Enabling Mobility in Heterogeneous Wireless Sensor Networks Cooperating with UAVs for Mission-Critical Management

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Abstract—**Wireless sensor networks (WSNs) have the promise of revolutionizing the capture, processing, and communication of mission critical data for the use of first operational forces. Their low-cost, low-power, and size make it feasible to embed them into environment-monitoring tags in critical care regions, first responders uniform gear, and data collector sinks attached to unmanned aerial vehicles (UAVs). The ability to actively change the location of sensors can be used to mitigate some of the traditional problems associated with static sensor networks. On the other hand, sensor node mobility brings with it its own challenges. These include challenges associated with in-network aggregation of sensor data, routing, and activity monitoring of responders. Moreover, all different mobility patterns (e.g., sink mobility, sensor mobility, etc.) have their special properties, so that each mobile device class needs its own approach. In this article, we present a platform which benefits from both static and mobile sensors and addresses these challenges. The system integrates WSNs, UAVs, and actuators into a disaster response setting and provides facilities for event detection, autonomous network repair by UAVs, and quick response by integrated operational forces.**

I. INTRODUCTION

The ability and performance of intelligent systems providing wireless sensing-computing-actuating are of growing interest. Wireless sensor networks (WSNs) are used to increase the efficiency of many applications, such as target detection and disaster management. Wireless sensor networks with static nodes have been developed and also experimentally applied for detection and monitoring activities [1].

The main objective of the sensing-actuating system is to detect events (e.g. fire) by means of sensors and wirelessly communicate this event and assist other nodes to deliver the event. A typical scenario would consist of a field covering several square kilometers with hundreds of sensor nodes. These nodes would run a mission task and deliver their data to specific sink nodes. Sinks collect (sensor) data and act as insertion point of new mission tasks. However, static WSNs have some limitations. The use of *mobile sensor* nodes could provide significant improvements. They can provide the ability to closely monitor the objects that we want to guard in WSN and to look at the events at a smaller granularity than static nodes.

In order to retrieve information from the sensor network, the mobile sink node needs to remain within communication coverage of the network. A mobile sink inside the monitored region can reduce the hop distance between the sensor nodes and sink. The mobile sink collects the data from the sensors when it passes by. Another possibility is to deploy multiple sinks. Introducing *multiple mobile sinks* in WSNs can provide fast and energy-efficient data collection with well-designed networking protocols.

Mobility of sensor and sink nodes can be achieved by some vehicles or people carrying sensors. It is more efficient to use vehicles instead of people in some cases like disaster management applications due to harsh environmental conditions during the disaster. For this purpose, using the aerial and remotely piloted vehicles is a promising idea. Also, the aerial vehicles can transport and deploy sensor nodes to sites with difficult or impossible access and without communication infrastructure to repair node failures and to keep the sensing system alive.

Design and development of a platform that will enable the cooperation of UAVs with ground wireless sensor-actuator networks comprising static and *mobile* sensors is the main concern of this article. The platform offers self-deployment, self-configuration and self-repairing features by means of cooperating autonomous helicopters. The cooperation of these aerial vehicles with the ground wireless sensor network offers many potentialities such as disaster management, civil security management, and filming applications. In this article, we discuss the requirements, challenges, and opportunities of this platform with a focus on fire detection scenarios.

The remainder of this article is organized as follows. In Section 2, we introduce application scenarios and the device classes used in these scenarios. Section 3 presents the architecture overview of our platform and addresses the challenges of networking layer of the platform. The main focus of this article is routing protocol which supports mobility of sensor and sink nodes is discussed in Section 4. In Section 5, we present concluding remarks and we outline some areas for future work.

II. APPLICATION SCENARIO

The protection in case of natural or human-made disasters is today main concerns of our society. Recent terrorist attacks pointed out the limitations of existing technologies to protect people. On the other hand, many countries (e.g. Southern Europe countries) suffer from forest fire devastation every year, with high social, ecological and economical costs. In spite of research and development efforts, there is still a real need to develop systems for surveillance, early detection, localization, monitoring and contribution to the fire extinction. Thus, the need of systems to protect people and to save lives in case of disasters is evident. The application scenario that motivated this work is the one of disaster management.

We believe that mobility dimension plays an important and unexplored role in these scenarios. Cooperation of the static and mobile sensors presents a viable solution for mission-critical event management. In the project AWARE (EU-IST-2006-33579) [2], we extend these ideas by designing and developing a self-adapting, mission-critical management system that incorporates mobility advances in WSNs. The following WSN setup is being considered:

- **Multiple Mobile Data Sinks –** Sinks are the interface between the wireless (mesh) sensor network and the mission control centre. Control center provides the cooperation and communication of heterogeneous objects in the network transparently. Sink devices are typically capable of communicating via multiple interfaces i.e. to the sensor network and to the control centres. Sinks can be either *mobile* (e.g. attached to UAVs or firefighters) or static. In the case of mobile sinks, mesh networking becomes more complex, because the location or the future location of the sink is not known or predictable.
- **Static Ground Sensor Nodes** – A set of sensors is deployed in a large geographical area in order to monitor particular value(s) of interest, e.g. the temperature, humidity and the concentration of toxic materials in the air. Autonomous *helicopters* and/or *human operators* such as firefighters typically deploy the ground sensor nodes. Helicopters deploy the sensors on an open region. Inside the buildings, firefighters carry out the deployment. Once sensors are deployed, these ground sensor nodes remain at fixed locations and are therefore suitable to act as reliable communication backbone in the ground WSN.
- **Mobile Sensor Nodes –** In our scenario, after some time that the fire event detected, a certain subset of the sensors, co-located in the region, become *hot*, in a sense that their readings exceed a pre-defined tolerance threshold. Therefore, we would like to ensure the quality of reading of the sensors' data for the area bounded by the set of the hot sensors, call it the *critical region*. *Vehicles and UAVs with other sensors* are used to collect information in this dangerous and inaccessible critical region. Therefore, a team of aerial systems (helicopters) carrying sensors is used in co-ordination with ground sensors to get more reliable data about the event and also, to locate the victims of a fire to help the rescue, for example.

  Other *mobile* sensors are the nodes on the firefighters. Firefighters carry a set of (i) *physiological*, (ii) *kinetic-(acting)*, and (iii) *environmental* sensors. These sensors on the firefighters form a *body area network* (BAN) which consists of a set of *mobile* and compact intercommunicating sensors, either wearable or implanted into the human body, which monitor vital body parameters, movements, and environment [3]. *Physiological* sensors can be ECG (electrocardiogram) sensors for monitoring heart activity, EMG (electromyography) sensors for monitoring muscle activity, and blood pressure sensors. *Kinetic* sensors are used to estimate user's activity. Accelerometer based step detection sensor are used to monitor the movement of firefighters and to decide whether they are walking, running, or lying on the floor, etc. The firefighters could also carry some *environment* sensors like chemical and biological sensors e.g. to detect the level of contaminants. In case of a fire, NOx and COx sensors could be used to monitor the danger due to the inhalation of the smoke. With *BAN*, the condition of firefighters can continuously be monitored e.g. to prevent body heating, to rescue them when they do not move anymore, and to monitor the environment conditions for warning them about possible dangers. This sensor information obtained from BAN is transmitted between members of the brigade and finally to the vehicles that are linked to the control centre. Firefighters have also a positioning system on their uniforms; thus, control center learns their location and prevent entrapment by the fire.

We implemented the WSN described above with the fire detection setup for the first field tests. The main objectives of the first field tests were to obtain feedback for the design of the platform and to record data to develop the different subsystems and functionalities.

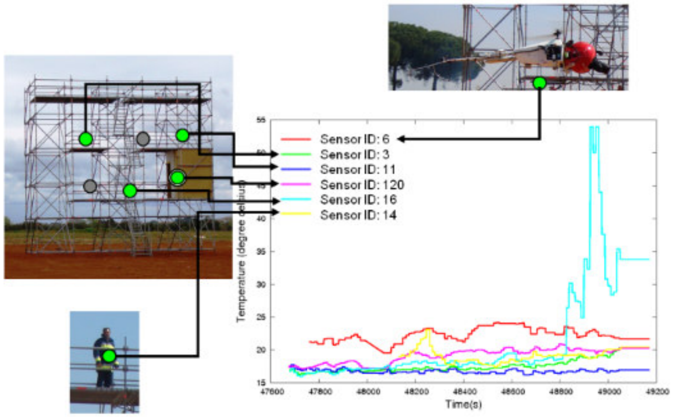

Figure 1. AWARE experimentation scenario and temperature data collected from WSN

As illustrated in Figure 1, a three-floor building was simulated by means of the structure. There is a ladder providing access of the firefighters to the three levels. A closed room was also installed in the first level. Firefighters and fire trucks participated in the experiments. Smoke and fire machines where used to simulate the fires.

The first step is the detection of a fire inside the building by means of the WSN deployed in the structure. A set of nodes of the WSN detected the fire and generated an alarm. Figure 1 illustrates the sensor data obtained in the experiment. The green line in the temperature diagram corresponds to the node close to the fire.

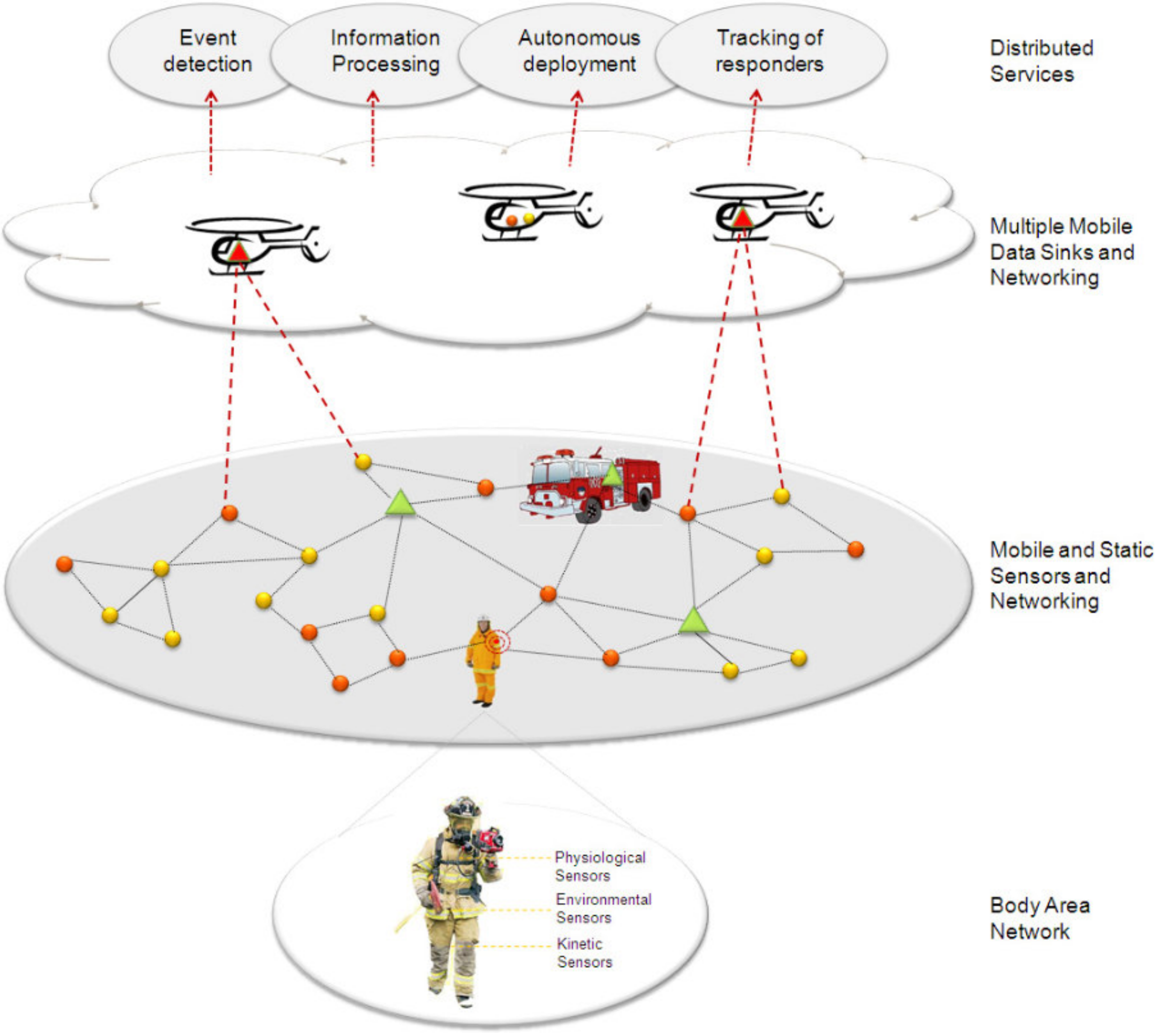

Figure 2. AWARE Sensor Network Architecture

III. ARCHITECTURE OVERVIEW

The architecture of the AWARE platform comprises a number of heterogeneous sub-systems. These are described in relation to the global architecture in Figure 2. We have two key system layers of abstraction: the sensor and networking layer, and the distributed services layer.

The sensor and networking layer contains the sensor nodes (the physical sensor and wireless transmission modules) and the network protocols. Ad-hoc routing protocols allow messages to be forwarded through multiple sensor nodes taking into account the *mobility* of nodes, and the *dynamic change of topology*. In this layer we have *multiple mobile sinks* attached to UAVs, fire trucks, and firefighters. These sinks of network are the points of interest where the data gathered by the network must go to. They have more capabilities than normal nodes, i.e. they can communicate directly with each other via hi-speed links, and have more processing power. Each sensor node chooses a sink node in such a way that a reliable network is formed to collect data from the network. Therefore, assigning each node to a sink and handling the dynamics of these mobile sinks and change of assignments are also concerns of this layer. To provide more efficient dissemination of data, some sensors may process data streams, and provide replication and caching.

The distributed services layer contains distributed services for supporting mission critical management applications. These distributed services collaborate with each other. We have identified four major services with the corresponding opportunities. The *event detection* service supports reliable and timely detection of events. It is even capable of monitoring events in critical regions with mobile sensors. The *information processing* service deals with aspects of collecting and processing data. This service allows vast quantities of data to be easily and reliably accessed, aggregated, manipulated, filtered, disseminated, and used in a customized fashion by applications. Another service is *autonomous deployment*. This service supports detecting routing holes in the critical regions of the network and sends UAVs carrying sensors on-board to these regions to deploy additional nodes. It provides the ability of dynamically adapting the network to the requirements of the situation by increasing the coverage or repairing the connectivity of the network. *Tracking of responders* is also very important for safety-critical events. The *body area network* is used for this purpose. Collection of sensor readings from physiological and motion sensors and processing and integration of data from various sensors providing better insight into the user's state are the main concerns of this service.

All these services support mobility and reconfiguration. The coordination of the services is carried out by a control center. The cooperation strategies to be developed in the platform will open many opportunities for monitoring the full disaster scenario by integrating all the information to guide the operational forces to mitigate its effect or even to generate automatically actuations such as the activation of fire extinguishers.

A. Networking Layer Challenges for Mixed Mobile/Static WSNs

In a WSN, we can observe three communication data types. Sensors typically deliver data in *streams*: they produce data (e.g. temperature, humidity, etc.) continuously, often at defined time intervals, without having been explicitly asked for that data. This kind of data does not need to be transferred reliably since it has generally the same content as the previous reading. Second type of data type in a sensor network is *critical data*, for example, coming from the event region or the body area network on firefighters. The critical data transmission should be reliable and in a timely manner for mission-critical applications. The data exchange *from (mobile) sensors to (mobile) data sinks* is to be taken by the messages containing sensor readings (*streaming*) or detected events (*critical data*). These messages have to be forwarded until they reach a sink, where they will be presented to the control centre. The data sent *by (mobile) data sinks to (mobile) sensors* are generally new *commands* to specify or change the operation mode of the network (i.e. sample rate etc.). The command data is also important to delivery in time in case of events.

Each of these different data type needs different QoS level. The networking protocols should change their operation depending on the importance of the information in packets. For example, important events that are detected should be transmitted reliably at all costs, while sensor reading that are collected just to get an impression of the environment are not to be transmitted at all costs. The latter messages should give priority to the important events. The objective of the designed networking protocols is to adapt behavior based upon the required QoS.

We can summarize the basic challenges of sensors and networking for mobile WSN in mission critical management applications as follows:

Latency – The objective of the networking protocols is to minimize latency i.e. time between the generation of information and the delivery of packet to its destination device. Especially, *latency* should be reduced for packets travelling in the direction of the sink.

Reliability – How reliable the communication between nodes will depend on type of communication data. Although the wireless transmission and multihop routing can cause packet losses in WSN, the objectives of the networking protocols are to provide reliable communication for *critical data* and *commands* from gateways. The networking protocols should ensure that the sensing data is being transmitted to the destination successfully. We address the reliability of the dynamic WSN in the point-multipoint routing scenarios by a data-centric approach.

Dynamics and Self-adapting – The networking protocols should be able to deal with mobility of WSN devices. Expected speeds range from running persons to rapidly moving UAVs or vehicles: 0-50 km/h. Handling mobility in wireless sensor networks focuses on how to create new connections quickly for mobile sensors while maintaining a reasonable QoS level. Moreover, the devices self-organize at power-up and quickly reconfigure as devices join, leave or move around in the network. They also adapt to changes in the network traffic and propagation conditions. These capabilities enable mobility of individual devices or the entire network, and minimize installation effort, which is one of the requirements of the AWARE platform.

Current data-centric routing protocols generally assumes rather static networks, leading to strong performance degradation in dynamic environments e.g. GRAB (GRAdient Broadcast) [4]. A network wide reflooding of routing setup messages is the common solution to network topology changes. The situation gets worse when the data sink moves and a stable network is hardly possible to form. In our research, we try to maintain the communication when sensors move, such that less energy is used to re-setup the network.

Heterogeneity – In AWARE WSN, we have different types of sensors on different device classes. These different sensor platforms have to cooperate with each other to achieve a common task – mission critical management.

IV. A ROUTING PROTOCOL FOR MIXED MOBILE/STATIC WSN

This section will focus on the routing algorithm for mobile WSN. In WSNs, a typical mode of communication is from multiple data sources to a (*mobile*) data sink, rather than point-to-point communication between a pair of nodes [5]. In our research, we shift the focus from the *address-centric* approach (finding short routes between pairs of addressable end-nodes) to a more *data-centric* approach (finding routes from multiple sources to a single destination based on data types, which allows in-network aggregation of redundant data). Data-centric technologies have been proposed to perform in-network aggregation of data to yield energy-efficient dissemination in WSNs [5]. However, not much work in the data-centric routing domain has been done in relation to the dynamics of WSNs. In this section, we focus on the dynamic aspects of AWARE scenario and present a new reliable cost-based, data-centric routing algorithm (RCDR) for AWARE WSN.

A. Global Gradient and Global Cost Setup

RCDR proposes a *global gradient* paradigm. When a data sink wants to collect data from the network, it sends out a data query to set up a *global gradient* in the entire network. While this query message propagates in the network, each sensor establishes its own cost value toward this sink. Then any data sent towards the sink follows through the *global gradient* by multipath routing. The multipath degree is controlled by the *premium cost* of the data. *Sensor movement adjustment scheme* and *Sink movement compensation scheme* efficiently resume the disrupted *global gradient* by local interactions between sensors. Thus, reflooding, which takes a lot of energy in the network, is reduced to a minimum, while still maintaining the reliability of the network. When the source node has processed the data from the surrounding sensors, it sends the aggregated report to the sink via the *global gradient* as shown in Figure 3. To increase the reliability of these aggregated data, they are sent via multiple adjustable routes to the data sink.

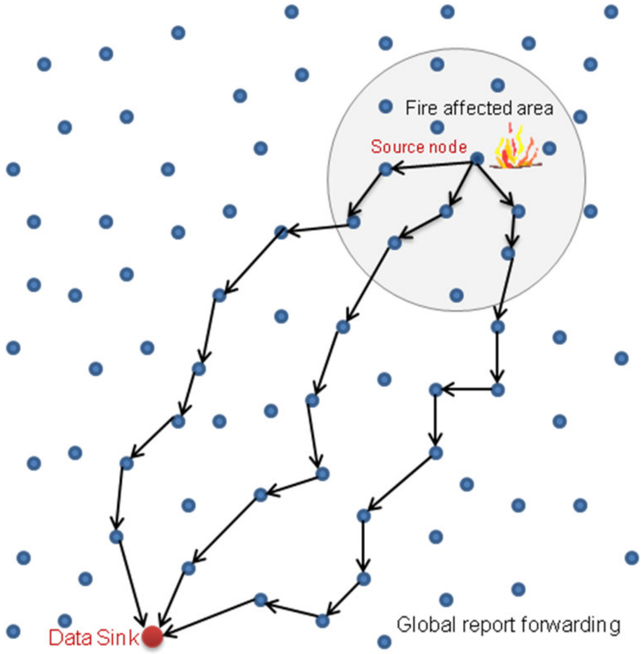

Figure 3. RCDR Overview

The gradient setup follows flexibility approach for the cost concept, in order to control the characteristics of data forwarding. Moreover, *waiting time* and *forwarding probability* are used to minimize the delay and reduce the broadcast storm problem. A broadcast storm happens when a message that has been broadcast across a network results in even more responses, and each response results in still more responses, creating a snowball effect.

In our WSN, each node has a link cost table to all its neighbors. A link cost C_{ij} is the cost between neighboring nodes i to j. When the data sink wants to receive events, the following *global cost setup* steps are executed:

1. Sink sends a Data Query (DQ) to the network, and it sets $C_{DQ} = 0$
2. Each sensor i defines a cost C_i from itself to the sink node, and it initially sets $C_i = \infty$
3. If intermediate sensor i receives DQ from its neighbor j, it sets $C_i = min(C_i, C_{DQ} + C_{ij})$
4. Sensor i sets its Lowest Cost Neighbor (LCN) to the sensor j where it could transfer data with the lowest cost
5. After a random time out $T_w \in [T_{min}, T_{max}]$, sensor i rebroadcasts DQ with $C_{DQ} = C_i$ and a forwarding probability p_f

The last step ensures that the node only broadcasts once the same DQ message, although multiple copies could be received from different neighbors. After time out T_w, any copy of the same DQ message is ignored. After the *global gradient* setup, each node in the network should have a cost C_i and the whole network becomes a directed graph toward the sink. The node that did not receive a cost after the global gradient setup (because of collision or errors) will obtain one by the *sensor movement adjustment scheme*.

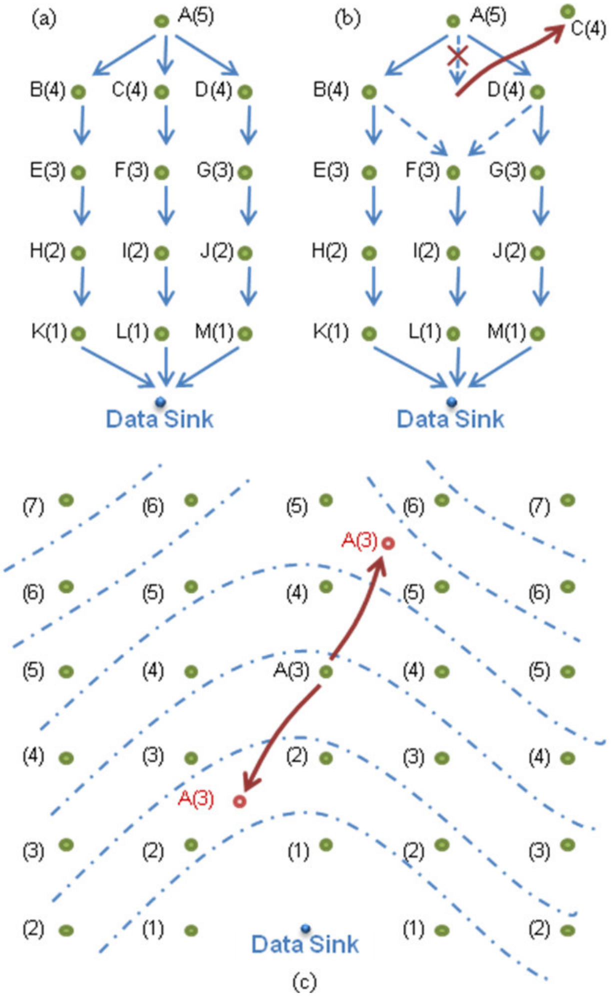

Figure 4. (a)(b)Sensor movement in a dense network and (c) The effect of sensor movement in two directions

B. *Sensor Movement Adjustment*

When the data travels in the network towards the sink, it flows through the lower cost nodes as shown in Figure 4 (a). If the connections between node A and node C breaks because node C moves away from node A, the data from node A can still go through both node B and node D. If the network density is high enough, the data will bypass the troubled link and will resume the reliable multipaths as shown in Figure 4 (b). Thus, the movement of an individual sensor node does not break the data transfer in its original location area.

The effect of a moved sensor node in the new allocated location area is also negligible. When a node moves, it could move in two directions in respect to the sink, as shown in Figure 4 (c). If node A moves into a higher cost area, it will have the lowest cost value among its neighbors. Then, it forwards any data from its neighbors, but, in turn, its neighbors forward none of its data. If node ***A*** moves into a lower cost area, it will have the highest cost value. Then, it forwards no data from its neighbors, but its neighbors forward any of its data. In both cases, node ***A*** is excluded from the network communications.

On the other hand, if more and more nodes are excluded from the data forwarding, the network becomes very unreliable. A network wide reset is needed from the sink to restore the gradient field. However, frequently resetting consumes too much energy from the energy restrained sensor nodes. A *sensor movement adjustment scheme* is designed to minimize the effect of sensor movement by local interactions.

The movement of sensor nodes in the network can be detected by the changes of its neighbors. A cross-layer approach similar to [6] allows the node to obtain neighbor information from the MAC layer in a very efficient manner. When a new neighbor joins or an old neighbor leaves, the sensor node takes different actions to adjust its own cost value.

If a node ***i*** notices that one of its neighbors ***j*** has disappeared, the following rules are executed:

1. If ***j*** is LCN, ***i*** sets $C_i = \infty$ and sends a Cost Query (CQ) to its neighbors
   - ***a.*** Each neighboring node ***n*** replies with its own C_n
   - ***b.*** If sensor ***i*** is LCN of sensor ***n,*** sensor ***n*** also executes the step (1) after a delay time
   - ***c.*** Sensor ***i*** sets C_i and LCN according to the steps in *global cost setup*
2. If ***j*** is not LCN, ***i*** ignores the mobility

If a new neighbor ***j*** comes in, the following steps are executed:

1. Sensor ***j*** initiates a Cost Update (CU) message and sets its value $C_{CU} = C_j$ (its cost to the sink)
2. Sensor ***j*** sends CU message to its neighbors
3. When a neighboring node ***n*** receives CU
   - ***a.*** If $C_n > (C_{CU}+C_{nj})$, it sets $C_n = C_{CU}+C_{nj}$ and LCN to ***j***

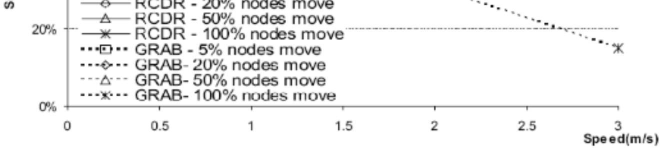

Figure 5. The success ratio of RCDR and GRAB under different speed of sensor movement

In the simulation, we try to discover the reliability of the *Sensor movement adjustment scheme* under different mobility conditions. A network of 60 sensors with a radio range of 150m is randomly placed on a rectangular area of 800x800m. We only set up a global gradient in the network and let one random sensor in the network generate data reports to the data sink. This gives a data flow for 10 minutes with a data rate of 2 packets/sec, after which another random node takes over. A certain percentage of sensors in the network follow the random walk model and move in the network and the other sensors remain static during the course of the simulation.

We compared the success ratio of data delivery between RCRD and GRAB under different moving speeds. As shown in Figure 5, when only 5% of the sensors in the network move with a speed of less than 2m/s, both RCRD and GRAB are rather reliable. When more sensors move in the network, the success delivery by GRAB decreases sharply. And when the speed is more than 2m/s, its success delivery ratio is less than 50%. This means that GRAB is very unreliable and almost non-operational in a dynamic network. On the contrary, RCDR shows a much better resilience to the changing topology due to the *sensor movement adjustment scheme*.

C. Sink Movement Compensation

In AWARE WSN, various scenarios require the data sink to be able to move in the network while collecting the sensing data. Any data loss caused by the sink movement decreases the reliability of the network. Particularly in the data centric route scenarios, any movement in the network will disrupt the network setups and results in data losses. When the sink moves, a network-wide broadcast is needed to restore the network gradient. This section introduces a new *sink movement compensation scheme* with negative gradient, which only requires a local update in order to compensate for the sink movement.

When the *global gradient* is set up in the network, sensing data can travel from the sensor nodes to the data sink by following the gradients. When the sink moves away from its current location, it should be able to first detect its own movement before it can carry out adjustment for the gradients.

The movement of the data sink can be detected by an additional localization mechanism. As only a limited number of sinks are needed to collect data, additional hardware on these sinks would not significantly increase the cost of the WSN.

When the sink detects its own movement (or relative movement), it follows the steps below:

1. Sink decreases C_{DQ} to -1 and broadcast a Degrade Update (DU) messages with a Hops-to-Live (HTL) field set to ***h***
2. Each node ***i*** receiving DU follows the steps of *global cost setup* and ***i*** sets its new cost as follows:
   - a. If HTL > 0, ***i*** lowers C_i and rebroadcast DU with HTL = HTL – 1
   - b. If HTL = 0, DU is not rebroadcasted anymore

The DU message propagates until it reaches the ***h*** hops neighbors. Thus, all the sensors in this degraded area set their costs one step lower towards the new location of the sink. This creates a small funnel with negative gradient around the sink in the *global gradient* field. As a result, when the data sent by the node reaches the vicinity of the sink, it will still flow to the new allocated sink by following the "small funnel". In this way, a network-wide readjustment is avoided by only a locally restricted gradient broadcast.

The sink repeatedly decreases the cost and increases the HTL of the DU messages when it moves again. So that the DU messages can still reach the original location of the sink, the degraded area will expand accordingly. The proposed relationship between the cost and HTL is $\boldsymbol{h} = \boldsymbol{H} - \boldsymbol{C_{DQ}}$, where $\boldsymbol{H}$ is a constant.

However, the efficiency of routing data through the degraded area decreases as the sink moves further away from its original location. Firstly, the diameter of the degraded area continues to increase. More nodes are involved in the local broadcast when the sink updates the gradient cost. Secondly, the data sent back by the nodes need to travel more to reach the sink than the shortest possible path. A network wide gradient reset is done by sending out new DQ messages is required to re-establish the gradient field in the network when the diameter of the degraded area gets too large compared with the network diameter.

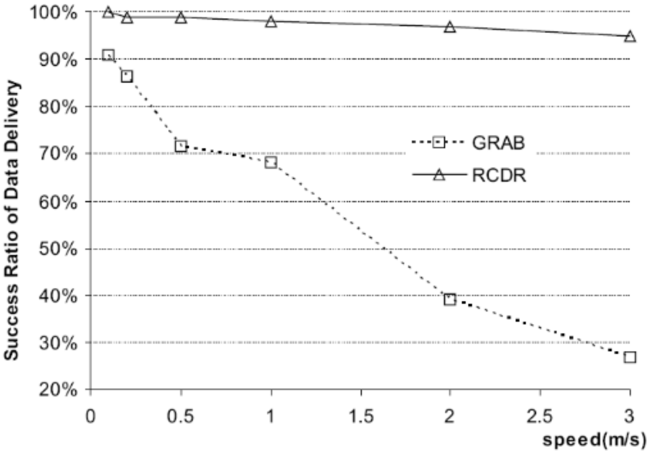

Figure 6. The success ratio of RCDR and GRAB under different speed of sink movement

In this simulation, we tried to find out the reliability of the network under *sink movement compensation scheme*. All the sensors, except the data sink, remained static during the course of the simulation. The sink follows a random walk point model with different speeds. Figure 6 clearly show that compared with GRAB, the *sink movement compensation scheme* improves the reliability of the network by 20% at lower speeds and more than 75% at higher speeds. The "disasters" situation of sink movement in GRAB is solved well by our scheme.

V. CONCLUSIONS

In this article, we address the opportunities and challenges of integration of mobile sensor network technologies into disaster management applications. The ultimate goal is to use the advantages of mobility with the low-cost embedded devices and thus improve the response time in mission-critical situations. We presented a data-centric routing protocol that supports establishment of global gradient that only sends the aggregated data from the center of the event to the data sink via multiple adjustable routes to increase the reliability. Also, the global gradient is supported by some local algorithms (sensor and sink movement schemes) which are designed to resume the network gradient when the network topology changes, especially the mobility of the data sink is solved by a negative gradient. The simulations and field tests confirm the feasibility and reliability of our routing protocol.

Consequently, we consider as future work to evaluate the performance of gossiping as an alternative to data-centric routing to improve the data delivery rate for multiple mobile data sinks. As such, any moving sink node can be inquired about events occurring elsewhere in the network.

ACKNOWLEDGMENTS

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