Distributed Coverage Area Reporting for Wireless Sensor Networks

Lodewijk van Hoesel, Paul Havinga

Department of Electrical Engineering, Computer Science and Mathematics, University of Twente
Postbus 217, NL-7500 AE Enschede, THE NETHERLANDS
E-mail: l.f.w.vanhoesel, p.j.m.havinga@utwente.nl

***Abstract*—In order to efficiently deal with subscriptions or other location dependent information, it is key that the wireless sensor network informs the gateways what geographical area is serviced by which gateway. The gateways are then able to e.g. efficiently route subscriptions which are only valid in particular regions of the deployment.**

In our distributed approach of establishing a description of WSN coverage area per gateway, we let nodes keep track of the convex hull of the coverage area. In this way, gateways are efficiently informed of the service areas, while we limit the amount of information each node needs to store, transmit and receive.

I. Introduction

The AWARE project (EU IST-2006-33579) considers self-deploying of wireless communication infrastructure with autonomous, unmanned aerial vehicles (UAVs) [11]. 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 route location dependent subscriptions efficiently to the set of gateways that service the particular region of interest. In the envisioned AWARE application scenarios, gateways are interconnected via a powerful mobile ad-hoc network (MANET) and each communicate with a subset of the sensor network. Furthermore, gateways 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 the wireless sensor network provides an accurate and up-to-date coverage area description to gateways. In their turn, gateways can then handle subscriptions more efficiently.

II. Approach

Our approach is as follows. 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 localisation mechanisms [2], [7], [10], [6], [4], GPS or by other means (e.g. [5]). The exact format of the coordinates is not of interest, but we assume that throughout the WSN, the same coordinate system is used. 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. We distinguish two strategies to assign sensor nodes to gateways:

1) **Metric space decomposition** — The deployment area is divided into regions e.g. sensor nodes report to the gateway that is *geographically* closest. This is known as Vonoroi decomposition of the area.
   Given all positions of the gateways, a gateway can exactly determine which area should served by it and nodes can determine to which gateway they should report. Note that this strategy implicitly assumes that when a node is in the coverage area of a gateway that it also can communicate with the gateway. In practical cases, this is not necessarily the case.
2) **WSN topology** — Multi-hop routing of messages in the WSN is highly optimised for e.g. energy-efficiency (e.g. messages travel via shortest reliable paths) or latency (e.g. paths with congestion are avoided) [1], [9]. 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 [12], [8], [3]. In that case, all topology constraints, such as connectivity, and load balancing are taken into consideration.

In our approach, we consider grouping of nodes that takes the WSN topology 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. 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.

III. Distributed coverage area reporting

In this section, we discuss our design for distributed coverage area reporting.

A. Algorithm

Nodes determine the routing cost function to any of the gateways that can be reached within the (connected) multihop 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 (Section III-B). The mechanism to do this is fairly simple for the two dimensional case: the node checks (using a determinant calculation of a 3x3 matrix) if the coordinate is geometrically left of all line segments that make the convex hull, if so, the coordinate is ignored. Otherwise, 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 neighbouring nodes closer to the selected gateway. These nodes merge the received convex hull with their local convex hull. Optionally, the convex hull is reduced (Section III-C) 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.

When the routing trees change e.g. due to node failure or mobility, the routing mechanisms make sure that generated messages still arrive at a gateway (if the network remains connected). In our distributed convex hull creation algorithm, this has the following consequences:

- The new gateway can update immediately its coverage area as soon as the messages arrive (if the messages carry coordinates of the source node).
- The gateway that previously served the node(s) is not actively updated of the change of the routing tree. The old coordinates of the convex hull describing its coverage area will disappear due to the coordinate timeout mechanism. It can thus occur that gateway have overlapping coverage areas. This does not affect the functioning of the handling of position dependant information, yet it reduces its efficiency. Communication between gateways can play a prominent role in the solution to this.

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 dependant information e.g. gateways can use the information whether a certain subscription is relevant for their coverage area. If not, the gateway 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.

B. Creation of coverage area descriptions

Let the function $\Omega : \mathbf{C} \rightarrow \mathbf{H}$ create a minimal (ordered) set of coordinates $\mathbf{H} \subseteq \mathbf{C}$ that envelops the coordinates $\mathbf{C} =$

$\{c_0, c_1, \ldots, c_i\}$. **H** is called the convex hull of the coordinate set **C**. Note that $|\mathbf{H}| \leq |\mathbf{C}|$.

Now if a new coordinate c_{i+1} is added to the set **C**, the following holds:

$$\Omega\{\mathbf{C}, c_{i+1}\} = \Omega\{\mathbf{H}, c_{i+1}\} \tag{1}$$

The proof follows directly from the fact that **H** envelops **C**. We conclude that it is possible to build a convex hull from a set of coordinates. Consequently, nodes only have to store (ordered) coordinates on the convex hull, opposed to all coordinates.

Next, we present a simple algorithm that builds a convex hull from a set of coordinates. The nodes and gateways implement this function to keep their local coverage area description accurate.

Let **A** be the set of coordinates that a node or gateway receives (**A** is either a single coordinate which is extracted from a sensor reading or a locally broadcasted convex hull) and let **L** be a convex hull representing the (local) coverage area description. The coordinates **L** are always ordered such that they describe the convex hull counter clockwise. Initially, **L** contains the coordinates of the node itself.

If **A** is an empty set, our algorithm applies no changes to **L**, otherwise per coordinate in the set **A** the following procedure is executed:

1) Define a_i as current coordinate to investigate from the set **A**. If this coordinate is already present in **L**, move on to the next coordinate.
2) Define $n = |\mathbf{L}|$ as the number of coordinates in the convex hull:
   - **One coordinate ($n = 1$)** — Add the coordinate to **L** and order the coordinates such that the coordinate with lowest y value is first in the set.
   - **Two coordinates ($n = 2$)** — Check if a_i is geographically left of the line $l_1 \rightarrow l_2$ (see below). If so put the coordinate at the third position in the convex set **L**, otherwise insert the coordinate between l_1 and l_2. Our algorithm judges if coordinates from **A** need to be inserted into **L** by checking if a coordinate is *left* from a line segment (hence the counter clockwise ordering of coordinates in **L**). Coordinate u is left of the line segment $v \rightarrow w$, if

     $$\det \begin{bmatrix} v_x & w_x & u_x \\ v_y & w_x & u_y \\ 1 & 1 & 1 \end{bmatrix} > 0 \tag{2}$$

     In fact, this function checks if the (oriented) area given by the vectors $v \rightarrow w$ and $v \rightarrow u$ is positive and hence u is left of the line segment $v \rightarrow w$.
   - **More coordinates ($n > 2$)** — Check for all line pairs ($l_1 \rightarrow l_2$, $l_2 \rightarrow \ldots$, $\ldots \rightarrow l_n$, $l_n \rightarrow l_1$) if the coordinate a_i is geographically left of the line segment. If so, continue with the next coordinate pair.

     If it is not left of the line segment, then record the starting coordinate of the line as begin point b. Continue with the next line segments until a_i is left of the line again. Remove all coordinates from b until the current line segment and insert a_i instead.

C. *Compression of coverage area descriptions*

The proposed mechanism for distributed coverage area reporting requires that nodes (periodically) transmit the convex hull that describes the local coverage area. Message sizes grow with the number of coordinates that are part of the convex hull. Consequently, larger coverage area descriptions result in higher energy expenditure of the nodes. Therefore, compression (i.e. approximation of the convex hull with a smaller coordinate set) is an attractive option to limit resource consumption, such as energy and bandwidth.

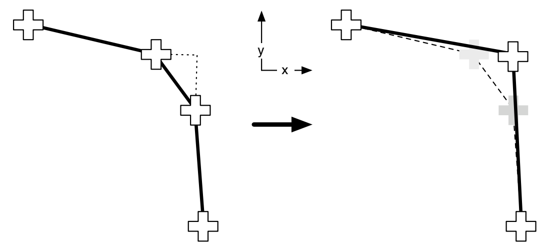

Fig. 1. Compression reduces the number of coordinates in the convex hull

Our compression algorithm accepts as input a convex hull and a maximum convex hull size c. Until the convex hull has been reduced to maximum size c, our algorithm does the following. First, it finds two coordinates l_i and l_{i+1} which represent the shortest line segment in the convex hull. These two coordinates are removed from the convex hull and are replaced with one coordinate, such that l_i and l_{i+1} are both left of the new coordinate. A compression step is illustrated in Figure 1.

IV. Simulation results

We implement our distributed coverage area reporting algorithm in a OmNet++ simulation model (http://www.omnetpp.org). Our main objective is to demonstrate that the proposed mechanisms result in accurate coverage area descriptions at the gateways.

As underlying routing protocol in the simulated WSN, our model uses shortest path routing. However, other routing protocols can be used that e.g. consider other routing cost functions. Our simulation setup uses 297 static nodes and 3 randomly chosen gateways. All are deployed in a 140 x 80m area and have a circular transmission range of 30m.

The nodes do not report any data to the gateways, but once every ten simulated seconds they transmit a coverage area report to a neighbouring node that is closer to their selected (closest) gateway. We model this scenario, because it is the most critical one. It models that no subscription is active yet in the network, while the gateway still needs to be able to get insight in the region it services.

Whenever nodes or gateways receive coordinates, the local coverage areas are updated and —optionally– compressed before they are propagated to other nodes. At each node we record the summed size of all coordinate sets it receives and the size of the coordinate set it propagates.

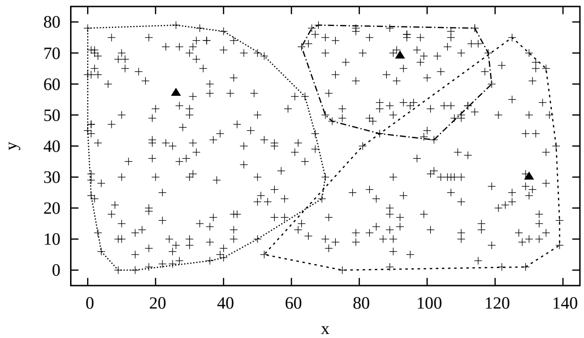

Fig. 2. Coverage area description as collected by the gateways (triangles). No convex hull compression is applied

Figure 2 shows the coverage area descriptions as the three gateways have collected in our simulation. The coverage area descriptions clearly indicate three regions associated with the three gateways. The regions slightly overlap due to the position of the gateways and all nodes are within at least one service area.

TABLE I
Statistics of reported convex hull sizes. No convex hull compression is applied

	Received	Transmitted
Average	0.40	1.15
St.dev.	3.62	0.94
Maximum	55	12

In this particular network setup, we look at the sizes of the reported convex hulls. Nodes report on average quite small convex hulls: on average 1.15 (Table I). Reason for this is that many nodes are not forwarding data of other nodes. These leaf nodes therefore report only a single coordinate (i.e. their own position). In our simulations, this is the case for 285 nodes. The remaining 15 nodes forward messages from other nodes and deal with larger convex hulls. On average the reported convex hulls for these nodes contain 4.1 coordinates, with a maximum convex hull of 12 coordinates (Table I).

In practical implementations, this vast amount of coordinates would demand quite some resources from nodes. If we assume that coordinates are represented by four bytes, the total amount of 48 bytes would not fit in a single, 32 byte packet of TinyOS (a commonly used programming framework for WSNs, http://www.tinyos.org). To limit e.g. energy consumption of nodes and the bandwidth that is used, we apply compression to coverage area reports before they are transmitted.

Figure 3 shows the coverage areas as collected by the gateways when compression is applied. In our simulation, each node compresses its report to at most four coordinates. The figure clearly shows marks of compression (e.g. bottom left in Figure 3), yet all nodes are within at least one coverage area.

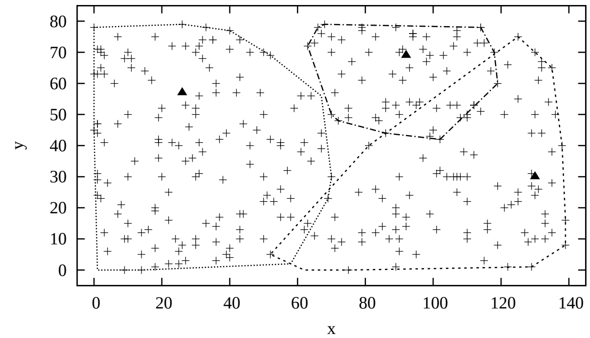

Fig. 3. Coverage area description as collected by the gateways. Convex hull compression to 4 coordinates is applied

When compression is applied, nodes report on average smaller convex hulls than when no compression is applied (Tables I and II): at most 4 coordinates. If we neglect the 285 leaf nodes, the transmitted coverage area reports contain on average 3.0 coordinates. Compression is thus a valuable mechanism to reduce the resource consumption of nodes, however, in practical applications, a trade off should be made between the compression factors and the accuracy of the coverage area report.

TABLE II
Statistics of reported convex hull sizes. Convex hulls are compressed to 4 coordinates

	Received	Transmitted
Average	0.39	1.09
St.dev.	3.53	0.49
Maximum	55	4

V. Conclusion

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 their turn, gateways can handle subscriptions or other location dependent information more efficiently.

In our approach, nodes use their routing protocol to select a gateway to report to (e.g. because the route to that gateway has the lowest routing cost). 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 neighbouring 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.

In our future, we want to exploit the locally create coverage area descriptions for (geographical) routing within the wireless sensor network.

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