Combined Coverage Area Reporting and Geographical Routing in Wireless Sensor-Actuator Networks for Cooperating with Unmanned Aerial Vehicles

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Abstract. In wireless sensor network (WSN) applications with multiple gateways, it is key to route location dependent subscriptions efficiently at two levels in the system. At the gateway level, data sinks must not waste the energy of the WSN by injecting subscriptions that are not relevant for the nodes in their coverage area and at WSN level, energy-efficient delivery of subscriptions to target areas is required. In this paper, we propose a mechanism in which (1) the WSN provides an accurate and up-to-date coverage area description to gateways and (2) the wireless sensor network re-uses the collected coverage area information to enable efficient geographical routing of location dependent subscriptions and other messages. The latter has a focus on routing of messages injected from sink nodes to nodes in the region of interest. Our proposed mechanisms are evaluated in simulation.

Keywords: Wireless sensor networks, geographical routing, coverage area reporting, multi-sink networks

1 Introduction

The AWARE project (EU IST-2006-33579) considers self-deploying of wireless communication infrastructure with autonomous, unmanned aerial vehicles (UAVs) [1]. The AWARE platform targets to enable operation in sites which are difficult or impossible to access and which are without a pre-existent communication infrastructure. One of the focus application scenarios of the AWARE project is disaster management and civil security, in which wireless sensors collaboratively detect critical events (such as fire), or continuously monitor environmental conditions. In these applications, wireless sensors are the ears and eyes of the AWARE platform. They are added to the network on the fly and might be attached to mobile objects.

When wireless sensor networks (WSNs) contain multiple gateways, it is key to handle location dependent subscriptions efficiently to the set of gateways that service the particular region of interest. In the envisioned AWARE application scenarios, data sinks are interconnected via a powerful mobile ad-hoc network (MANET) and each communicates with a subset of the sensor network. Furthermore, data sinks collaborate with other MANET enabled devices to extract contextual information from the sensor network by inserting subscriptions. These subscriptions inform the wireless sensors which information needs to be published and are only inserted into the (local) sensor network if relevant.

In this paper, we propose a mechanism in which (1) the wireless sensor network provides an accurate and up-to-date coverage area description to gateways and (2) the wireless sensor network re-uses the collected coverage area information to enable geographical routing of location dependent subscriptions and other messages. The latter has a focus on routing of messages injected from sink nodes to nodes in the region of interest (Figure 1).

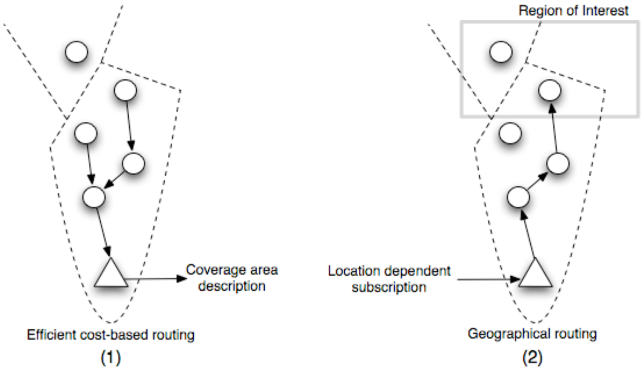

Figure 1: The WSN provides coverage area description to gateways (1) and reuse of collected information to route location dependent subscriptions (2)

2 The AWARE platform

The application scenarios considered in the AWARE project [1] motivate the research presented in this paper. The goal of the AWARE project is to develop a platform of self-deploying and self-organizing wireless sensor networks in collaboration with autonomous helicopters. The architecture of the AWARE platform comprises a number of heterogeneous sub-systems, which are described in relation to the global architecture in Figure 2. We have two key system layers of abstraction: the *sensor and dynamic networking layer*, and the *distributed services layer*.

The sensor and networking layer contains the sensor and the network protocols, which allow messages to be forwarded through multiple sensors taking into account the mobility of nodes and the dynamic change of topology. Assignment of each node to a sink in a reliable manner and handling the dynamics of the mobile sinks and sensors, and change of assignments are the concerns of this layer. The wireless sensor network can contain multiple mobile sinks e.g. attached to the helicopters, other vehicles, or humans. These sinks can communicate directly with each other via MANET links.

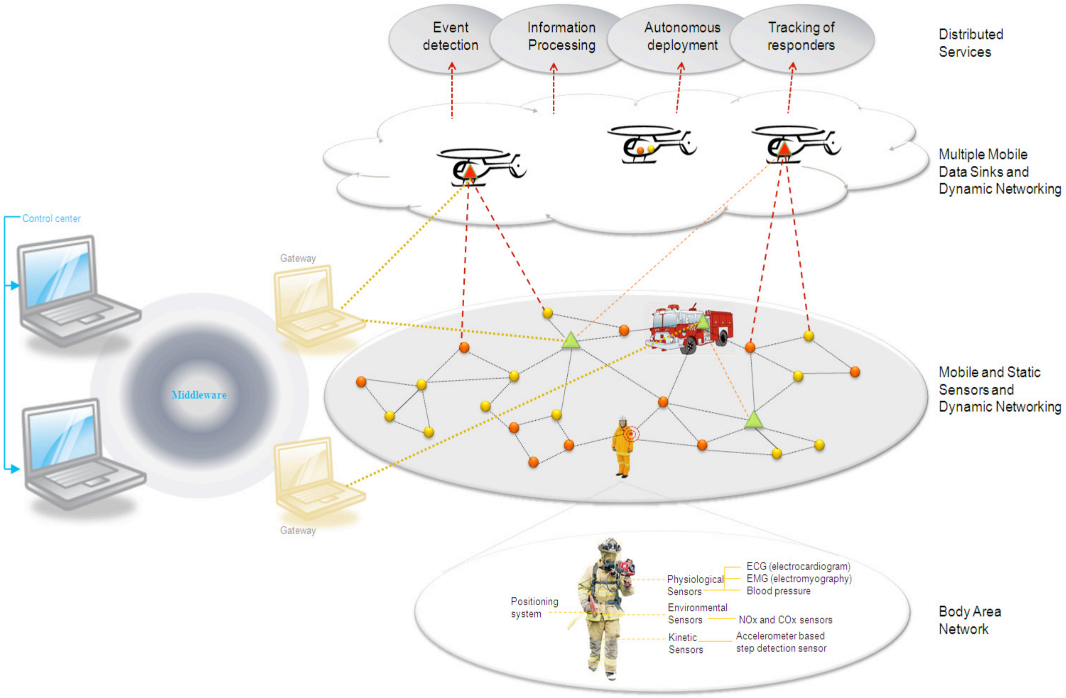

Figure 2: Overview of the AWARE platform architecture [1]

The distributed services layer contains different services to support mission critical management. We have identified four major services with the corresponding opportunities. The event detection 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. The autonomous deployment supports detecting routing holes in 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. Readings from sensors on responders are collected/processed/integrated to provide a better insight into the user's state.

The coordination of the elements in the system is carried out by a control center. The middleware depicted in Figure 2 provides a publish/subscribe communication interface between all devices such as UAVs, responders and sensors in the system. Devices that produce data register themselves as data publishers. The middleware then creates the corresponding abstract data channel that takes care of taking this information to other devices, which have registered themselves as subscribers to receive the data. Since the middleware tracks the data flow in the AWARE system, it can deliver the statistic data on system functionality to the control center to monitor the state of the system and its components. Also, the collected data can be archived in control centers for future information retrieval.

3 Related work

Nodes in a multi-hop wireless sensor network collaborate in forwarding packets to their destination(s) [2]. By the term routing protocol, we understand the mechanisms to select the ”best” node out of the set of nodes in radio range for forwarding the data to its final destination. In general, routing protocols try to optimize global performance (i.e. for example minimize network-wide energy consumption) by making local decisions on the best node to forward the data to. Another message routing strategy for wireless sensor networks is described in [3]: *geographical* routing. Instead of advertising an interest for data, or requesting to establish a route to a certain destination device, nodes use a routing technique based on node coordinates. Nodes are assumed to know their own position and the position of the sink node (i.e. the node where the data needs to be delivered). The idea is that nodes advertise data along with the coordinates where it must be delivered. Nodes closer to the sink node consider themselves candidates for relaying the message.

Face routing [4] routes packets along faces of planar network graphs by using simple *right hand rule* and proceeds along the line connecting the source and the sink. Although it guarantees to reach the destination, it does so with $O(n)$ messages, where n is the number of network nodes, and a simple flooding algorithm already reaches the destination with $O(n)$ messages. Also, it is not competitive with the shortest path algorithm in terms of cost depending on the number of hops between the source and the destination.

Adaptive Face Routing (AFR) [5] is the first algorithm competitive with the shortest path between the source and the destination. It basically enhances Face Routing [4] by the concept of an ellipse-bounding region restricting the searchable area. With a lower bound argument AFR was shown to be asymptotically optimal. On the other hand, AFR is not practicable due to its pure face routing concept. For practical purposes there have been attempts to combine greedy approaches (always send to the message to the neighbor closest to the destination) and face routing; for example *Greedy Perimeter Stateless Routing* (GPSR) [6], however, without competitive worst-case guarantees. There have been some other proposals for practical purposes to combine Greedy routing with face routing like the GOAFR and GOAFR+ algorithms by Kuhn et al. [7,8], which remain worst-case optimal.

In most of these protocols, the packets are sent from source to a destination position. For some other scenarios like AWARE scenario given in Section 2, it is also sufficient for some packets (e.g. subscriptions, etc.) to reach any destination currently located in a given area (i.e. geo-casting). Yu et al. in [9] proposes *Geographical and Energy-Aware Routing* (GEAR) algorithm, which shows how to broadcast a message to all the nodes in a target region. GEAR uses greedy forwarding to forward packets to the nodes that are always progressively closer to the centroid of the target region, whilst trying to balance the energy consumption at the intermediate nodes. Once the message is delivered to the centroid of the target region, it then uses restricted flooding, namely *Recursive Geographic Forwarding*, to broadcast the message all remaining nodes in the given region.

There are some other protocols based on *window spanning infrastructure* (WSI) for routing to the specified message window (i.e. destination region). In this approach, the message first is forwarded towards the message window by an end-to-end routing protocol. Once the message reaches the window, an infrastructure within the message window is built along with the message propagation. The method in [10] uses a Greedy technique to find a routing path from message originator to a node N_c located at the center of the message's spatial window. This first part of the routing is similar with the approach used in GEAR. For the routing inside the window, the framework proposed in [10] uses two different approaches namely *WinFlood* and *WinDepth*. The *WinFlood* algorithm consists of a constrained parallel flooding, where a node broadcasts the message to its neighbors only if its own location is inside the message's spatial window. The alternative solution, *WinDepth*, is based on depth first search policy.

As we have seen from the related works given in this section, the first step of the window message processing techniques is generally based on Greedy approach which cannot guarantee that a routing path to a node in the message's spatial window will be found. The main difference between the protocols is observed in the second phase that is the routing inside the specified message window. However, our approach uses a different technique, based on *coverage area description*, in the first phase of the routing that is forwarding the packet from source to the given area. In the following sections, our approach is described in detail.

4 Distributed coverage area reporting

In this section, we describe how the sensor network is partitioned in the case of multiple data sinks and how the description of coverage area per sink is established.

4.1 Multi-sink partitioning of the sensor network

We assume that each of the nodes in the wireless sensor network has the ability to obtain an estimate of its position. This can be either by localization mechanisms [11-15], GPS or by other means (e.g. [16]). Whenever a node publishes information, it is augmented with the current position of the node.

Assume that several gateways are deployed in a certain area and that each of these gateways connects to one or more wireless sensors, which in their turn are part of a multi-hop network structure. In this setup, it is beneficial for e.g. bandwidth reasons to divide the sensor nodes between the gateways. Multi-hop routing of messages in the WSN is highly optimized for e.g. energy-efficiency (e.g. messages travel via shortest reliable paths) or latency (e.g. paths with congestion are avoided) [2,17]. The efficiency of the network can be affected if messages need to be delivered at a particular gateway, while –from routing perspective- another gateway is more attractive. Therefore, another strategy of grouping nodes with gateways is to let the grouping be implicitly created by minimizing routing cost functions [18-20]. In that case, all topology constraints, such as connectivity, and load balancing are taken into consideration. Basically, the routing strategy of the wireless sensor network determines which node reports to which gateway. However, gateways have no prior knowledge on what area they cover and this information needs to be (dynamically) collected to efficiently deal with subscriptions that are valid only for particular regions. Note, that due to dynamics in the topology or node mobility, the set of nodes reporting to a particular gateway might change over time. This stipulates that a dynamic mechanism for collecting the coverage area is required. This mechanism can be passive or active, as we describe below.

A passive mechanism to obtain a coverage area description is to update the coverage area description whenever the gateway receives a sensor reading that is augmented with position information. Nodes that are not publishing data (e.g. no subscription has been injected into the WSN that matches their properties) would be excluded from the coverage area description. To overcome this problem, nodes can periodically publish their position information to the selected gateway, even if there is no relevant subscription active for them. A drawback of the passive mechanism is the amount of data that has to be transported within the wireless sensor network.

In this paper, we investigate a pro-active mechanism to establish a coverage area description. We let nodes (distributed) keep track of the local coverage area and apply a form of compression to the coverage area description: we describe the area with its *convex hull* i.e. a minimal and ordered set of coordinates that envelops the positions of the nodes that belong to a particular gateway. In such way the gateway can be efficiently informed of the service area while we reduce the amount of information each node needs to store and transmit/receive.

4.2 Establishing a coverage area description

In this section, we discuss our design for distributed coverage area reporting. Nodes determine the routing cost function to any of the gateways that can be reached within the (connected) multi-hop network. This requires gateway to announce themselves periodically through broadcast messages. We assume that the broadcast messages reach all sensor nodes in the connected network before the next broadcast period of the gateway, such that nodes can be sure that within one period all gateways can be discovered. Next, nodes select a gateway with minimum routing cost and send all their generated messages to this gateway. Meanwhile, nodes keep track of coordinates that are either (1) included in messages carrying sensor data, or (2) are explicitly transmitted. Using the received coordinate information, the nodes create a local version of the coverage area description, represented as a convex hull:

1. Nodes start with a convex hull with one coordinate, namely their own coordinate. This coordinate is either programmed during deployment or estimated using localization mechanisms.

2. When coordinates are received, the node checks if these need to be added to the local convex hull. If so, the node adds the coordinate to the local convex hull and (potentially) removes coordinates that are no longer on the convex hull. Nodes only store coordinates that describe the convex hull of their local coverage area and other coordinates are discarded.
3. To keep the local convex hull accurate, a time out mechanism is implemented to remove old coordinates from the local convex hull. The time out of a particular coordinate is reset, when a node receives a message containing the coordinate.

Periodically, the local convex hull is transmitted to neighboring nodes closer to the selected gateway. These nodes merge the received convex hull with their local convex hull. Optionally, the convex hull is reduced using some form of compressing before transmitting (in order to limit memory usage by the algorithm and energy consumption by reducing the size of transmitted/received coordinate list). Since most data will be augmented with position information in practice, explicit transmission of coordinates and local convex hulls would not be required to happen often. However, we do consider periodic transmission of local convex hulls to capture the area covered by none data producing sensor nodes.

With the above described algorithms, the WSN gateways are informed of the convex hull describing their coverage area. Next, this information can be used to optimize handling of position dependent information e.g. gateways can use the information whether a certain subscription is relevant for their coverage area. If not, the sink can decide not to insert the subscription in the WSN, which in the end saves energy and prolongs the lifetime of the wireless sensor network.

5 Geographical Routing using Local Convex Hulls

In the previous section, we discussed how nodes create local convex hull to facilitate coverage area reporting of partitions of the wireless sensor network. In this section, we discuss how this information can be reused to enable efficient geographical routing in the wireless sensor network, in particular the geographical routing of location dependent subscriptions that are injected at the data sink of the WSN and need to be executed in a particular region of the sensor deployment.

In fact, the local convex hull describes the area from which messages flow through the node towards a data sink. Our geographical routing exploits this information by using opposite routing paths i.e. a certain area can be reached by a node, if the area overlaps with the local convex hull description. We note that the reverse routing paths are not necessarily the cheapest paths in terms of routing costs. However, we assume that reverse routing paths are feasible to reach the particular region.

First, we have a closer look at the structure of location dependent subscriptions. We assume that these subscriptions consist of two parts: (1) a description of the area in which the subscription must be executed, and (2) a command sequence (e.g. sensor types, sample rates, critical thresholds, aggregate functions etc.). In this work, we are mainly concerned with the first part of the subscription.

We define $R = \{r_0, r_1, ..., r_n\}$ to be the coordinate set describing the region of interest extracted from the subscription, $L_i = \{l_0, l_1, ..., l_m\}$ the (compressed) local coverage area description of node i and p_i the (estimated) position of node i. The region of interest in the subscription R is in fact described as a closed polygon. We assume that the closed polygon is also a convex hull and that a subscription is generated per closed area. However, our assumptions about R are merely a choice to reduce the complexity of the routing functions described below.

5.1 Routing and executing decisions

The routing decisions in our proposed geographical routing protocol are straightforward. Upon receiving a location dependent subscription, sensor nodes or data sinks analyze the region of interest polygon in the subscription and carry out the following:

1. *Execute decision with forwarding* - The node checks if its (estimated) position is within the region of interest polygon in the subscription. If so, the device executes the subscription and propagates the subscription to neighboring nodes. Note that the execution of subscriptions might also be controlled with additional constraints in the subscription.
2. *Forward decision without execution* - The device checks if its local coverage area description geographically overlaps with the region of interest polygon. If so, the node decides to propagate the subscription e.g. using restricted flooding (Section 3).

The execute decision is in fact similar to the well-known point-in-polygon problem; the node checks if its position p_i falls within the polygon R. In [21] several algorithms are presented to efficiently determine if a point sits in a polygon. In general, these algorithms need complex geometrical operations, however, if we assume that R is a convex hull, the decision if p_i falls in R can be reduce to checking if p_i is geographically *left* to all line segments $r_0 \rightarrow r_1$, $r_1 \rightarrow r_2$, ..., $r_n \rightarrow r_0$. Then, per line segment in R, a node has to carry out three multiplications and two additions/subtractions. Namely, coordinate u is left of line segment $v \rightarrow w$ if

$$\det \begin{bmatrix} v_x & w_x & u_x \\ v_y & w_y & u_y \\ 1 & 1 & 1 \end{bmatrix} > 0 \qquad (1)$$

In fact, this function checks if the (oriented) area given by the vectors $v \rightarrow w$ and $w \rightarrow u$ is positive and hence u is left of the line segment $v \rightarrow w$.

The forward decision is more complex. The node checks if R geographically overlaps with L_i and if so, the node forwards the subscription. We distinguish two cases when the areas R and L_i (partly) overlap: one or more coordinates from the sets R or L_i fall within the polygon of the other set *or* one or more line segments from R intersects with line segment(s) from L_i. If neither of the cases is true, the node discards the subscription.

The same methodology as used in the execution decision can be to check the first case. If the case evaluates true, the areas overlap and the subscription can be forwarded without evaluating the second case. In [22, 23] describe how the intersection point of lines can be efficiently checked using determinant calculations. Per set of line segment 6 multiplications and 9 additions are required. Whenever two line segments intersect, the check is aborted and the subscription forwarded.

6 Evaluation of routing accuracy

In this section, we evaluate the proposed combination of coverage area and geographical routing in terms of routing accuracy i.e. how well the proposed mechanisms deliver messages to the region of interest defined in a subscription. We define the following metrics:

- *Execution ratio* (ER) - The ratio of nodes that are within the region of interest and execute the subscription with the total number of nodes within the region of interest. This metric measures how well the routing is able to deliver the subscription to the region of interest.
- *False execution ratio* (FER) - The ratio of nodes that are outside the region of interest and execute the subscription with the total number of nodes outside the region of interest. Energy is wasted when subscriptions are executed outside the region of interest. The false execution ratio measures this effect.
- *False injection ratio* (FIR) - The ratio of data sinks that inject the subscription while none of the nodes in its partition executes the subscription with the total number of data sinks. Irrelevant subscriptions lead to higher energy expenditure in the WSN partition when injected. We measure this effect with the false injection ratio.

We implemented the coverage area reporting and geographical routing in a Matlab WSN model and study the accuracy of the routing under different conditions. Table 1 summarizes our simulation parameters. Nodes are randomly deployed in the deployment area. However, disconnected networks are discarded.

Table 1: Simulation parameters

Data sinks	5
Sensor nodes	95
Deployment area	400m x 400m
Transmission range	65m
Region of interest	square, 80m x 80m, center of deployment area
Runs per scenario	100

Table 2: Simulation results in ideal case (a), and simulation results with compression of local convex hull to 3 coordinates (b)

	(a)		**(b)**	
	Mean	**Std.dev.**	**Mean**	**Std.dev.**
ER	1.00	0.00	0.97	0.13
FER	0.00	0.00	0.00	0.00
FIR	0.08	0.13	0.11	0.14

First, we evaluate the proposed geographical routing without any disturbing factors (Table 2). In this scenario, our geographical routing scheme is able to deliver the subscription accurately to the region of interest as can been seen from the ER and FER results. However, some false injections exist. This is due to the fact that the convex hull of the coverage area can overlap with the region of interest without a node being present in the target area. This effect is due to our choice of describing the services area with a convex hull.

Next, we introduce compression of the local convex hull. In this scenario, each node reduces its local convex hull to at most three coordinates. This reduces execution time of the algorithms and message sizes nodes receive and transmit. We study the effect of the more energy-efficient operation on the accuracy metrics (Table 2). On average we see a 3% reduction in ER and a slight increase in FIR. We conclude that when compression is applied our algorithms are less successful in delivering the subscription to the target area.

In our scheme, we assume that nodes are able to estimate their position (Section 4.1). However, most localization schemes introduce errors and the accuracy of position estimates is also affected by node mobility. We model these errors as additive normal distributed errors to both x and y coordinates of nodes. As consequence, the service area descriptions do not match the reality exactly and the execute decision gets less accurate.

Table 3: Simulation results with additive normal distributed error with $\sigma=5$ and $\sigma=10$ in position estimates

	$\sigma=5$		$\sigma=10$	
	Mean	**Std.dev**	**Mean**	**Std.dev.**
ER	0.86	0.21	0.77	0.27
FER	0.00	0.01	0.01	0.01
FIR	0.07	0.12	0.09	0.12

Table 3 summarizes the effect of errors in position estimates on our geographical routing scheme. The results show that ER decreases with increasing position estimation errors. Additionally, we see that FER is indeed affected by inaccurate position estimates. In the worst case (σ=10), 1% of the nodes outside the region of interest are executing the subscription on average.

7 Conclusion and future work

In this paper, we proposed a mechanism in which the wireless sensor network provides an accurate and up-to-date coverage area description to gateways. In our approach, nodes use their (cost-based) routing protocol to select a gateway to report to. Next, nodes keep track of all coordinates that flow through them towards the selected gateway and create actively a local coverage area description that is periodically forwarded a neighboring node along the route to the gateway. This ensures that coverage areas are up-to-date, even if nodes are e.g. mobile and that coverage area reports include nodes that are not publishing sensor data. As result, gateways are informed of the area they service. Additionally, we let nodes reuse the collected information to efficiently route location dependent subscriptions to a particular target region.

Simulation shows that the proposed routing is able to deliver the subscriptions accurately to the region of interest in the simulated scenarios. On average 97% of the nodes in the target area is reached, even if local convex hulls are extremely reduce to three coordinates (for energy and memory consumption reduction). However, inaccurate position estimates result in significant lower execution ratios (86% and 77% in the simulated cases) and introduce even executions of subscriptions outside the region of interest.

In our future work we intend to compare our geographical routing scheme with existing geographical routing protocols. Energy-efficiency is one of the key metrics to consider. Additionally, we are interested in a comparison with respect to the presented accuracy metrics.

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