ISSN (Online) : 2319 – 8753
ISSN (Print) : 2347 - 6710

International Journal of Innovative Research in Science, Engineering and Technology

An ISO 3297: 2007 Certified Organization, Volume 3, Special Issue 1, February 2014

International Conference on Engineering Technology and Science-(ICETS'14)

On 10th & 11th February Organized by

Department of CIVIL, CSE, ECE, EEE, MECHNICAL Engg. and S&H of Muthayammal College of Engineering, Rasipuram, Tamilnadu, India

The Unceasing Detection of Adjoining Nodes, Its Connectivity, Weakness Impact on Wireless Sensor Networks and Actor Networks

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Abstract—The continuous detection of sensor and actor nodes in wireless sensor actor networks (WSANs) is facing new challenges notably in coordination. In this paper, a survey has been made to categorize, and bring into perspective existing researches on continuous connectivity of sensor node and its impacts on coordination ranging from a node failure to disability of actor nodes to communicate with other actors permanently. Actor nodes with noticeable amount of high power can help weaker sensors in different scenarios such as data forwarding and routing and many sensors can help few actors in the regions that actors are sparsely deployed. Actor nodes can mobilise, carry and charge sensors during the detection of inter-actor network. From the knowledge acquired from the survey, we describe that actor node along with sensor nodes in a WSAN can cooperate to provide the continuous detection of sensor nodes when the network connectivity is affected by any of the sudden interferences.

Index Terms — Wireless Sensor Networks Sensor nodes, Actor nodes and Actor Networks, Wireless Sensor Networks, Connectivity, Weak Connectivity, Coordination.

I. INTRODUCTION

In this paper the introduction to Wireless Sensor Networks (WSNs) [1] and Wireless Sensor and Actor Networks (WSANs) [2], are discussed and then a detailed comparison of these two types of networks is made. Given that the continuous detection of sensors and connectivity in Wireless Sensor and Actor Networks constitute the main objective of our paper. The concept of connectivity and its issues are explained next. We then point out our survey method in selecting related research works in this paper.

A. Wireless Sensor and Actor Networks

WSNs are considered as a large number of wirelessly connected static sensor nodes. In the earlier years of research on WSNs, sensing the various from the environment, simple processing on the sensed data, and forwarding data to a static sink or base station for further action. A wide variety of sensors have been used to sense various sensory data such as wind speed, humidity degrees, flowing rates of liquids, temperature, intensity of light, and rainfall amount. WSNs have been applied to many areas such as in object tracking and in monitoring of natural phenomenon. There are still some shortcomings to make WSNs fit and beneficial to real-time applications that require more functionalities than just sensing and tracking. There was a need for an active entity, called actor, in the network to do physical actions such as moving, targeting, patrolling, chasing and catching, mine disposing, and carrying and replacing sensors.

WSANs are a type of wireless network made of sensor and actor nodes. Actors or actuators are usually fewer in number than sensors. Actors have larger transmission ranges and higher energy transmission ranges and better processing capabilities. Actor nodes may also be mobile robots that communicate with other actors and sensors. WSANs are heterogeneous because sensor nodes differ from actor nodes. Sensor nodes that usually have limited resources are responsible for gathering sensory data while actor nodes with richer resources are responsible for performing actuation tasks using the gathered data.

Each WSAN often has a base station or sink node. Multiple stationary or mobile sink nodes are possible

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too. If the sink in a WSAN cooperates in network activities, it is said that the network has a "semi-automated architecture". A WSAN has an"automated architecture" if the sink does not participate in network coordination activities as shown in Fig. 1 [3]. In semi automated architecture, sensors route gathered information to the sink using the inter-sensor network, i.e., the network connecting sensor nodes in a WSAN. The sink decides and sends commands to actors using the inter-actor network. In this architecture, sensors and actors do not coordinate with one another. Thus semi-automated architecture actually consists of two distinct networks: a wireless sensor network and a mobile ad hoc network (MANET). In semi-automated architecture, the inter-sensor network can use the protocols of WSNs and the inter-actor network can exploit matured MANET protocols [4].

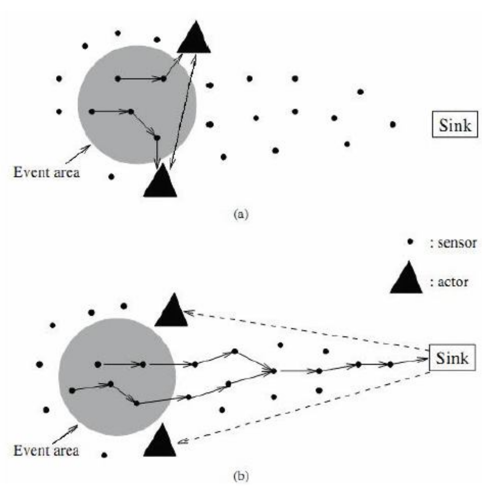

Fig. 1. (a) Automated and (b) semi-automated architecture of WSANs [3]

Actors perform tasks. Actuation tasks are more important.

A task may require and involve more than one actor, and the actors performing a certain task require coordinating their actions with one another. In WSNs, sensor nodes only perform read operations to collect data on events occurring in an environment, while sensor nodes in WSANs do the reads and the actor nodes do both the reading from the environment and do actions as writings to the environment, creating new challenges [5].

B. Continuous detection in WSANs

There are five classification or levels of coordination in WSANs, namely sensor-sensor, sensor-actor, actor-actor, sensor-sink, and actor-sink coordination levels.

Sensor-sensor coordination is required in any inter-sensor network. Sensor nodes may need to coordinate in order to ensure their sensed data are accurate and precise. A faulty sensor node can report invalid data, so sensors may require coordinating to find most accurate data. Sensor nodes require coordination for many reasons including for power management, time synchronization, and localization. Sensor-actor coordination and actor-actor coordination are required by WSANs having automated architecture. In sensor actor coordination, sensors may need to select one or more actors to send their data to. This type of coordination involves actor selection and data reporting. In typical applications of WSANs, actors must perform actions limited by a deadline starting from event detection by sensors. Thus sensor-actor coordination should be real-time in reporting events [6] in many applications.

Actor-actor coordination is required when actors want to coordinate their actions themselves. The main challenge is whether to involve all actors for the purpose of coordination or not. In a centralized decision making approach, a leader actor coordinates all actors. A decentralized decision making approach may involve more actors to decide collaboratively on actions. Task assignment is another challenge in actor-actor coordination. Single-tasks and multi-tasks are two types of tasks. Some tasks may require only one actor while some other tasks may require more actors. Even some tasks may require special types of actors with specific capabilities.

During coordination, an actor may find another actor a better choice for example because of its distance to the event. An actor that is not able to perform all actions for an event assigns the actions to another actor using coordination. Multiple actors that receive the same event must have a reliable connection to coordinate and select the best actor to do the required actions. The best quality for connectivity is needed when actors must do a set of actions in a synchronized manner. The order of execution of actions and predefined time scales should be conserved. Out of order executions of actions, queries, and commands [7] in WSANs can arise due to poor coordination leading to inaccurate and unreliable results. It is noticeable that an actor needs to communicate with sensors and other actors, so actors must have their required medium for communication with at least two types of devices. Other types of media may be required depending on application type. For

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example, in a border control application, it may be required that some actors communicate via a satellite.
Sensor-sink coordination and actor-sink coordination are two additional types of coordination required by WSANs with semi-automated architectures in which sinks cooperate in network activities. We refer the reader to a detailed taxonomy of coordination in WSANs that has been presented by Ruiz-Ibarra *et al.* [8].

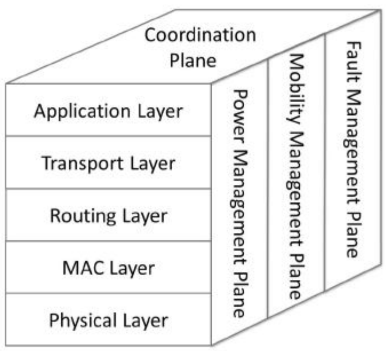

Fig. 2. Coordination plane impact on other planes in WSANs [2]

Akyildiz *et al.* [2] have depicted that coordination constitutes an important plane of the protocol stack of WSANs, and that coordination critically influences the other two proposed planes, namely, the communication and management planes (Fig. 2). They have also stated that the coordination plane determines how a node behaves based on data received from the communication and management planes. The coordination plane is more important to actors because they perform physical actions. This is why social behaviours of actor nodes are decided in the coordination plane. We are considering the impacts of weak connectivity on coordination and continuous detection of node in this paper.
The review of the impacts of other planes such as power management on coordination on connectivity is recommended as a future work.

C. Connectivity in WSANs

To provide a desired level of coordination, the network must be connected. Many research works in the domain of Connectivity problems reduce the quality of services a WSAN can provide. Connectivity problems create network holes or void areas. Holes in turn create many problems in the network especially in coverage, routing, and security of network [10]. Holes create latency in network routing, and nodes around holes consume more energy widening the holes. If the inter-sensor network has a hole then no event can be detected in the area of hole and an intruder can enter the area of network. Actors are not informed because they could not receive any hint data from sensor nodes.

According to [3], the unique characteristics of WSANs include heterogeneity, real-time requirement, and coordination. Coordination in WSANs is strongly influenced by connectivity problems. For example, a sensor node with a faulty sensing device may report invalid sensory data if it cannot connect to its neighbours to check the validity of its sensed data. Another example is when sensors report their sensory data to unsuitable actors because of connectivity problems. In case an actor has problem in connecting to other actors, it may ignore a vital action or an action may be executed more than once by some actors.
For example, consider an application wherein some of the actors patrolling an environment are informed by sensors about the entrance of an intruder. If actors cannot connect, they cannot coordinate and may consequently move toward the event area leaving some parts of the network unattended and vulnerable to intrusions. In a fire fighting application, the coordination policy may be to cover an environment in a mutually exclusive manner implying that actors should not extinguish fire simultaneously on the same region. Actors that cannot coordinate because of connectivity problems will not completely cover the environment and may use more water.
Connectivity problems are frequent in WSANs. Most real world deployments of WSANs are in wide spread areas and coverage of all points by sensors is impossible [11]. In real world, random deployments of sensors cannot guarantee required connectivity. Sensor and actor nodes may fail because of hardware and software faults. The environment of a WSAN is usually complex and noisy. In harsh environments, sensors and actors may be destroyed. For example, in under water sensor actor networks, actors may disappear during sea floods. In hostile environments, enemies may harm sensors and actors. Actors are fewer in number and larger in volume than sensors. Furthermore, actors have mechanical parts and even in ordinary situations have a predefined lifetime.

D. Our Survey Approach

The previous research works [12]–[21] on connectivity, coverage, and coordination in WSANs have inspired us to prepare the survey presented in this paper. WSANs have been surveyed from different viewpoints in [2],

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[3], [8], [22]–[29]. The number of surveys on WSANs is restricted compared to the number of surveys on WSNs and MANETs because research works on WSANs are much less than WSNs and MANETs. To the best of our knowledge, this paper is among the very first to survey connectivity weakness impacts on coordination in WSANs. None of the previous works have comprehensively considered inconsistencies a WSAN faces when connectivity problems occur or continue during the network lifetime. Pitfalls can be avoided when constructing WSANs in practice by considering connectivity issues reported in this paper. To achieve better results, solutions surveyed in this paper can be used.

In this paper, we present a survey of connectivity issues by way of presenting a new categorization of weak connectivity in the context of coordination in WSANs. Achievements and challenges related to connectivity are presented in the context of the proposed categorization with an emphasis on weak connectivity. We consider weak connectivity ranging from a simple connectivity problem, where an actor cannot find other actors, to a sparse WSAN; Given the vast amount of scholarly research works on connectivity topic in different types of wireless networks relating to WSANs, we had to come up with a policy to select the most related ones to explain the problems and solutions as complete as possible. The reasoning behind our choices is described below.

Some research works have been specifically proposed for WSNs, MANETs, and mobile sensor networks. When the ideas proposed in these works were relevant to some parts of our survey, we have selected and briefly explained the most relevant ones for better understanding of issues related to connectivity and coordination in general. However, we have explained research works specifically designed for WSANs in more depth. We have selected and explained only one work from a group of similar research works and then outlined its differences with other works in the group.

In a WSAN, sensor nodes may be considered mobile or actor nodes may be considered stationary. However, we have focused on mainstream related research works that have considered actors as being mobile and sensors as being stationery. Most research works on WSANs we have cited in our survey use WSANs with automated architecture. Some research works have different steps. We have decided to focus and only describe those parts of works that relate to weak connectivity and coordination and are of interest to our survey.

II. WEAK CONNECTIVITY CATEGORIZATION IN WSANS

In this section we first present details of our categorization and then review research works that have tried to improve connectivity of a connected WSAN.

We have defined the top-level categories of our proposed categorization of weak connectivity in WSANs. Each top-level category has a number of subcategories that include related surveys and research works on weak connectivity. We explain each category in a separate section containing a subsection on each subcategory. However, before presenting these categories in detail in the next sections, let us briefly explain each subcategory here.

The Weak Inter-Actor WSAN category contains three subcategories.

In the first subcategory, named 'Movement Based', IAN has less connectivity issues and actors can move to recover IAN connectivity. In the second category, named 'Partition Detection by Sensors', connectivity problems are more serious and sensors must find partitions of IAN. In the last category, named 'Disconnected IAN Recovery', actors cannot communicate and sensors must play the role of relays between actors.

The Weak Inter-Sensor WSAN has two subcategories. In the first subcategory named 'Sensor or Relay Placement by Actors', the ISN connectivity issues are repairable by the deployment of new sensors, and actors can relay ISN traffic in some parts. In the second subcategory named 'Data Carriage by Actors', a sparse network must be patrolled by actors to gather data of sensors.

The last category is the most challenging category wherein both ISN and IAN are weak. This category has three subcategories.

The first subcategory, named 'Mutual Cooperation of ISN and IAN', includes research works that try to recover the network from weak connectivity through mutual cooperation of sensor and actor nodes. Research works in the second subcategory, named 'Coordination at All Levels', use coordination at all levels to handle weak connectivity. Finally, the third subcategory, named 'Simpler Constraints', includes other researches that focus on applications that do not require full connectivity to achieve coordination. This allows simplified constraints on connectivity of WSAN.

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Improving Connectivity of a Connected WSAN

There are many research works that have tried to enhance quality of services of WSANs, few of which have tried to improve one of the most important quality of service parameters, namely connectivity, that is also our concern. This means that these works have tried to enhance network connectivity of a connected WSAN. We do not include these works in our categorization because we have only focused on works related to recovering from weak connectivity as well as on works that provide coordination between all types of nodes of WSANs during weak connectivity.

There are some research works that have proposed approaches for repairing weakly connected networks and also for improving the connectivity of WSANs when the network is connected. These approaches have a preventive attribute against weak connectivity.

We have also highlighted this preventive attribute in our summary of surveyed works in Table I. Hereafter in the current section, we only review briefly some approaches that aim to keep a network connected but have no plan to repair it when it becomes weakly connected.

1) General Connectivity Improvement Approaches: Generally, any approach that can save the energy of sensor or actor nodes prolongs the lifetime of nodes and consequently reduces connectivity problems. Energy harvesting [30], power management and control [31], and data aggregation [32] are some examples. The main goal of data-aggregation algorithms in sensor networks is to gather and aggregate data in an energy efficient manner to prolong the network lifetime [32]. Power management encompasses a wide range of topics. For example, some sensors in a dense deployed area can go to sleep for energy saving. Energy-harvesting with the aim of converting ambient energy to electrical energy has emerged as an alternative to power sensor nodes [30]. In general, any approach that can save energy of nodes increases the quality of service factors of a WSAN. Interestingly, energy harvesting, power management, and data aggregation improve network coverage too.

Another general connectivity improvement approach is to deploy more nodes in the network than required. Additional nodes may be turned to sleep or off modes. When network connectivity or coverage in a region goes below a required threshold, spare nodes can be awakened or turned on to level up the connectivity and coverage to desired degrees.

There are many general connectivity improvement approaches that we have ignored for brevity. Now we review some special approaches that directly improve connectivity.

2) Specific Connectivity Improvement Approaches: Node placement at deployment time and during network lifetime can improve network connectivity. New nodes can be deployed near critical nodes whose failure may partition the network. Generally, a node or link is critical if its removal from the network graph partitions the network. Placing a number of resourceful relay nodes (actors) among static nodes (sensors) is another solution.

Some approaches move a subset of actors in a connected network to new locations such that new connected network becomes more tolerant against node failures. Bi-connected and in general k-connected networks are some examples. In a bi-connected network, if any node is failed, the network remains connected. In a k-connected network, removing k-1 nodes from the network cannot partition the network. Forming network backbones, such as connected dominating set (CDS), has been proposed as a solution in many works. A CDS is a subset of nodes of a graph. Every vertex in the graph is either in CDS or is adjacent to a vertex in CDS and any vertex of network graph can find a path to another node through CDS.

CDS makes a backbone for the network and provides a stable connectivity. When the inter-actor network is connected and an actor needs to move because of its mission, a proper replacement algorithm must keep the network connected. For example, consider a network that has the objective of minimizing the time required for an actor to reach the spot that needs attention. Since the network may lose its connectivity if actor nodes are relocated freely, the coordination layer should limit the movements of actors to ranges that do not impair the connectivity of the network [33]. Actors must consider application-level requirements in actor movements.

Resource-rich actors can provide services such as

1) Long range data communications, 2) persistent data storage, and 3) actuation. The key idea is to exploit the capabilities of rich actors to reduce communication, computation, and memory usage of small sensor nodes.

Durresi *et al.* [35] have proposed a protocol named DEAP that takes advantage of actor nodes. The network uses resources of actor nodes whenever possible to reduce the energy consumption of sensor nodes. DEAP contains a random wakeup protocol that deactivates sensor nodes for energy preservation. DEAP considers actor nodes as powerful and higher energy level nodes that are always awake allowing the neighbouring sensors to go to sleep. DEAP uses actor nodes in routing. The same idea has been used by Paruchuri *et*

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al. [36] by considering the case where the network is not partitioned but actors help sensor nodes in some points to prevent energy overconsumption of sensor nodes. If a sensor node has an actor node as its neighbour, the sensor transfers its duties to the actor and goes to sleep. By exploiting a mobile sink, load balancing may be achieved to prevent near sink nodes from dying soon [37].

Because of converge cast pattern or many-to-one pattern of traffic in WSNs where messages are forwarded from sensors to the sink, nodes near the sink experience more traffic that depletes their energy fast. This issue is known as the *funnelling effect* [38].

Luo *et al.* have used a mobile sink to balance the traffic load and in turn to improve the network lifetime. Because they consider a sink node that is mobile, their work contains a routing protocol for sending data to the sink. Mobility pattern of sink is discrete; sink moves and sojourns. The sojourn time is much longer than the moving time. This pattern limits the extra overhead of routing to the mobile sink. Some approaches such as cooperative transmission and the directional antennas [39] require special hardware to improve connectivity. Now we explain one of the best connectivity improvement approaches. Atay *et al.* [40] have considered a network containing mobile sensors and a set of mobile actors. Their proposition is also applicable to a WSAN containing static sensors. Motion of mobile sensors is not controlled but motion of actors is controlled by the network. The duty of actors is to move to appropriate regions and work as mobile sensors and build communication bridges. They have introduced a new property into graph, namely, k-redundancy. The k-redundancy of a node is defined as the minimum number of node removals required to disconnect any two neighbours of the node. This means that in order to make two neighbours of a k-redundant node unreachable to each other, it requires k nodes to be disconnected from the network in addition to that node. They have used this property to represent the goodness of connectivity among the neighbours of each node. A node could create a communication bridge between any pair of its neighbours, but if there are alternative routes between the neighbours, the importance of that node on connectivity reduces. The goal is to achieve k-redundancy for all mobile sensors. Each sensor continuously checks its k-redundancy and requests assistance from a mobile helper actor if k-redundancy becomes less than its minimum desired redundancy. Two methods have been proposed for connectivity repair in [40].

In the first method, the network directs actors when the k-redundancy of a sensor becomes less than a minimum value. To avoid unnecessary deployment of actors, each sensor connected to a helper actor periodically runs a connectivity detection mechanism. If all sensors can communicate to one another without the help of the helper actor, the helper actor is unnecessary and leaves that region.

In the second method, the network places the actors at locations that minimize the repair time in case k-redundancy becomes less than the minimum value. Finding the best locations to minimize expected repair time can be represented as the facility location problem. Because the facility location problem is NP-Hard, a heuristic approach is proposed. The best policy is as follows. The actor moves to the point that is closest to it and close enough to repair the network. It is noticeable that they have assumed the existence of obstacles in the environment and have limited the speed of sensors and actors. K-redundancy approach can be enriched for WSANs where sensors are static. Because the location of sensors is almost invariable, based on k-redundancy algorithm, a long plan can be presented for the required number of actors and their locations.

III. WEAK INTER-ACTOR WSAN

In friendly environments, an actor may lose some of its abilities because of hardware failure. Moving parts, wireless devices, electrical parts, or sensory devices mounted on an actor may fail and consequently disable the actor. In hostile environments, an actor may be destroyed completely by intruders. In addition, software faults may exist in both types of environments and cause errors and failures. Actor failure is one reason for connectivity weakness. There are environmental constraints such as obstacles and media problems too.

In this category we assume that the inter-sensor network is connected and the inter-actor network is partitioned or some actors cannot communicate with other actors using the interactor network. Based on approaches proposed in the literature, we have grouped the research work in three sub-categories as mentioned below.

A. Movement-Based

Given a reasonable degree of actor density, partitioning can be repaired by actor replacement. Abbasi *et al.* [41] have proposed a solution in which each actor node gets information on its one-hop and two-hop neighbours. When one of the actors fails, other actors move to restore connectivity using a localized algorithm. The idea has been to identify the least set of actors that should be repositioned in order to establish connectivity

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among disjoint network partitions. To do that, their approach, called DARA, picks one of the neighbouring actors of the failed node to replace the failed node. Since this may disconnect the children of the moved actor, their approach strives to pick a neighbouring actor that will cause the least number of cascaded movements. Moving a node may require a cascaded relocation that ripples throughout the network to avoid breaking connectivity in other parts of the network.

Akkaya *et al.* [42] have used an algorithm, called PADRA, based on CDS. In case of a failure, PADRA selects a non CDS node for replacement whose movement does not partition the network and requires minimum travel distance. Cascaded movements are done if required.

Younis *et al.* [43] have relaxed the two previous works ([41], [42]) by proposing a localized approach that requires only one-hop neighbourhood information. Their algorithm is named recovery through inward motion (RIM). The restoration process is distributed and requires no coordination among nodes. Every node sends heartbeat messages. Missing heartbeats from a node shows its failure. Neighbours of the failed node move toward the failed node and stop when they reach *r/2* from the failed node where *r* is the communication range. This way all neighbors of the failed node get connected.

Imran [44] *et al*. have later found that a more optimized approach can be proposed using variable transmission ranges for nodes, given the fact that all neighbors need not move toward the failed node. Their so called volunteer-instigated connectivity restoration (VCR) approach employs fewer nodes than RIM. Moving the actors that are busy conducting a task and forcing them to terminate current tasks might have negative or severe side effects to the application level [45]. For example, forcing a group of actors currently involved in extinguishing a fire to terminate their current tasks and to move away to maintain connectivity can have severe negative effects on the mission of application [45].

Abbasi *et al.* [45] have proposed an algorithm called C2AM that restricts movements of actors based on two indices: mobility readiness index (MRI) and mobility potential (MP). MRI is defined as a value between 0 and *l*. Each actor computes its MRI based on its current task. The value 0 of MRI means that actor can move freely and the value *l* means that actor cannot move. MP is the number of one-hop neighboring actors that can move.MRI has higher priority than MP and in case of same MRI of neighbors MP is checked. Using information of two-hop neighbors, C2AM selects the best actor for replacement. In case of missing heartbeats from an actor, other actors can find that the actor has failed. Based on MRI and MP, a neighbouring actor is selected for replacement. Cascaded movements are applied according to application restrictions on movements.

Simultaneous failures of many actor nodes especially those nearby requires more attention. For example, in a battlefield environment, a bomb may destroy many actors near each other. Many works consider restoring connectivity when only one actor fails. This is a critical issue requiring special attention when WSAN is deployed in harsh environments.

Alfadhly *et al*. [48] have had a preliminary attempt to recover connectivity of a WSAN in case of multi-actor failures. They have modelled the recovery problem as an Integer Linear Program (ILP). Their objective has been to form a connected network, to minimize travelled distance of actors, and to minimize covereage loss. Their work only identifies a lower bound on total travel distance connectivity restoration and it is not a practical approach because ILP requires information about all actors to be solved. Solutions with preventive attribute are required to avoid multi-actor failures. Also the idea proposed in [49] can be used to handle multi-actor failures. When an event occurs in an environment, actors move in the environment to handle the event and also preserve network connectivity, and when the event ends actors return to their locations. A force-based strategy is used in this work. Their event-based relocation that determines the positions and densities of nodes for a large scale-event can be adapted to the multi-actor failure problem.

1) Isolated Actors: In a partitioned inter-actor network, an actor may be isolated or orphaned. An isolated actor cannot communicate with other actors directly, or more formally said there is no edge between the actor and other actors in the inter-actor network graph. The mission of the actor may put the actor in this situation. Upon experiencing a disconnection, the actor can try to find sensor nodes through which to connect to other actors. Depending on the circumstances, the actor may take one of the following actions:

• If the actor cannot find a path to other actors, but it can communicate with some sensor nodes, it can move along the path offered by the inter-sensor network to establish a connection to other actors. In this case, an on-demand discovery method can be used. Fig. 3 shows an example.

• In case no such sensor node is found to guide the path toward other actors, the actor may move based on some heuristics or go toward a predefined location [33]. A GPS device can direct the actor to a predefined location.

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• In case the actor finds a path, but it cannot move to the vicinity of other actors because of its mission or obstacles, a special-purpose routing and coordination mechanism is required. In this case, the actor must periodically communicate with other actors through sensor nodes. It must consider the limited energy of sensor nodes and use an energy-aware coordination mechanism. The points we have enumerated above on isolated actors are just a series of initial ideas requiring further research.

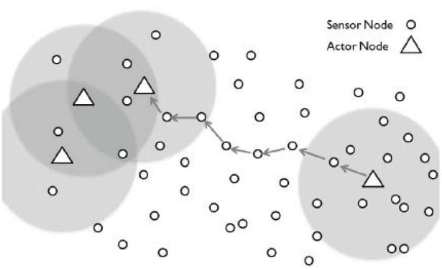

Fig.3 An isolated actor finding a path to other actors through sensor nodes

B. Partition Detection by Sensors

One way for detecting partitions is to use the information provided by the connected inter-sensor network. Akkaya *et al.* [53] have proposed an algorithm to detect a partitioned interactor network using the inter-sensor network. The algorithm initiates a search process first by using the underlying sensor network in order to detect the possible sub-networks of actors in the region. The approach uses a quorum location service at the background. For a brief description, quorum location service has usually two quorums: search and update quorums. In its simplest case, a node sends its location to north and south directions hop by hop and other nodes find the location of the destination node by sending messages toward east and west directions. Two quorums intersect at an intersection node.

Akkaya *et al.* [53] have proposed that a leader actor is selected in each partition of the inter-actor network. Using update and search quorums, leaders can connect through sensor nodes. Their algorithm then tries to connect the interactor network by actor movements. The actors of a partition can use sensor nodes to coordinate between partitions. Coordination must be local to consume less energy of sensor nodes. It is possible to connect actors using sensor nodes during connectivity repair time when actors move in the environment [12]. Sensor nodes are used to temporarily and rapidly re-establish actor-actor connectivity before this connectivity is permanently re-established through actor movements. This idea prevents packet loss in the network. Movements of actors take some time depending on actors' speed, but connection through sensor nodes is immediate. So this approach is useful for real-time and coordination critical applications. Because this approach requires location information, it is considered as a geographical approach. A topological approach for establishing connectivity between actors using sensors can be considered as a feasible future research. Furthermore, the algorithm uses two-hop neighbouring information. A version of algorithm with only one-hop information of neighbours is also desirable. The works reviewed in this subsection are applicable in real world because they use sensors to detect partitions of a weak IAN and to establish connection between actors in a limited time period before actors repair disconnections by movement.

C. Disconnected IAN Recovery

When actor density is low or many actors have failed, the inter-actor network is not reliable for actor-actor coordination. In addition, in some wide area applications, such as in border control, the inter-actor network may be disconnected due to large distances between actors that make coordination very challenging. The communication range can be limited in some environments such as underwater ocean monitoring. In these cases, the inter-sensor network can act as a communication medium for actor-actor coordination [2]. In environments such as in cities that have many obstacles, wireless communication may be obstructed, making actor-actor coordination difficult if actors are spread sparsely in the field. An example is shown in Fig. 4.

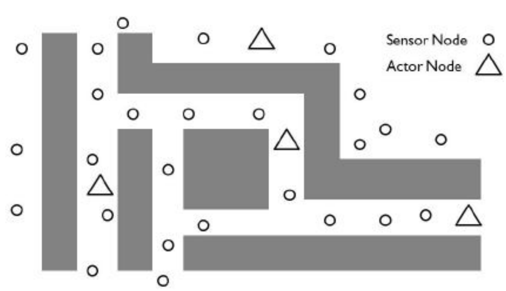

Fig.4 City buildings as obstacles

A network model for the disconnected IAN is presented. The model is as follows. A WSAN is represented as an undirected graph $G = (V,E)$. $V = S \cup A$ where S denotes a sensor set and A denotes an actor set. $E = (S \times S) \cup (S \times A)$ denotes an edge set that includes sensor-sensor and sensor-actor connections. *A*

ISSN (Online) : 2319 – 8753
ISSN (Print) : 2347 - 6710

International Journal of Innovative Research in Science, Engineering and Technology

An ISO 3297: 2007 Certified Organization, Volume 3, Special Issue 1, February 2014

International Conference on Engineering Technology and Science-(ICETS'14)

On 10th & 11th February Organized by

Department of CIVIL, CSE, ECE, EEE, MECHNICAL Engg. and S&H of Muthayammal College of Engineering, Rasipuram, Tamilnadu, India

× *A* is not included implying that there is no direct connection between actors.

1) Quorum-Based Approaches: Sedighian *et al.* [13] have proposed another approach by using the inter-sensor network as a backbone for partitioned inter-actor network. They have used the quorum approach as a backbone to establish connectivity between disconnected actors. The idea behind their work has been the quorum location service.

In XYLS, a node reports its location to the nodes located in a column using geographic routing. This means that the node sends its location update to the north direction and to the south direction until they reach the north and the south boundaries of the network. This column is named the update quorum or in some works the advertise quorum. When a node requires the location of another node, it queries its nearby nodes. In case no information is found, the query is sent to nodes in the east-west directions; the nodes encountered in this direction are called the search row or the query row in some works. The search row and the update column must intersect. This is the main idea behind strip quorum. In the approach proposed in [13], all actors send their location information to update quorum that is made by sensor nodes. Sensor nodes in the path get the message, update their local table that contains locations of actors, and forward the message in the quorum. When an actor needs to send a message to other actors, the message flows in the search quorum. In this approach, the sender actor finds the position of destination at the intersection sensor and sends the final message to the destination. It is obvious that long time use of the inter-sensor network by the inter-actor network for the routing purpose requires more capable sensor nodes. The strip quorum approach is applicable to sensor and ad hoc networks even when nodes are mobile. Considering static sensor networks and a few mobile sinks. All approaches reviewed here have shortcomings that limit their use in practice. We need some approaches that possess all of the following properties. There is a need for approaches that have been proved or at least shown that they guarantee discovery of actors, are load balanced and evenly consume the energies of sensors, and do not create hot spots on the network outline or some specific locations of the network.

2) Indirect Coordination: Indirect coordination is an approach to achieve coordination. Bio-inspired ideas are useful in this category because solutions in this category must be self-organized; Computational intelligence encompasses paradigms such as neural networks, reinforcement learning, swarm intelligence, evolutionary algorithms, fuzzy logic and artificial immune systems.

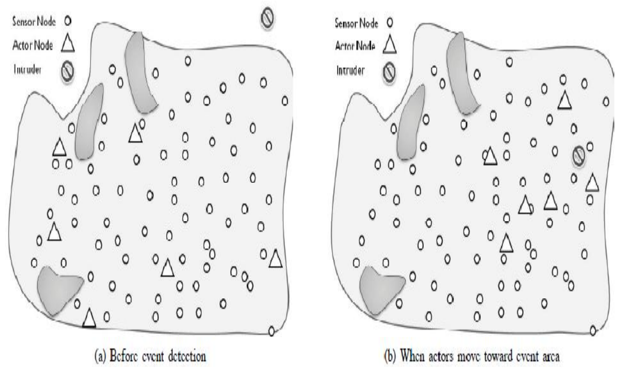

Fig. 5 A sample arrangement of distant actors

Some ideas especially in swarm intelligence are good candidates to be applied in WSANs when actors cannot communicate. Coordination in WSANs needs distributed versions of these approaches to be applicable in real world. Now we review a work that provides coordination without direct actor communication and specifically designed for WSANs.

In [18], mobile actor nodes charge sensors by an energy harvesting approach. Actors use sensor nodes for storing charge information as well as for when actors cannot use the inter-actor network for coordination. Actors do an implicit coordination through sensor nodes to divide sensor nodes to different groups dynamically and to make each actor responsible for charging one group. The actor moves in the environment and sends a message to advertise its ability to charge sensors. Sensors that hear the message increment their interest to the actor and respond to the actor. The actor selects a sensor based on parameters such as the current energy level of the sensor, its previous charge time, and the battery usage ratio of the sensor. When an actor charges a sensor, the interest of sensors to the charging actor will be at the maximum. Sensors decrement their interest to an actor when they receive no message from the actor implying that the actor has left the region. Each sensor has an interest table that shows its interest levels to actors, and only responds to the most interesting actor. Dynamic and unbalanced charge requests can be handled by this mechanism. The approaches of this subcategory are usually application specific. So we cannot identify best practices in this category. The type of application and its requirements determines which approach must be used.

ISSN (Online) : 2319 – 8753
ISSN (Print) : 2347 - 6710

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An important remark on solutions to recovery of disconnected actors on the subject of 'Disconnected IAN Recovery' in this subsection is that sensor nodes must provide some basic services to actor nodes. To clarify the above point, reconsider the state shown in Fig. 5 when an intruder has entered an enclosed area. Sensor nodes detect the intruder and inform the actors that are nearest to where the intruder has been detected; we refer to the detection of intruder as an event here. Being informed about this event, actors must cooperate to catch the intruder even if they cannot directly communicate. To achieve coordination, each actor must know the locations of other actors to figure out how far or near it is to where the event has occurred. In case there are other actors nearer to the event's location, this actor need not take any further action. To give an example, let us consider two actors that somehow decide to cover an event. These two actors must coordinate by finding each other to communicate. They then start moving to the event area to become close by. In case they cannot directly Fig.6. An example of a critical event portion communicate, they must temporarily communicate through sensor nodes in their vicinity until they can communicate directly.

The above example implicates the required services. The minimally required services to provide sufficient functionality are as follows [13]:

• A sensor node or an actor node needs to know the location of a specific actor.

• A sensor node or an actor node needs to find its nearest actor or n-nearest actors.

• A sensor node or an actor node needs to know the locations of all actors or some actors that are positioned in a specific region.

IV. WEAK INTER-SENSOR WSAN

Some portions of the inter-sensor network may use more energy and make inter-sensor network weak because of battery depletion. This may be due to the occurrence of more events in those portions. In a border control application, some points may be engaged with more events because of geographical conditions of the environment. Fig.6 shows a bottleneck in the field that adversaries must pass through. Events are triggered frequently in the bottleneck. In reality, sensors cannot be deployed in a desired way because of operational limitations. During network lifetime, sensor nodes may fail because of energy depletion as noted before, hardware failure and damages by adversaries or in harsh environments. These issues reduce the coverage of sensor nodes.

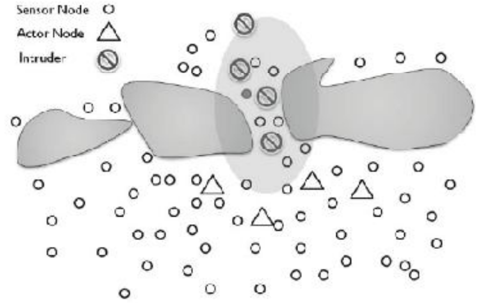

Fig. 6 An example of a critical event portion

A. Sensor or Relay Placement by Actors

As noted before although mobile sensor networks are out of scope of our survey, we explain a related topic, namely, mobile sensor relocation because the explanation clears static sensor placement by actors that is our target. Mobile sensor relocation involves two tasks: *replacement discovery* that is, finding a redundant sensor as the replacement of a failed node, and *replacement migration*, that is, migrating the replacement to the failed sensors position. Adding mobility to all sensors of a large network is very expensive. Also sensors usually have low energy sources. So mobile sensor relocation is not possible in all situations. Moreover, static sensors allow the use of more efficient routing protocols. By using more powerful actors, spare sensors can be replaced with failed sensors. Passive sensors in dense deployed areas of network can also be carried by actors for replacement with failed sensors; this is referred to as movement-assisted sensor relocation in the literature. We here review some existing related surveys on the topic and show how they have categorized 'sensor placement' differently from ours. As we have noted before, our categorization of Weak Inter-Sensor WSAN is based on the helps that actors can provide to ISN. We have thus categorized 'sensor placement' to two subcategories, namely 'Sensor Placement by Actors' and 'Actors as Relays'. Techniques for node placement in sensor networks are surveyed. The work has categorized the placement strategies into static and dynamic groups depending on whether the placement is performed at the time of deployment or when the network is operational, respectively. We review only dynamic techniques because static techniques are a type of approaches with preventive attribute that are applied when network is connected or during initial deployment. In a more recent work, sensor replacement has been surveyed. We review only the works surveyed that have assumed that sensors are relocated by actors In another new survey on the topic named "A Comprehensive Review of Sensor Relocation", have been presented by two categories: mobile sensor self-relocation, and robot/actuator assisted sensor relocation. Migration technique can be *direct* implying that a node can move toward a destination, or *shifted* resulting in cascaded movements. A sensor may use a sensor or actor as a proxy to advertise its information to reduce message overhead. Algorithm structure can be centralized or distributed. Sensors are considered as mobile nodes that either move by themselves or are moved by mobile actors. We only review robot/actuator assisted sensor relocation.. In the short chain problem, two terminals exist and relays should connect them. In the third problem, the gathering problem, no terminals are supposed and there are only *n* relays that must be gathered in one single point to meet each other. Relays must coordinate when restricted to a purely local view. The second problem may be useful in any Weak Inter-Actor WSAN with two partitions too. The best works are distributed wherein actors move sensors and act as proxies to reduce energy usage of sensors.

1) Sensor Placement by Actors: Some sensor placement protocols are proposed to heal sensing coverage holes but the ideas are applicable to connectivity problems too. Also when transmission range is equal or greater than the sensing range in the most common network model of WSANs, that is the unit disk graph model, coverage repair implies connectivity repair.

A new method have been proposed how to replace a number of failed sensors. An actor acts as a central manager and broadcasts itself to all nodes of the network. Live sensors report failed sensors to the manager. The manager then dispatches other actors toward failed sensors. Their work contains a distributed solution too. The environment is partitioned into some regions based on the locations of actors. A Voronoi diagram is constructed in the network and each actor is placed at the center of each cell. When a sensor node fails, the actor carries a spare sensor and replaces it and the network updates the Voronoi diagram. This work assumes that actors have enough spare sensor nodes during redeployment. Identification of spare sensor nodes provides an opportunity for replacing failed nodes with spare sensors. The approach proposed in [33] by Akkaya *et al.* uses recovery time and the imposed overhead as parameters in the selection of spare nodes. They have used a grid-based approach. Each grid has a head and each head identifies, advertises, and requests redundant nodes for its cell. They have used the quorum idea. Messages advertising the existence of redundant nodes flow in update quorums, while request messages for redundant nodes flow in search quorums. Using quorums, redundant sensors are moved to appropriate cells that require more sensors.

The approach proposed in [33] finds the minimum cost to collect passive sensors from all network area and deploy them in required void regions. Passive sensors report their locations to the base station and active sensors report void areas. The approach is modelled by a variant of Travelling Salesman Problem and solved using the ant colony optimization. However, the approach is centralized and a distributed version is required.

2) Actors as Relays: It have been considered *m* static stations (sensors) and *n* mobile robots (actors). Mobile robots are spread in the network and act as relays between disconnected stations. Their goal has been to minimize the number of exploited mobile nodes. They have used two strategies. In the GO-TO-THE-CENTER strategy that mobile robots run one by one, each robot moves to the center of the smallest enclosing circle around all positions of its neighbours (sensors and actors) within its viewing radius. This center is equivalent to the point that minimizes the maximum distance to neighbors of the robot. If another actor is available in the region, the robot deletes itself from the network by doing nothing or returning to the camp. In the EXT-GO-TO-THECENTER strategy, the robot checks if the sub-graph made by its neighbours is connected and if so it deletes itself.

An alternative method is used actors to bridge a sparsely connected network. Such a network is acceptable when a complete surveillance of environment is not required. For example, in a coastal monitoring application, sensor nodes may monitor water temperature and wave characteristics and actors may collect water samples for further analysis. In their approach, the network is clustered. When an event occurs in a cluster, the event detection information is propagated throughout the cluster. Clusters with higher probabilities of event occurrences are those that occupy larger areas and when visited by the actor lead to better results in event detection. It is used mobile elements for bridging regions of WSNs containing unstable or failed sensors. Bridging a partitioned inter-sensor network by actors limits the movements of actors. So the number of actors must be large enough because some actors are prevented from moving freely.

ISSN (Online) : 2319 – 8753
ISSN (Print) : 2347 - 6710

International Journal of Innovative Research in Science, Engineering and Technology

An ISO 3297: 2007 Certified Organization, Volume 3, Special Issue 1, February 2014

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B. Data Carriage by Actors

In some applications, sensors only sense the environment and actors as mobile elements collect sensors data. The following are the reasons for the use of mobile elements for data collection in these applications: 1) because the inter-sensor network is sparse, sensor nodes are far from each other and transmission in long distances requires more energy,
2) sensors must participate in routing of other sensors data, and 3) near sink sensors face huge forwarding traffics because of the funneling effect that drain their energy fast [86]. After the lifetime of a sensor network is over, there is a great amount of leftover energy that can amount up to 90% of the total initial energy. This is because of the funnelling effect of static WSNs. Non-delay sensitive applications such as animal migration and city traffic monitoring are some examples of the applications of this subcategory that are usually delay tolerant. This is because the speed of actors is much slower than electromagnetic or acoustic waves. A taxonomy on data collection by mobile elements in two categories: direct-contact data collection, and rendezvous based data collection. In the former category, actors move in the environment and gather data of sensors by one-hop communication. In the latter category, sensors send their data to a subset of sensors called rendezvous points. In some research works, these points are named collection points, gateways, or anchors. Actors collect data from these points. The direct contact data collection category has been further categorized by the way actuators tour the network. The rendezvous-based data collection category has been further categorized based on rendezvous point selection methods used. We have used this categorization in this subsection but there are some other categorizations too whose reviews below are useful to better understanding of the topic. The taxonomy is based on the help that actors provide to sensors and is compatible with our policy of categorization in Weak Inter-Sensor WSANs. Lee and Younis have categorized the works to three groups based on the roles of actors. The network may have three elements: collectors that tour the sensors and collect their data, a base-station that consumes the data, and a relay that forwards data from one node to another. We have looked at the topic from another angel in their survey.

They have defined three phases of data collection:

1) *discovery* process allowing sensors scattered in a field to contact a moving actor in a field,

2) *data transfer* for transferring sensory data by sensors to a moving actor after sensors have discovered the actor, and

3) *routing* that relates to a stable or partial path from sensors to moving actors.

We have categorized rendezvous based data collection as *proxy-based routing*. They have added *motion control* as an important factor and have surveyed the works in these four categories.

1) Direct-Contact Data Collection: The actors in the work are called the data MULEs. MULEs randomly move in the environment and collect data from sensor nodes. In sensor nodes are assumed mobile and actors are responsible to gather sensors data. Actors predict next directions and movements of sensors. PROSAN assumes that sensors repeat their pattern of movements in the network. A sensor node forwards information only to the nodes with the highest probability of delivering the message toward the destination. This idea can be optimized for static sensors. Sensors may be organized to clusters and only cluster heads send stored data to mobile actors.

We explain the Mobile Element Scheduling (EMS) problem in in more detail because our explanation clarifies the topic of data carriage among similar topics. They have described the differences between the EMS problem and the Prize Collecting Travelling Salesman Problem (PC-TSP) wherein a vehicle is routed to visit each city at most once. Gu *et al.* [93] have distinguished their work from Vehicle Routing Problem (VRP) that has been defined as finding a route for a vehicle that minimizes the total travel cost to deliver cargo between a depot and customers. Unlike TSP, VRP considers more than one vehicle and nodes can be visited more than once. In EMS deadlines are dynamic while in VRP deadlines are fixed and EMS is a continuous problem. To solve EMS, we] have proposed a Partitioning-Based Scheduling (PBS) algorithm that schedules mobile actors to visit sensor nodes before buffer overflow of gathered sensory data in sensor nodes. PBS first partitions the network to several groups in a way that nodes in each group have similar deadlines. In the next step, each group is divided into subgroups by locations of nodes. The path of movement of an actor in a sub group is solved using TSP. Finally, the schedules for individual groups are concatenated to form an entire schedule.

VII. WEAK INTER-SENSOR AND INTER-ACTOR WSAN

Sometimes both the inter-sensor network and the inter-actor network can be weakly-connected or disconnected as in harsh environments when actors combat against

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adversaries. This category specifically includes only a few works however the ideas of many works can be useful in this category. Different scenarios that may lead to this category should be considered in the future. When both the inter-actor network and the inter-sensor network have weak connectivity, WSAN becomes like a challenged network. In this type of network, disconnection is common. An actor or a group of sensor nodes can be damaged by enemies at any time such that the network may sometimes become partially connected. Intermittency of connection is another problem. Because missions are vital to actors, their first movement is guided by their mission rather than following any predestined algorithm

that yields the best connectivity. Furthermore, intermittent networks suffer from large delays. In this type of network, sensor nodes and actor nodes must store messages temporarily when connection is not available. When connection is established, buffered messages can be sent out. Coordination becomes very hard when the network is intermittent. Coordination mechanism must consider disappearances and appearances of nodes during network lifetime. A survey on routing protocols for intermittent networks and delay-tolerant networks (DTNs) has been presented. Opportunistic networks have also been surveyed. In opportunistic networks, mobile nodes can send data to others eventually even if no direct links exists at an instance of time. Some ideas in these types of networks may be useful in this sub-category for non-delay sensitive applications. WSANs need ordered delivery and execution, so connectivity is vital. Sensor nodes must help actor nodes and actor nodes must help sensor nodes whenever the other one needs help. When one or more actors fail, sensor nodes must rapidly provide paths to actors to connect. When some sensor nodes around a location fail, actor nodes must take up the duties of those sensor nodes or replace them if possible. One of the sources of weak connectivity in both networks is the obstacles. Obstacles can make both the inter-actor and the inter-senor networks weakly-connected. Obstacles have a

heavy impact on connectivity. Obstacles do not result in the removal of network nodes but rather they cause the removal of some edges from the network graph. This is problematic especially when an edge that is a bridge or cut is removed. Elimination of a bridge from a graph disconnects the graph. A model for WSNs including obstacles has been proposed. The model uses a collection of different shapes of obstacles. Some location-based routings are studied in this work. It is found that each routing algorithm performs better for a certain class of obstacle shapes. The notion of an obstacle is generalized to include communication holes in networks, classifying obstacles as communication and physical ones. Physical obstacles can produce communication obstacles. Furthermore, physical obstacles can prevent actors to move easily and freely. Many coordination protocols during actor positioning do not consider obstacles at all. But in real world, WSANs are mostly deployed in harsh and adversarial environments wherein static and even dynamic obstacles are common. Any coordination mechanism must consider that obstacles prevent actors to move easily and may reduce the speed of actors.

In this category, we categorize the approaches in three groups. There are only a few approaches that have been specifically designed for this category and more comprehensive approaches are required.

A. Mutual Cooperation of ISN and IAN

We have reviewed many ideas for Weak Inter-Actor WSANs and Weak Inter-Sensor WSANs. Combining these ideas makes solutions when both networks are weak. We show one possible combination. In Fig. 7, both ISN and IAN are partitioned.

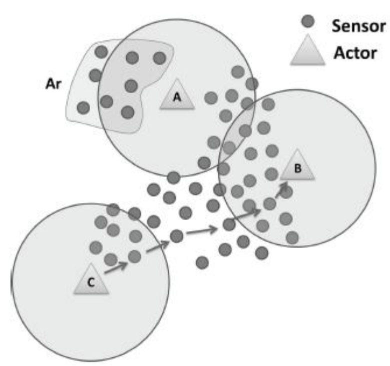

Fig. 7 Combination of solutions to Weak ISN and Weak IAN

Sensors in the disconnected area *Ar* cannot connect to other sensors and actor *C* is isolated from the inter-actor network. Actor *A* bridges the disconnected area *Ar* to the inter-sensor network, and the inter-sensor network connects actor *C* to other actors. In this category, we need solutions that recognize WSANs as a single network. A new method have been proposed a protocol named TARANTULAS that has this view on WSANs. In this work, mobile actor nodes and static sensor nodes support each other. Robots move to fill the communication gaps to enhance connectivity and localization while static nodes serve as landmark nodes

ISSN (Online) : 2319 – 8753
ISSN (Print) : 2347 - 6710

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International Journal of Innovative Research in Science, Engineering and Technology

An ISO 3297: 2007 Certified Organization, Volume 3, Special Issue 1, February 2014

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to help robots search for targets. Inter sensor network performs localization after deployment, and the localization accuracy is continually improved with the assistance of mobile robots that in turn use sensors as beacons for navigation. Mobile and static sensors mutually cooperate to enhance each others performance. Actors find connectivity void areas of the inter-sensor network and deploy new sensors.

VIII. LESSONS LEARNED AND FUTURE WORKS

In this section, we summarize the lessons learned from the works we surveyed in this paper
We also suggest feasible future works and research directions.

A. Lessons Learned

We summarize here the approaches proposed in the surveyed works in this paper. We combine all lessons learned from the reviewed works in Fig. 8 to show the overall flow of coordination in weak WSANs.

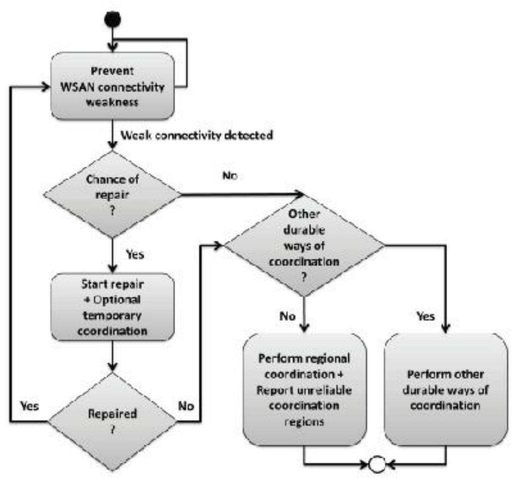

Fig. 8 Coordination flow in weak WSANs

For a connected WSAN, the prevention of weak connectivity is vital because suitable coordination can be achieved when WSAN is connected. Each general approach or attribute like data aggregation, load balancing, and deploying redundant nodes in the network that increase network lifetime, indirectly help weak connectivity prevention. Finding critical nodes and considering some nodes as backups is an approach with preventive attribute. Nodes can move to keep network biconnected, k-connected, or achieve better k-redundancy. Making computational backbones such as connected dominating set (CDS) is another approach. Mobile sinks can save energies of sensors because nodes around the static sinks deplete their
Hardware-assisted approaches such as energy harvesting and exploiting directional and smart antennas are also applicable to special applications. Cognitive radio is another solution. We have highlighted the preventive attribute in approaches that repair weak connected WSANS in our summary of surveyed works.

Despite all connectivity improvement approaches, a WSAN may lose its connectivity or may be weakly connected from the start. An approach is required to predict the probability of establishing connectivity if connectivity repair is applied. This is required because connectivity repair is costly. If the chance is low, it is better to ignore repairing the network connectivity. There are many approaches for repairing a weakly connected network when the repair is considered useful. Movement is one of the best approaches because it has a great chance to repair the network. For a weak IAN, especially when the failure of an actor is the cause of weak connectivity, many approaches use two-hop neighbour-hood information for repair. Some approaches use one-hop information and are more energy efficient. CDS-based approaches have a long list of research works. Some researchers believe that movement based approaches must move actors less frequently. If a movement-based approach should have a preventive attribute as well, it must make the network as much stable as possible that may require more movements. The coordination plane must restrict the movements of actors because movements may violate coverage, other running tasks, the power plan, and fault management. Movement-assisted sensor relocation is also useful in Weak Inter-Sensor WSANs. Relocating some spare sensors to locations where actors need them most improves the connectivity of ISN. Sensors can optionally route data between disconnected actors during repair time in a weak IAN, making virtual paths between actors. This is an important lesson learned because it always guarantees to connect weak IANs. Also actors can bridge partitions of a weak ISN or charge sensors.

The heterogeneity of WSAN nodes is an opportunity not a challenge in these cases. If the network is not repairable we must seek some ways to do coordination. In an IAN that is not repairable, sensors can provide a location service for actors to find each other and communicate indirectly. Quorum-based approaches are good candidates. Indirect coordination and bio-inspired

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methods such as ant-colony and swarm-intelligence are useful for coordination between actors too. The approaches must be designed for a specific application. Actors can patrol in an environment and carry data of sensors of a weak ISN. But a better approach exists that does not require actors to undertake all tasks but allows for sharing of tasks between sensors and actors. In this approach, sensors forward their data to some collection points and actors travel between collection points to gather sensory data. We have learned from reviewed works that some points in the network are more important and that actors should visit these points by considering their weights. Areas with more events usually generate more data and actors must visit these areas more frequently to gather sensory data and empty limited buffers of sensors.

What about a WSAN that is neither repairable nor capable of coordination? The answer is regional coordination. In any region that coordination is possible, sensors and actors must support each other to do coordination. In regions that coordination is not achievable at all, the network administrator must be informed about the locations of these regions. The coordination plane must have plans for all levels of coordination especially sensor-sensor, sensor-actor, and actor actor coordination levels. A protocol that only supports sensor actor coordination may be in conflict with the requirement of actor-actor coordination level. So protocols that support all levels of coordination are more practical. If a WSAN has intermittent connections, the coordination mechanism must consider intermittent nodes too. Sometimes regional coordination is desirable. We found some works that have shown that network-wide coordination for specific applications results in energy wastage and that coordination is only required in some regions of interest.

B. Trends and Future Research Directions

There are several important points and challenges that require further studies and research in weak WSANs coordination. In this paper we studied the impacts of connectivity issues on coordination but there are other issues such as coverage, power control, mobility management, fault management, and task management, that impact coordination too. So a review on the factors that impact coordination is recommended. In Section III, the concept of k-redundancy was reviewed. K-redundancy is used for a network containing mobile sensors and mobile actors. Considering static sensors in WSANs, k-redundancy can be optimized to use the least number of actors. Combining k-redundancy with other local measures such as local density will result in an appropriate measure of collection that shows the status of network in each region. In general, a measure is required to show the coordination policy that must be applied and thus the required connectivity, coverage level, and power plan for the whole network and for each portion of the network. We enumerated some points about isolated actors that were just a series of initial ideas. Due to the larger number of sensor nodes in WSANs compared to MANETs, the chance of establishing a path between an isolated actor and other actors through inter-sensor network is very high in WSANs. Failure of many actor nodes especially those nearby requires more research; many research works consider restoring the connectivity when only one actor fails. It is important that network can coordinate during multi-actor failures because repairing such a network takes a longer time. A preliminary research on this issue can be found in [48]. In harsh environments, multi-actor failure requires more attention. We need some solutions with preventive attribute that consider multi-actor failures. Specifying the probability of network partitioning for a number of neighboring nodes in different application scenarios is a potential future work. We noted that actor movement is a good way to repair network connection because it increases the likelihood of sustained recovery. However, movement may not be able to repair a weakly connected network. In a weak IAN, the number of actors may not be enough to repair the network connectivity while actors move. Some obstacles in the field may prevent movements as required and IAN may remain weak forever. Replacing sensors by actors in a weak ISN may not connect ISN if the number of remained sensors is low. In some environments, such as a jungle or a mountain, actors cannot relocate sensors as desired or the relocation of sensors may deplete the energies of actors and prevent them from doing their main job. A movement-based protocol must consider such constraints. So as a future work, movement approaches for connectivity repair must estimate the degree of repair success before performing repair. A distributed estimation is more challenging but it is required to provide scalable approaches. Also some layer of the protocol stack in actors such as mobility management may require movement and some other layer such as the power management may forbid movement, and the coordination layer must know the priority of them and perform a more appropriate action based on current circumstances. Different applications in WSANs must be categorized and the priority of connectivity compared to other factors must be investigated. In Section V, rendezvous or collection points were defined wherein sensors in a weak ISN forward their data toward the collection points and actors take data from data points. Given that static collection points create a funnelling effect, dynamic selection of collection points is a candidate future research direction. Also some direct-contact data collection approaches can be modified to be considered as rendezvous based approaches. Sensors and actors can help each other in detecting the obstacles. Neither WSNs nor MANETs nor mobile WSNs has this ability. Collaborative approaches to detect obstacles by mutual coordination of sensors and actors are a desirable future work.

IX. CONCLUSION

Given the importance of weak connectivity problem in wireless sensor actor networks (WSANs) to critical applications of WSANs, and also the lack of any classifications on the problem in WSANs literature, we proposed a categorization of connectivity in WSANs by focusing on weak connectivity and its impact on coordination. The categorization has been derived from existing researches in the area including our own previous researches on connectivity, coverage, and coordination in WSANs.

The categorization showed that proper coordination is feasible even in much challenged conditions. For example, when connectivity of the inter-actor network is weak, the sensory network can come to the aid. The desired level of coordination determines the effort required to keep up connectivity. In case the coordination is real-time, the inter-sensor network must participate in providing paths between actors at whatever energy consumption cost to sensor nodes. When coordination is not real-time and energies of sensor nodes are low, sensor nodes can assign some of their tasks to actors, saving more energy. Sensor nodes not only can help the inter-actor network in reading environmental data and sending gathered data to selected actors, but they can participate in actor-actor coordination too if required. Sensor nodes can store data required by actors, act as a localized memory for actor nodes, and provide communication between remote actors that are not in the communication range of each other. In summary and by considering the lessons learned from surveyed works, it is found that mutual cooperation of sensor and actor nodes must be taken into account more seriously in WSANs in order to beneficially utilize the full potentials of WSANs.

The impacts of other planes and layers such as the power management plane on coordination and real-time support can be studied further too.

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