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A review on the applications of multiagent systems in wireless sensor networks

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Abstract

Nowadays, the efficiency of multiagent systems in wireless sensor networks prompts the researchers to use these emerging mobile software packets in different simulated approaches or real-world applications. Heterogeneous and distributed wireless sensor networks could be integrated with the multiagent systems to map the real-world challenges into the artificial intelligence world. The multiagent systems have been applied from simulated approaches like object detection/tracking, healthcare, control/assistant, and security systems to real-world applications, including medical/human-care systems and unmanned aerial vehicles. Furthermore, the integration of wireless sensor networks with multiagent systems have emerged novel application, which is known as mobile robots. However, the extensive use of mobile agents in wireless sensor networks has posed different challenges for researchers, including security, resource, and timing limitation. In this work, we review recent simulated approaches and real-world applications of multiagent systems in wireless sensor networks, in which a set of common factors about the things that have been studied are extracted and compared to analyze the performance of mobile agent–based systems in the wireless sensor networks, as well. This analysis provides new research directions about multiagent systems in wireless sensor networks for interested researchers. Finally, a novel framework for dealing with the challenges of multiagent-based applications in the wireless sensor networks which have been mentioned is suggested.

Keywords

Multiagent systems, wireless sensor networks, mobile agent, simulated approaches, real-world applications

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Introduction

The term *wireless sensor networks* (WSNs) is defined as multi-hop network systems. They are formed through distributed, self-organized, and energy-constrained wireless sensor nodes and actuators, which collect data needed for a certain application from the monitoring area automatically in order to improve the performance of the monitoring systems and decrease the total costs.[1–3] The main operation of such WSNs is to collect required data from their Field-of-View (FoV). Right after that, the useful extracted information is sent to Base Station (BS) or sink to be performed extra processing or other purposes.[4,5] Figure 1 shows a general schema of a WSN with 15 wireless sensor nodes; the set of nodes is $N = \{N1, N2, N3, \ldots, N15\}$ and a sink that controls the whole system.

The main characteristics of WSNs are low-power processing and distributed sensing, which enable them

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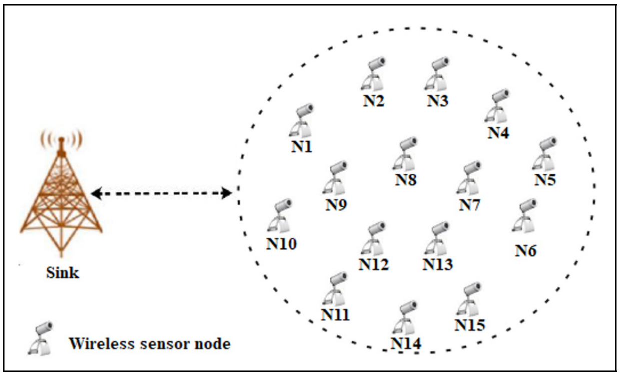

Figure 1. A general schema of wireless sensor networks.

as a common technology with several applications, including the following:

- *Traffic control systems*: It is cost-efficient to solve the traffic problem in metropolitan cities by using the WSNs, providing that all vehicles, traffic lights, parking slots, and city cameras are equipped with wireless sensor nodes. The information provided by the wireless sensor nodes, for example, helps the drivers to find low-traffic routes or vacant spaces to park.[6,7] Furthermore, the wireless sensor nodes scattered all over crowded cities can simplify the process of identifying traffic violations.[8]
- *Automated assistance for the elderly and biomedical health monitoring*: The WSNs offer a new technique to monitor and supervise the behavior or vital signs (body temperature, blood pressure, pulse/heart rate, and breathing/respiratory rate) of elderly people and patients, without disturbing their daily routines.[9–11] In such applications, several kinds of sensors such as multimedia or scalers are used to collect the necessary data from some supervised persons; the sensors process them and detect any abnormal behavior in emergency situations. Indeed, it is claimed that the WSNs could improve the life quality of elderly people and patients by obtaining data from their abnormal behavior and vital signs.
- *Environmental monitoring systems*: The potential of WSNs can be applied for environmental monitoring and surveillance. In fact, if the wireless sensor nodes are equipped with particular kinds of capability such as visual, temperature, or humidity sensing, they will be able to monitor wide range of environment like agricultural or residential areas without any human intervention.[12–14] Furthermore, the WSNs can be used in airports, sports stadiums, and crowded places that required immediate monitoring and security actions to detect potential violations.[15,16]
- *Virtual reality*: Setting up the WSNs in spectacular places such as museums and exhibitions could help the Internet users to visit them remotely (without any real presence). In the case of using the virtual reality, the Internet users can get a more realistic sense by changing the camera angle and watching the interesting scenes from different FoVs.[17] In addition to the entertainment applications, WSNs are used in the virtual meetings and conferences to enable the remote presence of participants.
- *Industrial process control systems*: The WSNs are used to monitor and control the industrial environments such as automobile, food, and medicine factories to enhance the productivity of the systems in a limited period of time and resources.[18,19] It should be noted that the use of the WSNs in the industrial field, in addition to increasing the productivity, simplifies the controlling process, increases the flexibility of systems, and reduces the cost of repairs and their maintenance.[20,21]

There are many challenges in the field of WSNs to meet the requirement of the applications in spite of the significant advances in hardware and algorithms; one of them is energy restriction. Since the wireless sensor nodes still provide their required energy using low-power batteries, the network is faced with energy discharge in all of these applications.[22,23] Furthermore, the WSNs are often applied in harsh and inaccessible environments for a long time to provide the requirements of the applications.[24] It is because there is no possibility of recharging or replacing the batteries of the wireless sensor nodes. For this reason, it can be argued that one of the most important challenges in the WSNs is the extreme energy restriction.[25] Since the efficiency of WSNs is extensively dependent on the network lifetime and its coverage, it is really necessary to consider the optimal algorithms for the object detection, the target tracking, the node clustering, and the data aggregation in such networks to reach the functional requirements such as reliability and being real-time.[26]

As it mentioned, to meet the requirements of the applications of WSNs, each wireless sensor node collects the data from its FoV in the monitoring area and transmits the processed information or the raw data to the sink periodically or based on sink demand. However, most of the wireless sensor nodes cannot send the collected data to the sink directly because of their long distance from the sink (the sending radius of the wireless sensor nodes is limited). In the state of

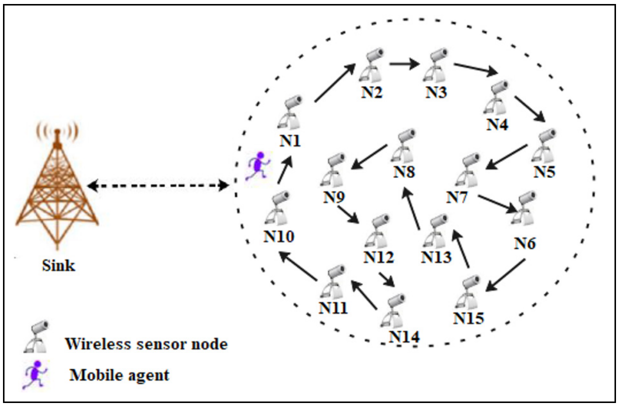

Figure 2. A general schema of a single mobile agent in wireless sensor networks.

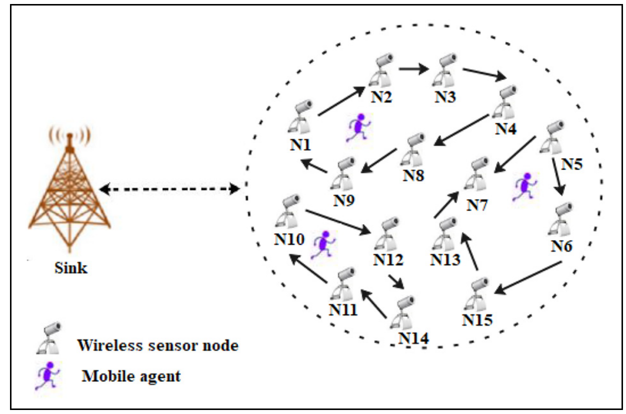

Figure 3. A general schema of multiagent system in wireless sensor networks.

perfect condition, in direct data transmission from the source nodes to the sink as well, the wireless sensor nodes that are away from the sink die much earlier than the close ones.[27–29] So, the performance of the whole network is reduced. Therefore, it is necessary to provide an energy-efficient data aggregation method to enhance the lifetime of the wireless sensor nodes and their quality of service (QoS).[30] Data aggregation is defined as an intelligent process to collect the data from the source nodes and, then, to change it by using different functions for optimizing injected traffic into the WSNs. As a result, the resource consumption of the sensor nodes and their transmission delay.[31]

However, it is proved that data transmission in WSNs consumes much more energy than the other local tasks such as data processing.[32] Therefore, it will be more energy efficient if each wireless sensor node saves its collected data from the monitoring area on a local memory and waits for a software such as a mobile agent (MA)[33] or the hardware such as mobile sink[34] to process and collect the required information. A *mobile agent* is defined as a software packet or a computer program that includes a particular computational code, which is based on the requirements of a certain application and an assigned itinerary to visit the sensor nodes one by one and collect their sensed data, then fusion, and dissemination it.[35,36] In other words, the sink applies an MA to the monitoring area to migrate through the wireless sensor nodes. The MA collects and reduces the sensed data all over the WSN and then returns back to the sink to deliver its load. Data aggregation by the MA injects a single traffic flow of data in WSNs instead of multiple ones. Also, software MA migration over the WSNs does not come across with the hardware (mobile sink) mobility challenges.[37] The general scheme of using a single MA to satisfy the requirements of the applications of WSNs is illustrated in Figure 2. However, using a single MA in WSNs has the following drawbacks:[38,39]

- Long delays in the scenarios that MA visits numerous wireless sensor nodes one by one.
- Increasing the packet size of MA during the data collecting process from the wireless sensor nodes to the sink. So, it increases the energy consumption of the close wireless sensor nodes to the sink.
- Decreasing the reliability of the WSNs when the packet size of the MA is increased; indeed, increasing the chance of being data lost in the cases that the MA migrates to several wireless sensor nodes.

To overcome the weaknesses of single MA approach in the WSNs, some authors suggested that the sink dispatches several MAs by working together as a multiagent system (MAS), over the network.[40] An MAS is considered as a set of MAs, which collaborate and coordinate with each other to achieve a certain goal. In other words, members of an MAS follow their own itinerary plan to visit a subset of the wireless sensor nodes and perform a unique task equally.[41] Figure 3 illustrates a general schema of the MAS, which includes three MAs in the WSN (The general Schema of WSN is shown Figure 1).

Due to the efficiency of MASs in the WSNs, many simulated approaches and real-world applications are raised in different academic and industrial fields. In literature, the MAs are used to deal with the academic challenges, that is, object detection/tracking, healthcare, control/assistant, and security systems.[42–47] Furthermore, the combination of the MAs and the WSNs causes the emergence of various real-world applications, that is, medical/human-care systems, unmanned aerial vehicles, and mobile robots.[48–50] The

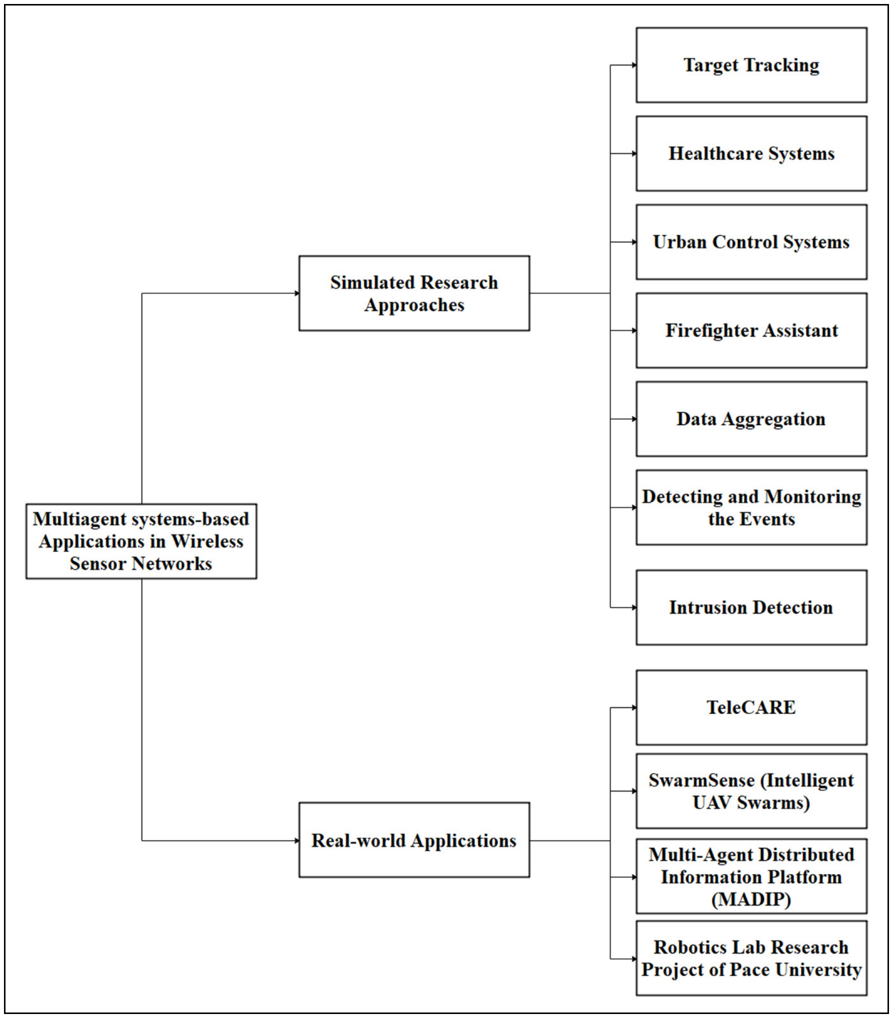

Figure 4. The overall scheme of mobile agent–based applications in wireless sensor networks.

overall scheme of MA-based applications in WSNs is illustrated in Figure 4.

The review presents the integration of MAs with the WSNs, their efficiency factors, limitations, and future research directions. In addition, a new framework for multiagent-based applications in the WSNs is suggested. The rest of the article is organized as follows. In section "Applications of MASs in the WSNs," an overview about the simulated approaches and the real-world applications of the MAs in the WSNs is given. The research papers and applications based on the WSNs' efficiency factors are compared, as well. Section "Challenges, open issues, and guidelines" includes the limitations and challenging issues about the combination of MASs and the WSNs and a novel MA-based framework for ad hoc networks. Finally, in section "Conclusion," the conclusion of the review and the future research directions of the MAs in such networks are discussed.

Applications of MASs in the WSNs

The role of the WSNs in commercial, medical, and industrial systems provides the simulated approaches and the practical applications, which can take advantage of artificial intelligence techniques directly. The purpose of these applications is to extend such networks in order to provide the intelligent and economical solutions to reduce the energy consumption of the wireless sensor nodes and improve the individual comfort level of everyday life.[51] In this section, an overview of multiagent-based applications in the WSNs is provided.

The application of the MASs in the WSNs has two main advantages. They are as follows. First, MAs reduce the bandwidth consumption by transmitting the data processing/collection software code to the location of those wireless sensor nodes which sense data from the monitoring area. Meanwhile, the improvement of bandwidth consumption will be more effective when

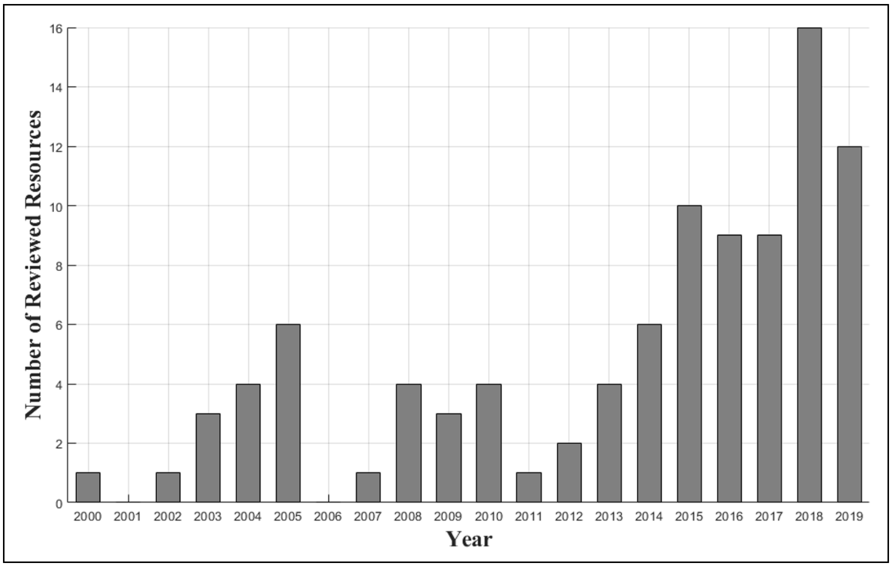

Figure 5. Dispersion of reviewed papers/websites and their publication year.

large amounts of data have been sensed by the wireless sensor nodes and are to be transmitted to the sink. Second, the MAs provide a high degree of flexibility and also facilitate collaborative information processed in the WSNs.[52] Due to the mentioned advantages, the MAs have extended as a common approach with several applications in the WSNs.

Among the variety of multiagent-based applications in this area, some of them are just presented as a model or a framework which are simulated or implemented in a small scale, for example, in academic laboratories. However, some MAS approaches in the WSNs are developed in large scale and are applied in the real-world systems. Figure 5 shows the dispersion of reviewed papers/websites of the multiagent-based applications in the WSNs and their publication year. The numerical results illustrate that recently, special attention has been paid to the integration of MAS and WSNs for improving the quality of human everyday life and the energy/other computational resource consumptions.

In this section, first, a brief overview on the approaches that is modeled based on using MAs in WSNs or implemented in a small scale for the research purposes will be presented. Next, a general overview on the real-world practical applications which use the techniques of software MAs for enhancing the performance of the WSNs is offered.

Simulated approaches

In this section, a short overview on the MA-based applications in the WSNs, which are modeled, simulated, or implemented in a small scale for the academic research purposes, is provided. Such applications are categorized as follows:

Target tracking. One of the most important applications of MASs in the WSNs is target tracking, which is developed for monitoring the motion paradigm of mobile targets and reporting their positions to the sink with a minimum latency. Tseng[42] applies an MAS for target tracking in the WSNs, which uses a simple localization algorithm called *trilateration* to report the provided locations of the mobile target to the sink periodically. In this approach, the wireless sensor nodes estimate the target location by the measurement of the information that they have or achieve from their neighbors. Indeed, the target position is indicated by the circles that are drawn based on the measurements provided by the MAs. To meet the requirements of the target tracking, MAS has three MAs: a mother agent and two child ones. The mother agent dispatches its children to the neighbor wireless sensor nodes to achieve the accurate information about the position of certain mobile target. It is worth mentioning that the mother agent can cooperate with other child agents to improve the target tracking process and reach more precise result.

To improve target tracking process in the WSNs, Xu and Qi[53] proposed another application of MAs. Their proposed method suggests that it is more efficient if an MA is dispatched over the WSN, after detecting a new mobile target. According to this hypothesis, the MA migrates to a wireless sensor node, which collects data progressively, processes it, and then returns the collected information to the sink in each case of new target detection. The overhead of unnecessary data aggregation and extra migration of MAs between the wireless sensor nodes can be avoided by the intelligent MA dispatching. Relying on the intelligent MA dispatching approach, Kamate and Yilmazer[54] claim that the smart use of MAs for target tracking in WSNs could improve the QoS in different real-world applications, including auto aerial vehicles, military/civilian monitoring, and traffic control.

Big data and distributed computing such as the MA technology are one of the mainstream issues in the WSNs. Ting et al.[55] express that the autonomous MAs are most acceptable model for the data tracking in a large-scale and resource-restrained WSN to deal with big data. Authors who reviewed the migration strategies of the MAs in WSNs revealed the characteristics of the target tracking in these networks and presented algorithms to solve the tracking problem by considering cooperation among the MAs. Providing an optimal approach for flocking control in the mobile WSNs is another main challenge to meet the requirements of different applications like the target tracking. To solve this problem, Khodayari et al.[56] present a method based on the meta-heuristic algorithms to control the flocking and track a target in ad hoc networks.

Healthcare systems. Recently, there are enormous developments in intelligent medical devices such as wireless body area networks (WBANs), healthcare telemonitoring systems (HTSs), and entertainment service providers.[57,58] In fact, patients and elderlies need continuous care attention and immediate reactions in emergency conditions, and sometimes their lives are at risk. Therefore, the combination of artificial intelligence approaches and ad hoc networks has attracted much attention from researchers and developers due to these challenges and growths. Service providers intend to increase the comfort of the patients and the elderly, and they offer capabilities to monitor vital signs at any time and anywhere remotely. Indeed, achieving effective approaches to provide remote healthcare systems have become a main challenge for the scientific communities.[59,60] HTSs are one of the acceptable methods to solve some challenge in this field, which allows the specialized personnel to supervise the vital/state signs of patients and the elderly at any time, from a remote medical center. These systems consist of three major subsystems: a local monitoring subsystem in the home of the patients or the elderly, a remote monitoring subsystem in the medical center, and a network which interconnects two subsystems.[61]

The operation of HTSs is that the data about the patients/the elderly, which consist of different parameters (body temperature, location of the patient/elderly one, and her or his vital signs), are collected by the wireless sensor nodes. It is more energy/memory efficient to process the collected data by dynamic and self-adaptable mechanisms which MAs would provide a well framework to do so.[62] For instance, Alonso et al.[43] proposed an HTS to enhance e-healthcare condition for the disabled and elderly people at their homes, at any time. Their presented system utilizes the SYLPH (service layers over light physical devices)[63] architecture, which integrates the heterogeneous wireless sensor nodes and an SOA (service-oriented architecture)[64] approach to improve the distribution of resources and facilitate the inclusion of new functionalities in highly dynamic environments. Furthermore, SYLPH architecture could be integrated by MASs to provide highly dynamic e-healthcare services.

To deal with the security challenges in the WBANs, Thamilarasu and Ma[65] use the migration and cooperative performance of autonomous MAs for intrusion detection. In this approach, every MA in the intrusion detection system (IDS) has learning capability, and could make a decision to distribute its learnings and experiences among computing wireless sensor nodes over the WBANs.

Urban control systems. Nowadays, due to the increasing urbanization and vehicle exhaust, residents of metropolitan cities are in conflict with traffic challenges such as unpredictable delays, high accident risk, extra fuel utilization, and air pollution. Moreover, commercial lighting control is another important issue that affects the government costs. The strategic approach to solve all these challenges is to integrate the urban control frameworks with the intelligent systems such as the WSNs and the MASs in order to enhance the decision-making process. For instance, using the combination of the MAs and WSNs for commercial lighting control provides a practical application that benefits the capacities of artificial intelligence approaches, distributed learning, decision making, and self-configuration. For instance, Sandhu et al.[66] proposed a WSN for lighting control of a commercial center, which makes decisions with MASs. In other words, their lighting control system is composed of the wireless sensor nodes to sense light, temperature, occupancy, actuation, and communication in a physical environment, and a MAS for emulating the success of the distributed model influences the model of the diagrams to provide the requirements of the lighting control systems, including decision making, learning, the flexibility of the system, human-computer interaction, and control data routing.

To improve the trip duration for residents of metropolitan cities, Cruz-Piris et al.[67] present a method which uses the centrality measurement of a graph to determine the optimal locations for the wireless sensor node installation in a traffic framework. For more efficiency, the wireless sensor nodes are integrated with an MA-based system composed of traffic light management agents, traffic light control agents, an intersection, and traffic jam detection agents. Through the other approach, the whole traffic control and management systems are automated using the capabilities of the MAs.[68]

To reduce the workload of the WSNs in an air quality monitoring process, Wang[69] presents an MA-based approach, in which, at first, the remote sink dispatches some MAs to the target monitoring region information, the data collection time period, and the type of data to be collected, over the network. The MAs migrate from one node to another in order to collect the data of the air quality, and then they transmit their collected data to the sink, once the time period expires. Using MAs, the data aggregation of air quality can reduce the workload of the networks, because each node will discard own load right after the MA leaves it.

Firefighter assistant. One of the MA middleware tools that improve the efficiency and reliability of adaptive applications in WSNs is called *Agilla*.[70,71] This middleware generates different MAs and dispatches them over the WSNs to perform several autonomous application-specific operations, and then it harvests the full potential of the wireless sensor nodes. Using the Agilla middleware, Fok et al.[44] presented an MA-based fire tracking approach to help firefighters. They integrate three types of MAs into WSNs to provide the requirements of this application:

1. Fire tracker agents detect the region which is on fire and die if their own wireless sensor node catches fire. The firefighters are inserted into the burning space, when the fire tracker agent completes the detection process. The fire tracker agents cooperate and coordinate with each other to determine whether a neighboring fire tracker agent is still present. If a neighboring agent breaches the field, the other one must clone itself quickly to cover the requirement of this vital application. Finally, if there is not any fire tracking agent in the field, a failure is something that occurs.
2. Static fire agents create the static shapes of fire in the desired area to evaluate the detection and tracking ability of the fire tracker agents.
3. Dynamic fire agent simulates fire spread throughout the WSN monitoring environment epidemically. The dynamic fire agent creates a fire upon arrival and then clones itself onto a random non-burning wireless sensor node which is in the neighborhood. The process of cloning to a random neighbor node is repeated indefinitely until it ensures all wireless sensor nodes to be eventually on fire.

Data aggregation. Data aggregation in the WSNs is one of the main challenges to enhance the network analysis factors. Data aggregation refers to any intelligent process that collects sensed data from different wireless sensor nodes, and then expresses it in a summary form by using a certain function to decrease the injected traffic in the network and optimize the resource consumption of it. However, one of the main challenges in the data aggregation from the wireless sensor nodes is the routing of the collected data from the source node to the sink. Accordingly, the data aggregation approaches in the WSNs are categorized into two schemes: client-server and MA.[72–74] Most traditional data aggregation approaches in WSNs are based on the client-server model. Each source node transmits its sensed data to the sink with the step-by-step methods. Since the bandwidth of the WSNs is lower than the one in a wired network, the data traffic of the network may exceed the capacity of it in the case of using client-server model. To overcome this challenge, the data aggregation using the MA scheme is introduced; a single or multiple MA(s) are dispatched over the WSN to collect, combine, and compress data from the source nodes. In fact, MAs perform the following tasks in order to decrease the data redundancy and traffic in the WSNs:

- Eliminating data redundancy over WSNs by applying context-aware processing in source nodes.
- Improving data redundancy over the wireless sensor nodes that are close to the sink node by performing data aggregation schemes.
- Reducing the data traffic over headed in WSNs by using data collection methods.

Based on these improvements, Dong et al.[45] use the combination of MAs and mobile sinks to decrease the data collection time. As a result, it enhances the lifetime of WSNs in agriculture applications such as predicting killing frosts. In this method, application-oriented scalable task-adaptive and flexible MAs collect data autonomously and find a route to the mobile sinks flexibly.

In order to enhance the lifetime of WSNs, Hussain et al.[75] proposed a sink-based data aggregation method which uses four types of agents: (1) The interface agent receives the requests of wireless sensor nodes and responds them, (2) the regional agent sends received requests to the cluster agents, (3) the cluster agents broadcast the requests in the network and process the data, and (4) the query agents organize the data requests to reduce the energy consumption of source nodes. However, sink-based data aggregation method does not handle the case of network failure.

Using the evolutionary algorithm enables the MAs to take an appropriate decision and improve the energy consumption of the wireless sensor nodes. For example, for constructing a data aggregation tree to transmit useful data of the wireless sensor nodes to the sink, Liao et al.[76] applied the learner MAs and ant colony algorithm. In addition, El Fissaoui et al.[77] present an energy-efficient distributed algorithm to collect data in the WSNs, which apply a clustering algorithm over the source nodes, then route an MA among the clusters. This approach offers alternative route for the MA in the case of node failure. Besides, there is the other new work that divides the monitoring area into four quadrants, which an MA is transmitted to any quadrant for data collection.[78]

Detecting and monitoring the events. A wide variety of applications are described among environmental area in the WSNs, including forest fire detection, agriculture, flood detection, earthquake disaster monitoring, and mapping the bio-complexity of the environment.[79,80] For instance, wireless sensor nodes have proven as the efficient devices to control the fire problem in forests (wildfire detection and monitoring). The basic idea of using WSNs for wildfire monitoring, once, was introduced to help in speedy discovery of the fire problem in San Francisco, California,[81] in which the integration of MAs and the wireless sensor nodes measures temperature, barometric pressure, and humidity data, which can help take immediate action to turn off the fire and predict the direction of its spread. Due to the efficiency of MA-based approaches in the WSNs, Trivedi and Srivastava[46] presented a framework to improve the forest fire detection and monitoring process by reducing the energy consumption of the wireless sensor nodes. The proposed framework includes the following:

- *Architecture of the WSN*: WSNs are formed into two types of architectural design—flat and hierarchical. The hierarchical design in the wireless sensor nodes is used to group some clusters based on different parameters. In each cluster, the cluster-head dispatches an MA to the source nodes for data aggregation.
- *Deployment scheme of wireless sensor nodes*: The wireless sensor nodes are deployed in two different models—homogeneous and non-homogeneous ones. In the non-homogeneous model, the source nodes are deployed randomly so that there can be no certain distance. In the random deployments, the energy consumption is very high as the distance between the nodes is not determined. In the detection applications, it is focused on saving the total energy of the WSNs. Therefore, the combination of a homogeneous deployment and the concept of clustering will be a suitable idea.
- *Intra-cluster scheme for data aggregation*: In each cluster, the wireless sensor nodes continuously monitor their FoV to sense the abnormal temperature change. The cluster-head transmits an MA to collect the data of its nodes. The forest fire can potentially destroy the wireless sensor nodes, which can be handled easily. But all clusters are destroyed when the cluster-head dies. So, if the cluster-head senses the risk of its death, it will dispatch an MA that has the information to check the nodes of the nearest cluster-head. So, after the death of its original cluster-head, the wireless sensor nodes will join to the closest cluster and will keep on doing their mission.
- *Inter-cluster schemes for data aggregation*: The MAs, which are dispatched by the sink periodically, check the cluster-heads to receive the data from everyone.

Intrusion detection. Security challenges are the vital concern in safety-critical applications of the WSNs. To prevent resource-demanding attacks and manipulating the information of the wireless sensor nodes or sink, all kinds of intrusions must be detected before that happening. To deal with the challenges, Zhang and Lee[82] proposed a collaborative IDS, which involved six blocks:

- *Local data collection block* is responsible for the real-time data collection from the user/communication activities and system call activities in the range of its radio receiver.
- *Local detection engine block* is responsible for analyzing the collected real-time data to prevent the occurrence of any anomalies that may exist.
- *Local response* and *global response blocks* receive information of the event from the local detection engine block, in the case of anomaly detection, in order to take an action against the possible intrusion.
- *Cooperative detection engine block* conducts the cooperation when the detection is inconclusive and needs more evidence.
- *Secure communication block* communicates between the neighbor MAs, which are required to have cooperated, in which any wireless sensor node can participate in the decision-making process.

After a predetermined threshold of time, the local IDSs trigger the global one which necessitates a collaborative decision of the wireless sensor nodes neighboring the flagged one. The decision-making process is made through a majority voting and then the intrusion detection is performed based on the means of entropy.

The collaborative IDSs are useful to detect the attacks against the routing protocols in the WSNs, including miss-routing, packet dropping, false route updating, and Denial of Service (DoS).

Following the idea of collaborative IDS, some works[83,84] used the MASs to achieve more efficiency in the case of network security. As a first example, Krishnan[47] presents an efficient distribution method for the MAs to improve the performance of IDSs. A suitable distribution method can distribute the processing load of intrusion detection process among all wireless sensor nodes to minimize the energy consumption of the WSNs. As a second example, to improve the intrusion detection accuracy in the WSNs, Riecker et al.[85] present an MA-based energy-efficient and lightweight approach to detect intrusions by monitoring the energy consumption pattern of the source nodes; they use a linear regression model for the energy consumption prediction. As a third example, to detect and mitigate the cross-layer attacks that utilize manipulating and jamming process, there is a new method which is based on Bayesian learning model to meet the security requirements of the applications of WSNs and has an acceptable performance.[86] Some other works proposed different MA-based key management methods to meet the military applications in the WSNs.[87]

Tables 1 and 2 illustrate the comparison of the performance parameters about the multiagent-based simulated approaches in the WSNs. In Table 1, general parameters of the simulated approaches, including application examples, important parameters, advantages, disadvantages, and simulation model/environment of the applications, are compared. Table 2 shows the comparison of network analytical parameters, including number of agents, agent mobility, sensor type, network type, operation environments, network topology, and routing protocol.

Real-world applications

Next step of our studies illustrates that WSNs suffer from the following drawbacks in the real-world applications without using the intelligent approach:[88,89]

- Long delay from the time when data are sensed by the wireless sensor nodes to the time when the sink receives the collected data/processed information.
- Unacceptable delay in the command transmission from the sink to the wireless sensor nodes.
- High power consumption of the step-by-step data aggregation approach, when the sensed data are sent to the sink, for some extra processing tasks.

To deal with these challenges, wireless sensor nodes could benefit the intelligent decision-making process offered by the paradigm of MASs. In the following, some applications of MAs in the WSNs are provided to illustrate the advantages of using intelligent systems in the real-world applications. Some applications are as follows.

TeleCARE. Nowadays, there are many studies in the field of the MA-based human healthcare in the WSNs. Most of these approaches focus on fall detection, heart rate monitoring, and pulse oximetry. A significant development is that some commercial products are available, which include the combination of the MASs and the WSNs. It is worth mentioning that the existence of MA-based commercial products for the human healthcare goals would not be possible without the availability of low-cost sensor nodes.

TeleCARE is one of the commercial products that alleviate the burden of elderly citizens on the healthcare system.[49] The aim of TeleCARE system is to develop a configurable framework for elderly support applications. This system focuses on virtual communities, which allow the elderly to stay at home, to keep them active socially, and to how independent lives. In addition, the system maintains a safety network of healthcare services for the elderly when it is required. The TeleCARE system proposed the multiagent-based approach as the main infrastructure instead of TCP/IP over the Internet, because of the following reasons:

- The processing code transmission between the wireless sensor nodes, autonomy, and real-time service provision is the important challenge in the human healthcare systems.
- Achieving scalability and high levels of flexibility is the other important factor in the human healthcare systems, which is provided to utilize the abilities of MAs in WSNs.

TeleCARE system attempts to be so open that different devices can integrate with its developed platform. The different levels of system infrastructure are as follows:

- External Enabler Level provides the communication over the network and interface between external devices. This level supports precisely secure communication between the wireless sensor nodes.
- Core Multiagent System Platform Level is the base component of the TeleCARE system, which controls the MAs and their interactions. Besides, this level handles the storage of data and the

Table 1. Comparison of the general parameters of multiagent-based simulated approaches in WSNs.

	Application examples	Important parameters	Advantages	Disadvantages	Simulation model/environment
Target tracking[42,53,54,56]	Auto aerial vehicles Military and civilian monitoring Traffic control	Energy consumption Accuracy Scalability Overheads	Improving Energy consumption Network lifetime Communication hops	Lack of trust Unacceptable delay	Random WayPoint model/JAVA
Healthcare systems[43,65]	Smart home for patients and elderlies	Real-time alert Movement recognition Energy consumption Accuracy Efficient tracking	Providing an adequate interaction between the users	Non-privacy for the users	Gaia/SysML
Urban control systems[66,67,69]	Traffic control Commercial lighting control Air quality monitoring process	Reliability Energy consumption Delay End-to-end packet delivery ratio Throughput	Supporting Highly deployable Self-configurable Adaptive Scalable systems	There is no idea about the security of the system	–
Firefighter assistant[44]	Fire tracking in harsh and dynamic physical environment	Energy consumption Detection speed Accuracy	Enhancing Efficiency Reliability Adaptively of the system	Do not receive an acceptable reliability	Experimental Test
Data aggregation[45,75–77]	Predicting killing frosts Urban traffic control Wildlife monitoring	Data rate The percentage of success packets Energy consumption Delay	Increasing lifetime of network	Unacceptable Delay Security for emergency applications	NetLogo/MATLAB
Detecting and monitoring the events[46]	Forest fires detection Agriculture Flood detection	Total dispatch delay Average waiting delay Accuracy energy consumption Cost No. of packets transmitted	Improving consumption energy of WSN	Long delay Unacceptable reliability	Custom simulator using C#
Intrusion detection[47,82,85]	–	Reliability Energy consumption The percentage of failure packets Robustness and speed	Detecting any potential attempt to corrupt the attack Increasing lifetime of network	Transmitted computation code over the network may be manipulated by an attacker	JADE/JAVA/WADE

JADE: Java agent development framework; WADE: workflow and agents development environment; WSNs: wireless sensor networks.

Table 2. Comparison network analysis parameters of multiagent-based simulated approaches in WSNs.

	Number of agents	Agent mobility	Sensor type	Network type	Operation environments	Network topology	Routing protocol
Target tracking[42,53,54,56]	Multiple agents/one agent	Mobile	Acoustic-amplitude sensors Computational sensor	Decentralized/ centralized	Outdoor/indoor	Cluster based Tree-based P2P Hierarchical	Tree-based Cluster based Mobi-cast Message-based
Healthcare systems[43,65]	Nine agents (seven predefined agents and two agents in SYLPH)	Mobile	Video, acoustic, and RFID sensors Environmental and physiological Sensors Accelerometer Gyroscope	Centralized	Outdoor/indoor	Star	TCP/IP protocol Collection tree protocol TDMA protocol
Urban control systems[66,67,69]	A single agent per node	Pseudo-static	GPS, DSRC devices Multimedia mobile nodes RFID sensors Crossbow ZigBee motes	Decentralized/ centralized	Outdoor/outdoor roadside/indoor	V2V P2P Star Mesh	ZigBee protocol Evolutionary algorithms
Firefighter assistant[44]	–	Static/mobile	GPS devices Temperature/ pressure detection sensor	Decentralized/ centralized	Outdoor	P2P Star	–
Data aggregation[75–77]	A single agent per cluster	Mobile	ZigBee motes Electrochemical sensor Environmental and physiological Sensors	Centralized	Outdoor/indoor	Star Cluster based Hierarchical	Collection tree protocol Evolutionary algorithms TCP/IP protocol
Detecting and monitoring the events[46]	A single agent	Mobile	Fixed and mobile light Sensors GPS equipped mobile Nodes Sensors and actor nodes Water lever/ pressure detection sensor	Decentralized/ centralized/ ontology based	Outdoor/indoor	Grid based Mesh Cluster based	TCP/IP protocol Collection tree protocol
Intrusion detection[47,82,85]	–	Mobile	–	Decentralized	Outdoor/indoor	Cluster based Mesh P2P	AODV DSR

WSNs: wireless sensor networks; SYLPH: service layers over light physical devices; AODV: ad hoc on demand distance vector; P2P: peer-to-peer; RFID: radio-frequency identification; TCP/IP: transmission control protocol/internet protocol; TDMA: time-division multiple access; GPS: The global positioning system; DSRC: dedicated short range communications; DSR: dynamic source routing.

manipulation of information to be supported by TeleCARE.
- Vertical Services Level is the application level of TeleCARE system and includes two sets of certain services: the vertical services (built upon the basic services of TeleCARE platform to support different interactions within others) and base horizontal services (provide the functionality for the vertical services, including virtual community support, web service access, and certain interfaces for the elderly).

SwarmSense (intelligent unmanned aerial vehicle [UAV] swarms). EpiSys Science (EpiSci) is a technological business, which focuses on research, development, and commercialization of novel technologies in the field of wireless communications and networking, distributed and autonomous control, and decision support systems.[50] Since 2012, EpiSci teams have been trying to solve technology breakthroughs based on deep technical expertise in different emerging fields; the business could develop innovative technological approaches for intelligence, defense, and commercial industries through the combination of Tactical Artificial Intelligence, Collaborative Intelligent Radio Networking (CIRN), and Wideband Digital Signal Processing (WDSP).

A common drone swarm system could consist of two drones (unmanned aerial vehicle)/over thousands of drones. The required autonomy increased to control such systems without any manual pilots, when the number of drones in a swarm system exceeded a predetermined threshold. Therefore, it is vital to create the autonomous drones which manage themselves automatically, effectively, and robustly in any anti-access, bandwidth-limited, and area-denied environments. To solve the problem, EpiSys teams try to provide the most effective common point for three technical fields: Artificial Intelligence-based Distributed Agent Systems (AIDAS), Cognitive Radio Systems (CoRS), and Self-Organizing Wireless Networking Systems (SOWNS) . Due to the interconnection of the MASs and wireless networks, EpiSys enables a group of drones to cooperate and coordinate them to perform the missions automatically, which require a large-area coverage, immediate data processing, efficient deployment without exact pre-planning, and uninterrupted cooperation and coordination during the emergency operations. A sample of SwarmSense is illustrated in Figure 6.

The future vision of EpiSci researchers is about to achieve the developments rooted deeply on the "system science" paradigm.

Multiagent Distributed Information Platform. The integration of two wireless and body area sensor networks creates a new technology named coherent body sensor network. Based on this integrated technology, Su and Wu[90] proposed a novel system called the Multiagent Distributed Information Platform (MADIP) to notify the remote care-provider of abnormality, to perform health monitoring for the elderly and patients automatically, and to offer medical advice from far away. MADIP includes six types of components, which map to the human agent in the real-world scenarios:

- User agent contributes as an intelligent gateway for the communication between care-providers and patients. This type of agents performs the required actions based on patient requests.
- Resource agent provides the accessed control to the resources within the system. The resource agent operates at a top level of trust.
- Physician agent is a mobile one that is used by care-providers to perform required system tasks. It monitors a patient/an elderly one without the care-provider being around.
- Diagnostic agent is considered as a data-analysis system. In other words, the diagnostic agent analyzes the data sensed from a patient/an elderly condition and predicts the sudden change in his or her body status.
- Knowledge-based data server involves two information warehouses (the user states and the profiles) to store physiological data collected by a physician agent. The user states warehouse includes collected data from the patient/elderly body states, including pulse oxygen saturation values and heart rate. The profile warehouse contains update electronic records of the patient/elderly one. As the resource agent receives the data from the corresponding patient/elderly one, it stores it in the user states warehouse and transmits a copy to the diagnostic agent for more analysis. This periodic process is considered as the most vital task of MADIP, because the efficiency of healthcare monitoring systems is highly dependent on transmitting the time-critical data.
- External services include the hardware and services, including email, instant message services, and mobile phones.

Since there are no specific factors to evaluate the performance of the MASs, MADIP provider focuses on the usability and readability of the whole system. An exact usability evaluation was performed to illustrate the effectiveness of the proposed system, including 20 care-providers and 30 elderly people and patients. Although the result of the evaluation was acceptable, the sample size was too small and the privacy issue was not considered.[91]

Figure 6. A sample of SwarmSense.[50]

Robotics lab research project of Pace University. The robotics lab of Pace University is managed by Dr. P. Benjamin who focuses on creating and testing the ADAPT cognitive architecture (based on the SOAR [cycle of State, Operator, And Result] architecture) for mobile robots[48] to create intelligent agent–based systems for security/intrusion detection improvement in the WSNs. One of their robots is the Pioneer II, which has two motors for controlling each wheel and 16 sonar sensors, a gripper, and a pan-tilt-zoom camera. In addition to preparing the exclusive robots, the robotics lab of Pace University has performed some projects in collaboration with other ones. It includes ADAPT (a cognitive architecture for mobile robots).[92] The ADAPT cognitive architecture is based on the RS language, which is developed by Fordham University's Damian Lyons. It provides concurrent programming, high-level abstractions, and distributed schemes. In addition, the Pace University Lab has tested some projects in the field of intelligent agents for the WSN security, soar agent for playing poker, and an intelligent soar assistant for the virtual world.

The comparison between the performance parameters and multiagent-based real-world applications in the WSNs is illustrated in Table 3.

Challenges, open issues, and guidelines

In this section, we analyze the limitations of MA-based applications in the WSNs and provide some recommendations to improve the performance of the integrated systems. Finally, we present a framework for energy-efficient and secure data aggregation by using the integration of the WSNs, Internet-of-Things, and MASs.

Challenges and relevant recommendations

There are several challenges about utilizing the MASs in the applications of WSNs. In this section, we sum up the limitations of MAS in the field of the WSNs; then we present some recommendations to enhance the performance of such integrated systems.

1. The first challenge of the MASs in almost all applications of the WSNs is security.[93–95] Personal health data and the business information of the organizations are their privacy and should not be in public or semi-public. Therefore, it is vital to keep the granularity of organizations/people private and secure while transferring over the WSNs. Although there are some efforts to keep WSNs secure, all these security methods focus on basic privacy mechanisms, that is, authentication, context removal, encryption, and data anonymity. The security of the data should be maintained, while the MAs are communicating over the wireless sensor nodes. Moreover, the new security challenges develop with the invention of novel technologies, for example, the integration of Internet-of-Things and WSNs.
2. In spite of recent developments in resource technologies of the wireless sensor nodes, WSNs still have to provide the power of data processing

Table 3. Comparison of multiagent-based real-world applications in WSNs.

	Usage	Number/type of agents	Agent mobility	Design/ development	Advantages	Disadvantages
TeleCARE[49]	Healthcare services for alone elderly and patients	–	Static/mobile	JAVA	Providing Safety network of healthcare services Configurable framework for healthcare support applications	Non-privacy for the users
SwarmSense (intelligent UAV swarms)[50]	Missions require a large-area coverage	A single agent for each drone	Mobile	–	Immediate process of collected data Efficient deployment without exact pre-planning Uninterrupted cooperation and coordination	An attacker can disturb the coordination between drones
MADIP[90]	Health monitoring for elderly and patients Offering medical advice remotely	Four agents	Static/mobile	JADE	Enhancing Usability Readability of the system	Non-privacy for the users Vague performance in large systems
Robotics lab research project of Pace University[48]	Intrusion detection Playing poker virtual world	A single agent for each robot	Mobile	RS language	Improving the security of wireless networks Providing concurrent programming, high-level abstractions, and distributed schemes for MAS	There is no detailed information about the projects

WSNs: wireless sensor networks; MADIP: Multiagent Distributed Information Platform; MAS: multiagent system.

and information transmission from energy-constrained batteries. Furthermore, the wireless sensor nodes have limited memory and computational capabilities. In addition, the WSNs have been applied in harsh and inaccessible environments for a long time. Thus, the resource limitation of the wireless sensor nodes is another challenge for MA-based applications.[96]

3. The multiagent-based approaches in the WSNs do not consider some mechanisms to satisfy the requirements of the delay-sensitive applications. Indeed, lack of attention to strict timing limitation in the WSNs undermines the performance of MAs in safety-critical applications of WSNs and leads to environmental damage, people injuries, or financial loss.[97]

Due to these challenges, we present some recommendations for enhancing the performance of MASs in the WSNs:

- Applying different techniques to provide the security, privacy, and trust in all the MAS-based applications in the WSNs, especially by considering the mobility of the agents, openness, and heterogeneity of the networks.

- Using more specialized approaches to minimize the resource consumption of the wireless sensor nodes, for example, evolutionary algorithms or optimization techniques.
- Using the efficient processing and communication protocols for the MAs by considering the different applications of the WSNs that require various QoS, for example, timing limitation.
- Providing the technical details of the presented applications for would-be researchers.

Our proposed framework

According to the survey of the multiagent-based applications in the WSNs, it can be concluded that the data aggregation is one of the most important challenges in such applications. Therefore, a framework is suggested for energy-efficient and secure data aggregation using the integration of the WSNs and the MASs. The overall scheme of the proposed framework is shown in Figure 7.

Relying on the recent advances in underlying network-based technologies, the integration of WSNs with the artificial intelligence mechanisms offers opportunities to meet the requirements of a large number of real-world applications. According to these features, it can be used for the combination of software MAs and the affordable wireless sensor nodes for data aggregation in urban society, for example, data collecting for the healthcare goals. The process of presented framework is as follows:

- First, all wireless sensor nodes are clustered. The nodes are set as the cluster-heads that (1) their geographical distance with the member of the cluster and the sink is minimum so as to reduce the transmission delay and the energy consumption of the network, (2) their residual energy is maximum to enhance the lifetime of the whole system, and (3) they have an acceptable security history to improve the network quality of services. After organizing the network system, determining the cluster-heads, and assigning all wireless sensor nodes to the clusters (according to their geographical distance with the determined cluster-heads), the system begins its operational process. First, each certain cluster members send their sensed data to the cluster-head periodically based on demand.
- In the next step, the cluster-heads are divided into groups according to their geographical distance with each other. Then, the sink dispatches MAs over the network. It assigns an MA to any group of cluster-heads to collect their aggregated data and deliver it to the sink. Indeed, each MA has a data aggregation code, route planning, and an empty space for the data collection. The system nodes clear out their memory as soon as their data are delivered to the MAs to avoid wasting the local resources.
- Finally, to enhance the security conditions in the proposed framework and privacy over the data transmission, the sink surcharges an encryption algorithm to the data aggregation code of the MAs. MAs collect the data of each cluster-head, encrypt, and aggregate it with the previous collected data. Then, after visiting all cluster-heads of their own group, the MAs return the result packets to the sink for further processing tasks. The sink analyzes and saves the received data after performing decryption algorithm, and it takes the necessary steps in urgent situations.

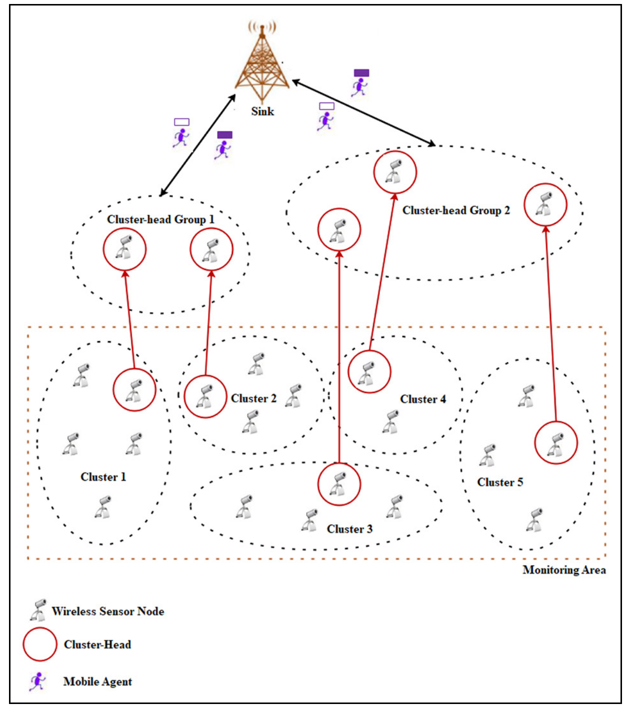

Figure 7. The general scheme of the proposed framework.

Conclusion

In this article, the applications of the MASs in the WSNs were reviewed. First, the key challenges behind the WSNs and the efficiency of using the MAs to solve them were discussed. Then, the applications/literatures of MASs in the WSNs were classified into two categories: the simulated approaches and the real-world applications. Nearly, using the capability of the MA technology in WSNs could enhance most of the academic approaches, that is, target tracking, healthcare systems, urban control systems, firefighter assistant, data aggregation, detecting and monitoring the events, and intrusion detection. Furthermore, MASs become an essential part of the real-world applications of WSNs, that is, TeleCARE, SwarmSense, MADIP, and robotics-based systems.

In spite of several researches in the WSNs, and all progress of MASs, security, resource, and time limitation are major challenges in the MA-based applications in WSNs. Therefore, it is necessary to improve the data privacy, the resource consumption, and the delay of the next-generation applications of MAS in the WSNs. To deal with the challenges of multiagent-based applications in the WSNs, a novel framework was suggested in the previous section.

In our future works, it is going to be intended to discuss the multiagent-based application on Internet-of-Things to enhance the interaction between the industry, the healthcare, and the security units with research centers.

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