, by connecting to the Internet only via gateway nodes through which the MA's were sent. The essence of this approach is shown in **Fig. 5**. The novelty of this idea is that a MA is dispatched and retrieved via the Internet; in between data collection is achieved in the manner that inserted MA collects data from the neighboring nodes where it resides on, thereby eliminating the need to traverse all the nodes. Solution provides availability of WSN through the Internet, which enables user mobility and connectivity. By allowing this, the WSN becomes vulnerable to security attacks via the Internet, who by draining power from gateway nodes could severe the connection of the rest of the nodes that reside in the same area as the depleted nodes, so appropriate security counter measures are supposed to be devised.

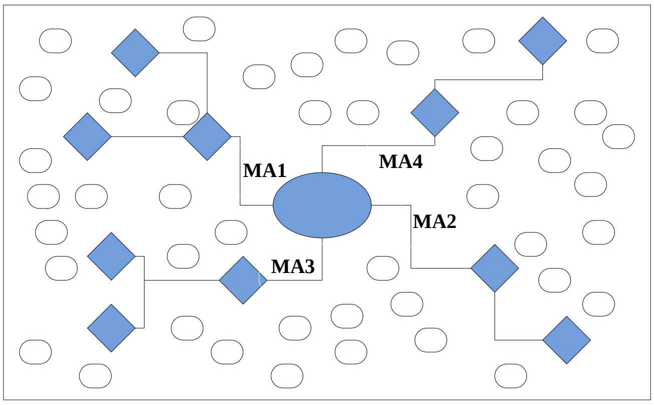

Fig. 6: Balanced itinerary planning for multiple MAs that is constructed based on minimum spanning tree, where each branch stemmed from the sink corresponds to a group of source nodes assigned for a mobile agent to visit.

2.5 Routing

2.5.1 Balanced Itinerary Planning for Multiple Mobile Agents in Wireless Sensor Networks

This technical paper was reported by [12] at Seoul National University and University of British Columbia, in 2011, on the subject of MA migration during data gathering in WSN's for reducing power consumption and hence increasing the life of sensor nodes. The main issue when using multiple MA's is grouping the nodes so that MAs between the nodes in a group consumes as little energy as possible. This is achieved by devising new agent migration algorithms that produces an agent migration itinerary.

In essence, this approach is shown in Figure 6. The network of WSN nodes is represented by a totally connected graph, for which we calculate a minimum spanning tree and generate the appropriate number of agents that equals to vertices coming out of the root of the tree. Since the algorithm has a flaw when MA hops between nodes are smaller in compare to the hops from the source node, its modification proposes a new algorithm that incorporates a balancing factor to balance the generated spanning tree in this special case. The results provide support for the idea claimed in this paper and shows the optimal trade-off between energy consumption and task duration by varying the balancing factor. Idea is salient and confirmed with simulation results, but there might be some cases when a specific hop count for different groups of sensors exists so that a balancing factor that is good for one group is bad for another group, so it might be a good idea that a balancing factor is chosen dynamically by the MA based on the node hop state in WSNs.

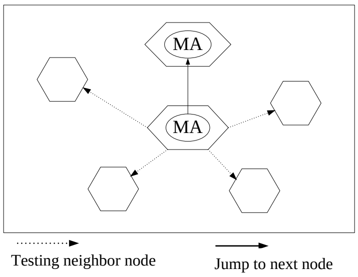

Fig. 7. Data gathering based on emergent event-driven in cluster-based WSNs by MAs, which dynamically clusters the sensor nodes based on the information of event severity degree. This information is gathered by MAs that traverse all member nodes.

2.5.2 A Data Gathering Algorithm Based on Mobile Agent and Emergent Event-Driven in Cluster-Based WSN

This research was on the subject of data acquisition in clustered WSNs in order to decrease power consumption and network delay in WSN nodes, done by [10] at the Yunnan University, Kunnang, China. This is achieved by introducing the mobile agent technology. Role of mobile agents is to gather sensor data from all nodes within a cluster and return it to a cluster head node, thereby reducing power consumption of individual nodes communicating to the head cluster node. The essence of the solution is presented in **Fig. 7**, which is characterized by dynamic routing of MAs in traversing the nodes. When a mobile agent calculates the next hop node, it computes the power consumption of the travel to that hop, path loss, and the stimulated intensity (*i.e., residual energy*) of other nodes. The solution is justified with experimental results from tests showing that the power consumption and network delay have decreased, opposed to conventional data gathering. The idea of dynamic routing of MA is effective and it appears very similar to the nearest town of TSP, but with a difference that the path to the next node is a variable in time. Therefore some optimization like recording the last next hop node and what is the optimal energy used for the hop could be taken into consideration, as an optimal solution could save time by using the first node that satisfies the optimal energy consumption for a hop, rather than testing all the neighbor nodes.

2.5.3 Exploring Sensor Networks using Mobile Agents

To address the problem of MA generation and routing a genetic algorithm, research was done by [16] at the University of California, Irvine and the Washington University in Saint Louis, on the subject of network exploration of WSNs using MA technology. The genetic algorithm is implemented to create a MA itinerary plan for each agent that is sent to WSN and MA tracking, where each MA itinerary is a route, with best energy preservation characteristics from the collection point throughout the WSN and back. If something unpredictable happens to a specific node which is a hop in MA's route that is solved by hoping to the next one along the route, this is based on the presumption that density of the WSN is favorable for this scenario. Measurements given in the surveyed paper support the claims of the proposed solution showing the genetic algorithm gives adequate results. Approach of this research is salient in the case presumed, but in case that density of the WSN is not adequate for the presumption, so that when MA has to skip a node in his route a problem arises, so lost MAs should be taken into consideration.

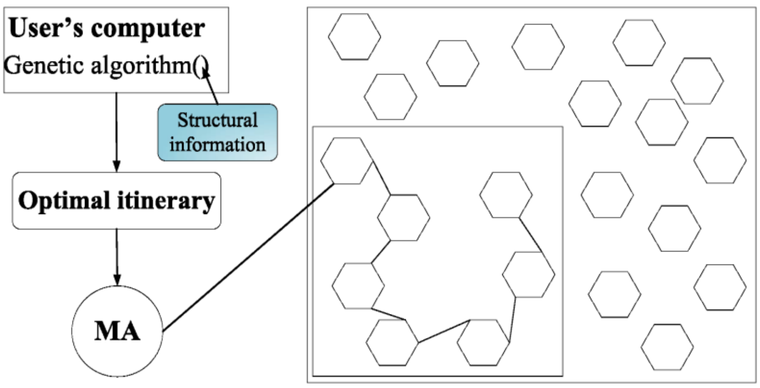

Fig. 8. Optimal itinerary analysis by MAs, where the data fusion code is moved to MAs on the data sites (represented by hexagon shapes) while the data stays at the local spots. By itinerary planning, MAs can achieve progressive fusion accuracy.

2.5.4 Optimal Itinerary Analysis for Mobile Agents in Ad Hoc Wireless Sensor Networks

Research of this approach done by [20], at the University of Tennessee was on the subject of mobile agent data fusion in WSNs to reduce network communication and decrease power consumption of the nodes. This was built on top of the optimal itinerary planning, so that there is no redundant node hoping by the MA, which directly affects power consumption on the nodes. The essence of this research is shown in **Fig. 8**.

Optimal itinerary is created by the Genetic algorithm proposed in the solution, so that computation and power consumption are reduced to a relative minimum. The approach shows promise reducing power consumption and finding the optimal itinerary is a good way to achieve that. But the suggestion that it should derive the stationary algorithm, because it is computation-intensive could be limited owing to the node failure inside WSNs.

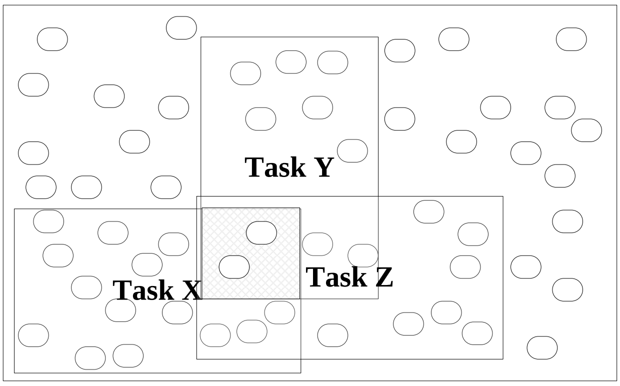

Fig. 9. MA-based data dissemination

2.6 Filtering

2.6.1 Data Dissemination based on Mobile Agent in Wireless Sensor Networks

This research done by [14] at Seoul National University of Korea was on the subject of data acquisition in WSNs, for reducing network load by introducing MA in a multi-hop environment without a cluster head. The role of MA in the proposed solution is to decrease the total amount of data by various techniques, among which the main one is to aggregate the code of a number of similar tasks into one. Tasks are aggregated by result data and filtering is done based on the combined task sensor overlapping in areas of individual tasks, thereby reducing the amount of data to be collected and the number of sensor nodes to be visited on the base of the combined task.

The solution proposes a good technique for filtering out redundant data, but it suffers that aggregating tasks into a combined task increases the latency time of individual tasks, which could be resolved by replicating a MA into multiple agents to concurrently do the job. Replicating MA's is feasible, but requires careful efforts of dividing the task into numerous parts where all the circumstances must be taken in consideration, e.g., *spatial position of nodes*, *area overlapping for tasks* and *keeping track of mobile agents*.

2.7 Configuration

2.7.1 Mobile Agent Based TDMA Slot Assignment Algorithm for Wireless Sensor Networks

Research was done by [18] Honeywell Technology Solution Laboratory, and presented at the Proceedings of the International Conference on Information and Technology: Coding and Computing, on the subject of TDMA slot assignment in WSNs. It introduced a better, performance wise solution by using MA technology. Algorithm devised is based on a MA created by the initial node (starting point for TDMA slot assignment), traversing all the nodes while assigning them with a neighbor unique slot. Two types of agents are taken with MA structure. One MA contains all the information about the node neighbor coloring of the WSN and the initial maximum number of slots needed, whereas the other one does not keep any knowledge about the node neighbors slots. As seen in the results of the surveyed paper this approach has shown slightly better performance for 100 nodes WSN. As mentioned in the paper multiple agents could increase performance of this approach, but then deployment should be carefully devised. One possible solution would be that from the initial point, each MA takes one of the vertices from the initial node and its work is finished when it arrives to the initial node for the second time, other approaches would incline WSN division in sections and information about specific sector is required by the MA assigned to that sector.

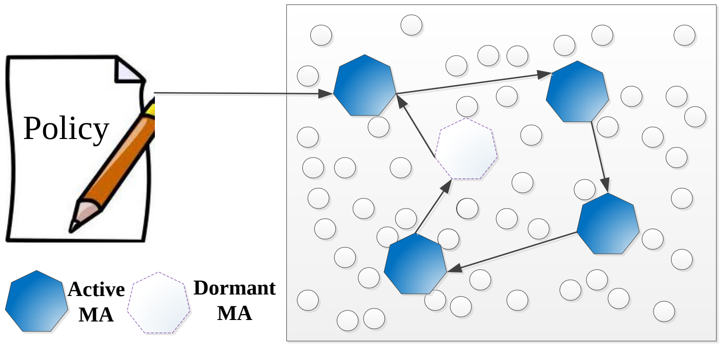

Fig. 10. MA-based policy management

2.7.1 Mobile Agent-based Policy Management for Wireless Sensor Networks

This research at Wuhan University of Science in Hubei, China, is on the subject of network management in WSNs [19]. It is built on top of an idea of using an MA for policy management on the sensor nodes. Policy management is executed by a mobile agent who resides in the WSN in a dormant state and activates when there's work to be done. The main principle of this approach is illustrated in **Fig. 10**. Keeping agents on standby increases time of response of enforcing a new policy. Idea given in the paper is novel and it also reduces network load, decreases power consumption and increases network management automaticity. Solution has a lot of potential; one could be for fault detection since by adding a function to the MA so that it checks for hardware glitches inside WSNs.

3. Mobile Agents in RFID systems

3.1 Identification-centric RFID Systems Based on Software Agent Intelligence

As an important wireless technology, Radio Frequency IDentification (RFID) has received increasing attention. It has been used in many industries to allow for quick access of the identification (ID) numbers or codes of objects. A RFID tag contains a simple antenna, transponder, and memory chip where ID information of the bearer object is saved [36][37]. This information can be read with a special RFID reader by irradiating the transponder with electromagnetic waves. Recently, RFID has achieved widespread success in miscellaneous fields, ranging from item tracking and tracing, inventory monitoring, asset management, supply-chain management to E-healthcare [8]. Once the object's ID is verified, the profile of this object can be retrieved from a database, and suitable service code can also be obtained. By following this centralized approach, the infrastructure recognizes the required actions that need to be performed with the object.

In this article, we characterize the existing RFID systems as "identification-centric RFID system (IRS)", indicating that they are targeted to the object tracking, i.e., traceability. Generally, IRS leverages passive information about the object, such as identification and/or description information stored in RFID tags, and the corresponding action decision is made by relying on a pre-established rule-based database. However, the static rule-based database cannot be updated in a timely fashion for new object types and/or environmental dynamics, which causes a synchronization problem. Thus, IRS has two disadvantages: 1) the object's profile database must be set up in advance to allow for interactions between a RFID tag and a profile database, and 2) when encountering a dynamic environment such as an emergency situation with difficulty of network access, the information stored in the database may not be up-to-date, or may even be unreachable, resulting in a human operation delay and/or service failure.

3.2 Code-Centric RFID Systems Based on Software Agent Intelligence

A new "code-centric RFID system (CRS)" is proposed as a solution to the problems existing in traditional IRS [22][23]. The proposed CRS incorporates code information that is dynamically stored in the RFID tag, facilitating other systems to perform on-demand actions for objects in various situations. To achieve this, MAs specifying up-to-date service directives that can be realized by intelligently handling network dynamics are encoded in RFID tags. Due to the limited availability of memory in RFID tags (e.g., *4KB*), we have designed a new compact high-level language for coding mobile agents stored in the RFID tags, which will be interpreted by a corresponding middleware layer in the RFID reader. By using these mobile agent-based RFID tags, an object can "tell" the system to intelligently execute actions in response to the occurrence of specific situations.

In addition, there is a growing interest in the integration of RFID with other technologies, *e.g., WSNs, Internet Protocol (IP) networks, and cellular networks*, for the development of scalable systems and applications that improve people's everyday lives. Following the continuous advances in wireless communications technologies, the capacity to achieve this is further enhanced when RFID is incorporated with these technologies to revolutionize a wide range of applications. By storing mobile codes in RFID tags, CRS enables a seamless integration with other systems. This new code-centric approach introduces the following benefits.

1) It effectively eliminates the requirement to retrieve the associated RFID-code action information from a database, and enables more robust systems for highly dynamic environments.
2) It can greatly reduce the overall system response time by retrieving service information from tags.
3) It helps to improve scalability at the database side, which is only indispensable now as a backup subsystem.
4) It allows for improved resilience, since the system can remain operational in case of database and network failures.

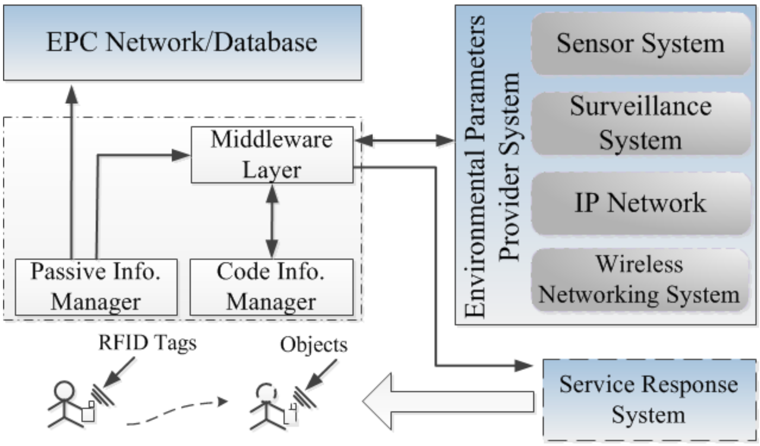

Fig. 11. Functional components of CRS

3.3 Event Processing Middleware for RFID-WSN systems by MAs

In [25][24], the authors argued that the design of future middleware architectures for sensor networks and RFID systems is challenging due to the underlying standards being subject to frequent changes. As a consequence, we identified a set of non-functional design goals, which should be considered when developing such middleware. By using software agents for engineering the middleware, they expect to be able to deal with frequent architectural changes as agents are a means for designing complex software in dynamic and distributed environments. Additionally, agents are from a software engineering perspective the natural answer to scalability, reliability, extensibility and adaptability issues-key concerns for the distributed processing of event streams. We proposed a three-layered, event-driven architecture following the state-of-the-art middleware designs, in which agents are the main actors responsible for processing the events.

3.4 RFID Security based on MAs

With the popularity of RFID technology, security and privacy has drawn increasing concerns. Most existing efforts focus on developing light-weight cryptographic modules insider of RFID tags and encapsulating communication protocols with RFID readers. However, the limited communication and computation capabilities of RFID tags [38][39][40][41], incur their ineffectiveness.

In [42][43], a MA based security scheme has been studied, which had strong cryptographic modules with a powerful CPU and battery, and hence ensuring the high-level security. It collected tags' secrete information partially and acted as proxies of tags that were in sleep mode. RFID readers interacted with these proxies rather than tags. To further reduce the communication overheads, a hash function had been exploited. However, this kind of scheme required that mobile agents could acquire more information of tags. Otherwise, the detection accuracy of the system would be decreased considerably. In outdoor environments, especially object tracking in uncertain environments, the deployment of mobile agents before the system is challenging.

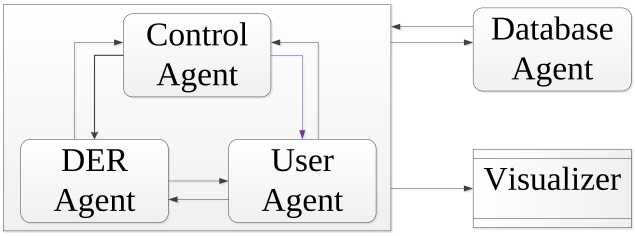

Fig. 12. MA based system design of smart grid

4. Mobile Agents in Smart Grid

Smart grid is an initiative that intelligently adapts to the information about the behavior of both suppliers and consumers so as to ensure the efficient, reliable, economic and sustainable electricity services. One way to achieve such intelligence is MA. We characterize smart grids by MA as system design and maintenance.

4.1 Mobile Agent based Design of Smart Grid Systems

Reference [26], demonstrated that the use of multi-agent systems to control a distributed smart grid was viable, which facilitated the seamless transition from grid connected to an island mode when upstream outages are detected? The essence of system design of smart grid is employing MAs in the grid acquisition, processing, storage and delivery.

As shown in Figure 12, control agent takes responsibility of voltage and frequency detection, and operational control. DER agent is in charge of storing information of energy resource, *e.g., power rating, fuel availability, and resource identification*. User agent is a gateway between grid suppliers and consumers, which provides users with real-time gird supply. Database agent aims to store system information and record the messages and data shared among agents. Thus, these four types of agents enable us to rapidly construct the architecture of a smart grid system.

Additionally, [27] and [28] also report their devise in the design of multi-agent based smart grid systems. The former analyzes the issues in real-world deployment and then puts forth the solutions, whereas the latter suggests that the interplay between MAs should be incorporated and hence facilitates inference and handover by complex network theory and methods.

4.2 Mobile Agent based Smart Grid Maintenance

Given the scale and complexity of smart grid, fault location detection is of paramount importance. Conventional approaches of fault location detection may not timely and accurately locate the faults owing to the losses of grid distribution and interference. In [29], a multi-agent grid management framework was presented to achieve high reliability, power quality, as well as power generation and consumption. The core idea shown in Figure 13, is that devising agents for power electronic compensators that can expedite a series of services, *e.g., reactive power generation, power flow control, harmonic compensation, and voltage regulation.*

In [30], an approach based on MAs was reported, which modeled the holistic grid network as the network on top of local MAs. Each MA is responsible for a grid distribution unit. When a fault occurs, every agent acquires transient zero voltage and current, and computes transient zero reactive power in special frequency bands. Through inter-communication and collaboration among MAs, all fault information is shared.

As a matter of fact, MAs in smart grid are much like sensors that capture information in grid distribution unit, and then route it to the controller or peers. Consequently, peer-peer and WSNs-based system design and diagnosis could be used to further improve the performance of smart grid systems.

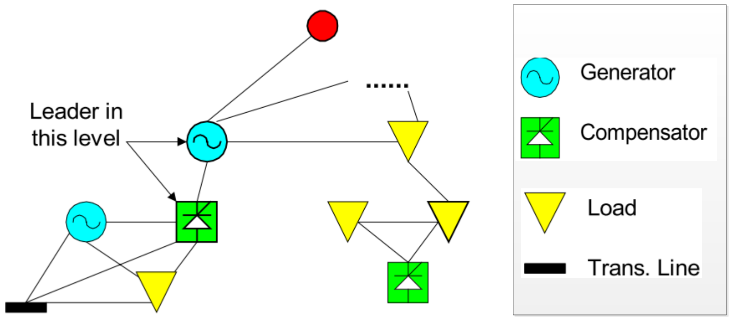

Fig. 13. MA-based system design in smart grid

5. Mobile Agents in M2M

The proliferation of communication technologies, the growth of technological capabilities of mobile devices, and the pervasiveness of sensors contribute to expand the Machine to Machine (M2M). M2M refers to a technology that enables nodes to communicate with other devices of the same ability.

In [31], research on augmenting agricultural decision support system was conducted at Casablanca University, Morocco, by exploiting multi-agent systems and constraint programming paradigms. This is because mobile devices are seriously limited by the communication and computation capabilities. The prototype was supposed to build in Java and agent UML to across desktop and mobile computing platforms. [32] extended the MAs into ubiquitous manufacturing systems, where PDA and mobile devices are capable of acquiring the machine status and data of CNC machines, thus enabling the anywhere-anytime controlling and monitoring of a manufacturing system. Similar with [31], it applied the MAs into the new field and improved the performance of existing processes. Consider that MAs are mainly customized to assist users in intelligently making decisions; efforts on MAs could be shared in application fields and then leverage the power of MAs in every working day.

6. Conclusion

Ubiquitous computing is a computing paradigm shift from desktop computing and mobile computing, in which Mobile Agents (MAs) are regarded as one of the killer technologies. Previous literatures on MAs do not embrace the latest progress in ubiquitous computing paradigm. To this end, we have proposed taxonomy of MAs, covering a holistic picture of agent technologies proposed for ubiquitous environments.

Given that ubiquitous computing involves a variety of research fields, among which WSNs, RFID, Smart Grid and Machine to Machine are crucial. We hereby have investigated the state-of-the-art efforts of MAs in these fields. We review the existing efforts, together with our solutions to the problems and drawbacks, by which we are seriously limited.

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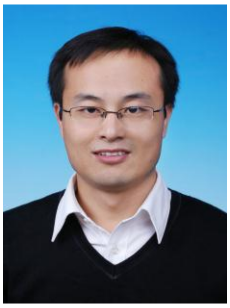

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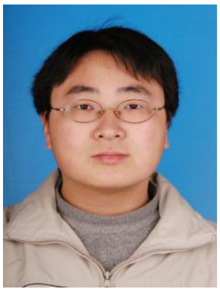

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