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Hop-distance based addressing and routing for dense sensor networks without location information

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Abstract

One of the most challenging problems in wireless sensor networks is the design of scalable and efficient routing algorithms without location information. The use of specialized hardware and/or infrastructure support for localization is costly and in many deployment scenarios infeasible. In this study, the wave mapping coordinate (WMC) system to address the localization problem is introduced for dense sensor networks and a highly efficient routing algorithm applicable to WMC systems is proposed. The performance of the WMC system is evaluated through simulations and compared with the performance of geographic routing without location information (GWL). The WMC system is found to be highly scalable and efficient with a simple system set-up procedure. Simulation studies confirm the high routing performance of WMC systems which is comparable to the performance of greedy geographic routing with the availability of location information.

Keywords: Sensor networks; Routing; Localization

1. Introduction

Wireless sensor networks (WSN), with the availability of small and inexpensive sensing devices that can be produced in large numbers, have a wide range of application areas. These applications include, but are not limited to, environmental monitoring, real-time data collection in diverse environments, monitoring complex machinery and processes, query based applications, distributed surveillance applications, habitat monitoring, and intelligent transportation systems. Due to the wide range of application areas of WSNs, research efforts to enhance the communication capability and quality of sensor networks has been growing over the last five years.

One of the major research topics for WSNs is the design of simple, efficient, and scalable routing algorithms. One such approach is the *geographic routing* [1–3] where geographic locations of sensors are used for making routing decisions. In *greedy geographic routing* [4], a node forwards packets to a neighboring node whose distance metric to the destination is the smallest. The distance metric is usually chosen as the geographic distance which is computed using

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node coordinates. In addition to the distinct advantages like simplicity and topology independence, geographic routing algorithms have also disadvantages: Geographic routing requires location information in every sensor node, which poses a rigid restriction on its usage since such information may not be available in many deployment scenarios.

Highly accurate localization can be achieved through the availability of a GPS device in each sensor node [5]. However, fast depletion of sensor energy sources and increased sensor costs arise as two major problems. Therefore, many schemes such as [6–8] propose to compute sensor locations without the use of GPS. Nonetheless, these solutions are based on reference infrastructures and the complexity of sensor nodes is increased with the required additional hardware. Due to these reasons, accurate location information is costly to obtain.

Routing in sensor networks without the availability of location information of sensors is a challenging task. Some recent methods aim to adapt geographic routing to environments without the location information of sensor nodes [9,10]. In [9], only a group of sensors do not know their coordinates while most others do. Hence, the problem of "lack of location information" is not fully taken into account in [9]. The geographic routing without location information (GWL) scheme in [10] uses neighborhood information to achieve localization without any reference infrastructure. GWL creates virtual coordinates of the sensors according to their neighborhood information. Then, routing is performed greedily using these virtual sensor coordinates. However, a large number of packet exchanges required by this solution incurs a high overhead. Furthermore, each sensor node needs to run complex optimization algorithms, increasing the sensor hardware complexity. Hence, although virtual coordinates of sensors represent a reasonably useful location information, the GWL scheme remains a complex solution, which is not desirable for WSNs.

In this study, the *wave mapping coordinate* (WMC) system and a highly efficient routing scheme specifically designed for WMC systems is proposed. WMC systems provide approximate localization when no location information is available in dense sensor networks. Furthermore, neither special hardware nor infrastructure support is required. It is found that WMC system makes it possible to efficiently and easily perform routing of packets. The performance of routing in WMC systems is tested for various *node density* and *sensor field size* values. The results are compared with those obtained by greedy geographic routing (GGR) with the availability of location information. It is observed that our new routing scheme is highly efficient in terms of packet delivery and path length. The performance of routing in WMC systems is also compared with the GWL method proposed in [10]. It is found that the routing scheme in WMC is superior to GWL both in terms of packet delivery performance and simplicity.

2. Wave mapping coordinate (WMC) system

2.1. Properties of sensors and assumptions

The sensing applications in this study are assumed to require dense and spatially random sensor network deployments. Neither complex hardware nor signal processing capability is envisioned for sensors. Sensors have very limited, if any, mobility and they do not necessarily have time synchronization. Furthermore, nodes have identical wireless communication capabilities.

One of the major aspects of the WMC system is that there are no specific nodes in the network that carry special properties. For instance, high-capacity sensors or beacons that have GPS hardware are not utilized. Due to the simplicity of sensor nodes and as the node functionality is kept at a minimum, such systems can be deployed densely at low costs. The high number of sensors in turn helps to gain more accurate sensing, higher robustness, and better coverage of the sensing area.

2.2. The WMC system

The WMC system was initially introduced in [11]. The construction of the sensor network coordinate system is based on the hop distances of sensor nodes to two designated sensors called *wave sources*. The nodes with the same pair of hop distances to the wave sources form groups as explained in Section 2.2.1. Hence, a pair of hop distances, one to the first source and the other to the second source, is sufficient to define a particular group. A third hop distance, hence a third wave source, can be used but is not necessary since an address ambiguity can be eliminated easily by the use of these two wave sources, as explained in Section 2.2.1. Therefore, the use of more than two wave sources in a two dimensional sensor network is unnecessary.

The system set-up of WMC systems is performed in two stages:

- Network-wide broadcasting stage.
- Group-wide broadcasting stage.

2.2.1. Network-wide broadcasting stage

The WMC system is based on grouping of sensor nodes according to their *hop distances* to two wave sources.

Definition. *Hop distance to WS*: The least number of hops that a packet sent by a WS traverses to reach a particular node.

The Network-wide broadcasting stage, which is the first stage of the set-up of a WMC system, is performed for this grouping purpose. Since there are two wave sources, every sensor node has two hop distance values, one for each of the two wave sources. These hop distances are regarded as the identification numbers for sensors. Hence, the pair of hop distances of a node is called the *ID-pair* of the node. Sensors having identical ID-pairs are in the same WMC group.

Definition. *WMC group* $G_{i,j}$: Group of sensors whose hop distances to the first and second wave sources are i and j, respectively. These nodes all have the ID-pair ij.

To determine the hop distances of network sensor nodes to the wave sources, each of the wave sources broadcast a packet to the network.

Definition. *The hop counter*: The *hop counter* field in a broadcast packet is used to keep track of the number of hops that the packet has traveled so far. This field is incremented every time the packet is rebroadcast by a node.

Every node in the network keeps track of the hop counters of the packets they receive. Upon receiving a packet originating from a particular wave source, a node checks the packet's hop counter to determine whether its value is less than those of the previously received packets from the same wave source. As a result of such updates of hop counters at nodes, all nodes determine the hop distances to the wave sources, and hence their ID-pairs, at the end of the network-wide broadcasting stage.

Definition. *Region*: The locality where a group of sensors with identical ID-pairs are found. For instance, the area where the sensor nodes of the group $G_{i,j}$ are located is a region.

The packets associated with a source node propagate in the network outwards from the source, forming a wave-like structure. Fig. 1 illustrates a WMC system showing this wave-like structure when node density is infinite. Each hop of this propagation can be thought to be a wave. The waves from the two wave sources intersect to form WMC regions. For instance, in Fig. 1, group $G_{5,8}$ is confined in a region that is five hops away from the first wave source and at a hop distance of 8 to the second wave source. The regions of a WMC system are found to have a perfectly regular orientation with well-defined sizes and shapes when the network density is infinite. Regions are also highly regular for high node density, which is not the case when the node density is low.

2.2.1.1. Address ambiguity. An observation of Fig. 1 is that there exist two different regions hence two different groups with the same ID-pair, that can be located in the sensor field. This situation is called the *address ambiguity*. The coordinate system is required to distinguish any pair of groups that have the same pair of hop distances from the sources. Such groups are found at opposite sides of an imaginary line connecting the sources. Therefore, the system should differentiate between the two halves of the sensor field that are separated by the imaginary line connecting the locations of the source sensors. This can be achieved through dissemination of a third identifier, i.e., a codeword, to the network

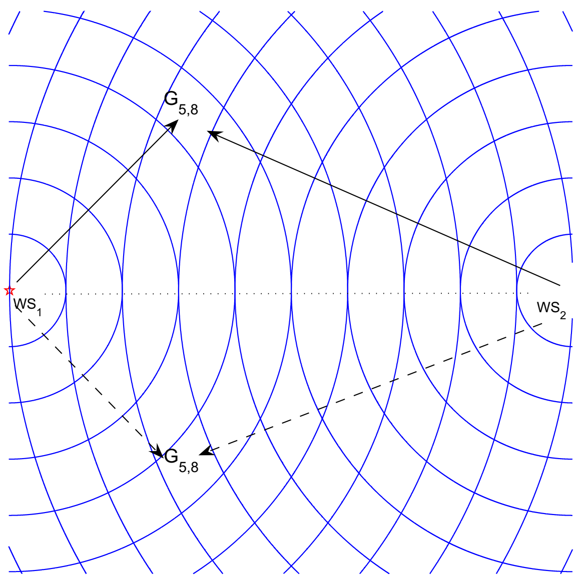

Fig. 1. A WMC group.

such that the identifiers of the two halves are different. This identifier can be sent by the groups where the wave sources are located. A codeword sent to one side should be blocked so that it is not diffused to the other side. This is achieved by the groups that are located on the imaginary line connecting the wave sources. Such groups are called *borderline* groups. The details of address ambiguity elimination can be found in [11].

A simpler way to eliminate the address ambiguity is to locate the source sensors along an edge of the sensor field. In this way, groups with identical ID-pairs cannot exist since the waves of a particular ID-pair can intersect only once, forming a unique group with that ID-pair. In this study, the performance of WMC systems is evaluated by placing the wave source along an edge of the sensor field as illustrated in Fig. 2. However, the methods described in this paper can easily be extended to a general wave source placement.

The effect of the distance between the two wave sources on a WMC system is investigated in [11]. When the wave sources are located close to each other, large regions with high uncertainty in location are formed along the line connecting the wave sources. Furthermore, with increasing separation of wave sources, higher regularity in the shapes and locations of WMC regions is observed. Therefore, the sensor nodes are located as far as possible from each other in a WMC system.

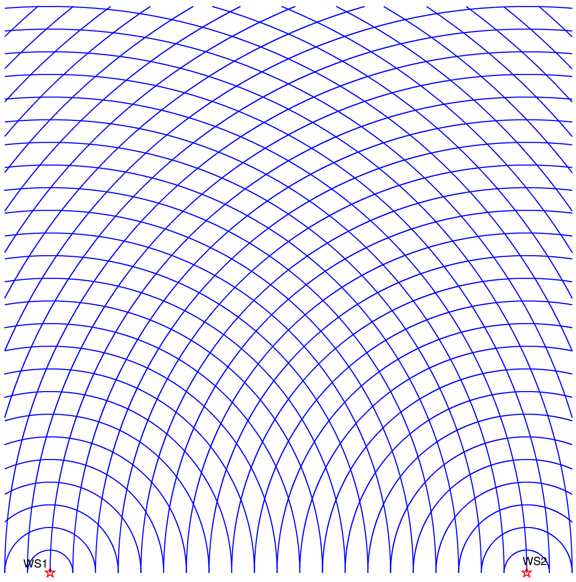

Fig. 2. The WMC grouping structure when sources are placed at one edge of the sensor field.

2.2.1.2. The effect of finite node density on WMC grouping structure. The WMC system is a collection of sensor groups $G_{i,j}$ for $1 \leqslant i \leqslant N1$ and $1 \leqslant j \leqslant N2$, where $N1$ and $N2$ are the largest ID1 and ID2 values that appear in the network, respectively. However, not every possible ID-pair (i,j) for $1 \leqslant i \leqslant N1$ and $1 \leqslant j \leqslant N2$ exists in a sensor network with random node locations and a finite node density. When the node density is infinite, the regions of the WMC system have circular boundaries and a perfectly regular arrangement of groups is obtained. On the other hand, the regularity of group shapes and locations deteriorate with finite node density. Edge effects arise as dominant factors that determine group locations near the borders of the sensor field. Furthermore, the WMC system may include groups with ID-pairs that are not envisioned by the ideal infinite density case. The introduction of these extra groups affects the routing algorithm used in the coordinate system, which is explained in more detail in Section 3.

2.2.2. Group-wide broadcasting stage

After setting up the group structure of the WMC system during the network-wide broadcasting stage, each group initiates a group-wide broadcasting stage. This second stage is performed for determining peer-to-peer communication paths between nodes of a given group. Each node sends a packet to its neighbors to indicate its ID-pair. In this way, a neighborhood table of neighboring nodes and their ID-pairs is prepared in each node. Table 1 shows the neighborhood table of node 132 in Fig. 3.

After nodes prepare their neighborhood tables, group-wide broadcast packets which include the neighborhood tables are sent. As the name implies, these packets are limited to the group nodes and are not forwarded out of the groups of their sources. Using the neighborhood information, unicast paths of the least number of hops between group nodes are determined using Dijkstra's algorithm within groups. As a result, a forwarding table that provides path information to other nodes of a group is obtained in each node. Note that the paths inside G have usually very small number of hops. The forwarding table of a node N in a group G includes:

- Indexes (which have local significance within G) of the nodes in G.
- The ID-pairs of the neighbor groups of G that are accessible from nodes of G in one hop.
- Unicast shortest paths to other nodes of G from N.

Table 1
WMC neighborhood table for node 132 in group $G_{7,7}$ of Fig. 3

WMC neighborhood table for node 132 in group $G_{7,7}$	
Node index	Group ID
435	$G_{7,8}$
765	$G_{7,8}$
234	$G_{7,7}$
21	$G_{7,7}$
788	$G_{8,7}$
785	$G_{7,7}$
2323	$G_{7,7}$
56	$G_{7,7}$
911	$G_{7,7}$
23	$G_{7,7}$
838	$G_{7,7}$
398	$G_{7,7}$
908	$G_{7,7}$
341	$G_{7,7}$

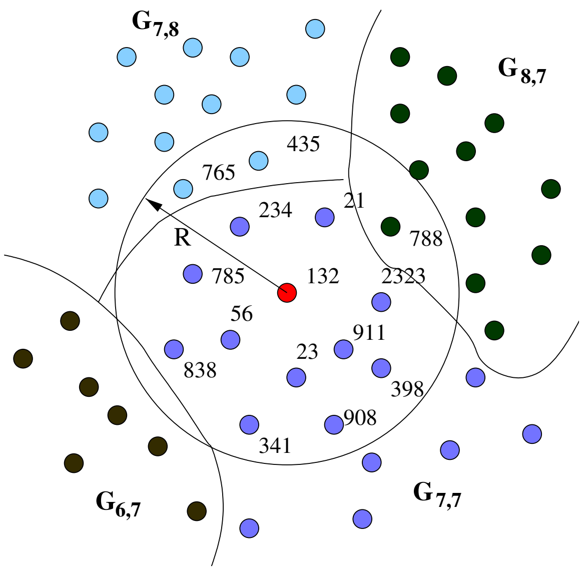

Fig. 3. An example neighborhood of a node.

3. Routing in WMC systems

In sensor networks where exact location information is not available, the grouping structure is a useful guideline to determine the paths between two nodes. In WMC systems, routing between groups and routing within a group are performed as two separate tasks defined as follows:

- Inter-group routing: routing between WMC groups.
- Intra-group routing: routing within a WMC group.

Packets sent from a source group S to a destination group D include the following information in a WMC system:

- ID-pair of S.
- ID-pair of D.
- Destination node's index in D.
- Set of the ID-pairs of the groups in the order they appear along the path from S to D.
- Set of the ID-pairs of visited groups by the packet.

The list of group ID-pairs form a guideline for routing a packet towards its destination. This sequence of groups is created by the inter-group routing mechanism. When necessary, the same mechanism is used to make corrections along the path. Inside a group, the packet is routed via intra-group routing decisions, which are developed based on the local neighborhood information. In the following sections, inter-group and intra-group routing methods are described in detail.

4. Inter-group routing

In inter-group routing, a packet is sent from one group to another over a series of intermediate groups. The major aim of the inter-group routing scheme is to determine how the next group that the packet in transmission will be forwarded to should be selected so as to minimize the overall path length from source to destination. However, this path of groups is not determined by the source group alone. In fact, this path is the result of a series of decisions made by each group on the path.

The initiator node: In a WMC system, the inter-group routing decision for a packet is made by the node that receives the packet from a neighboring group. This node is called the *Initiator* node. A node determines that it is an Initiator node if it is the packet's intended next node and if the packet that it receives comes from a neighbor node which belongs to a neighbor group. In the following, we present two approaches used in the inter-group routing scheme in order to find the next group to forward a packet. These are called the *Greedy Approach* and the *Imaginary Line Approach*.

4.1. The greedy approach

As explained in Section 2.2.1, the ID-pair assigned to a group designates that group's hop distances to the two wave sources. Hence, the numbers ID1 and ID2 in an ID-pair (ID1, ID2) can be considered as the coordinates of the group $G_{\mathrm{ID1,ID2}}$ in a two-dimensional space called the *hop-ID space*. A unit distance in such a space is one hop distance.

Definition. *Hop-ID space*: A two-dimensional space, where the first and second dimensions are the hop distances to the first and second wave sources, respectively.

In the hop-ID space, the distance between any two groups $G_{\mathrm{ID1}_i,\mathrm{ID2}_i}$ and $G_{\mathrm{ID1}_j,\mathrm{ID2}_j}$ is defined as follows:

$$D_{ij} = \sqrt{(\mathrm{ID1}_i - \mathrm{ID1}_j)^2 + (\mathrm{ID2}_i - \mathrm{ID2}_j)^2}. \quad (1)$$

Using the distance measure in Eq. (1), a group-wide greedy approach can be used to select the next group among the neighbor groups to forward the packet to. Each group determines the distances of its neighboring groups to the destination group according to Eq. (1) and selects the neighbor group with the least hop distance to the destination group. Hence, the distance metric in such a greedy scheme becomes the distance in the two dimensional hop-ID space.

Despite the simplicity of the greedy approach in the hop-ID space, a major drawback limits its usage for inter-group routing. In Fig. 4, the inefficiency of this approach is illustrated via an example source–destination group pair. The source group $G_{7,7}$ routes its packets to the destination group $G_{13,9}$. Using Eq. (1) to choose the next group, the sequence of groups is obtained as $G_{7,7}$–$G_{8,8}$–$G_{9,9}$–$G_{10,9}$–$G_{11,9}$–$G_{12,9}$–$G_{13,9}$, which is referred to as Path_1. However, as node density increases, the shortest path between any two sensors becomes more linear in a two-dimensional network. Furthermore, for infinite node density, the shortest path is on a perfectly straight line.

Hence, when the node density is high, the source group $G_{7,7}$ and the destination group $G_{13,9}$ in Fig. 4 are connected through a different sequence of groups. This sequence of groups is found on a line when node density is infinite and more linear with increasing density. Therefore, this path can be referred as the *optimal path* between the center of the source and destination groups. The optimal

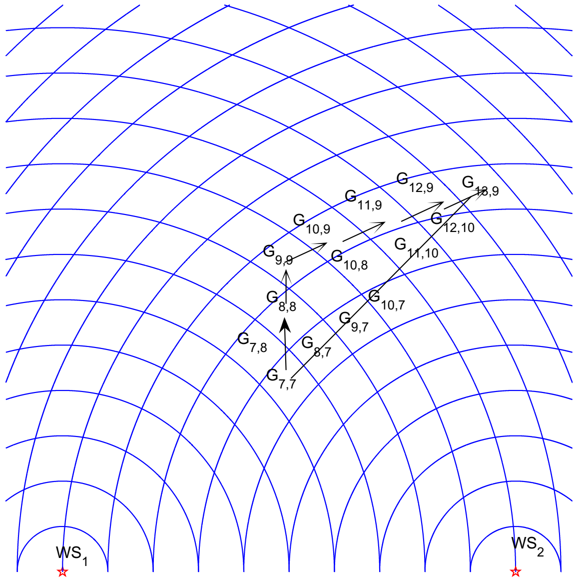

Fig. 4. Illustration of the inefficiency of greedy approach in inter-group routing in hop-ID space.

sequence of groups, Path_2, is $G_{7,7}$–$G_{8,7}$–$G_{9,7}$–$G_{10,7}$–$G_{10,8}$–$G_{11,10}$–$G_{12,10}$–$G_{13,9}$. It should be noted that the number of groups in the optimal path may be larger than the number of groups found by the greedy approach. This shows that a path with fewer groups is not necessarily closer to the optimal path than one with a larger number of groups. The major conclusion of this example is that the greedy approach, which chooses the neighboring group with the least distance in hop-ID space to the destination, is not an efficient way of determining the sequence of groups in inter-group routing for networks with high node density. However, as explained later in this section, the greedy approach is still used in some cases.

4.2. The imaginary line approach

Since the Greedy approach is not sufficient for inter-group routing, a method that considers the optimal path between the source and destination groups is required. As shown in Fig. 4, when node density is infinite, this optimal path between the source group and the destination group can be determined by drawing a line between the center of the source group, $G_{7,7}$, and the center of the destination group, $G_{13,9}$. This line passes through a sequence of groups which is the optimal sequence of groups as seen in Fig. 5. The imaginary line approach uses the grouping structure found in

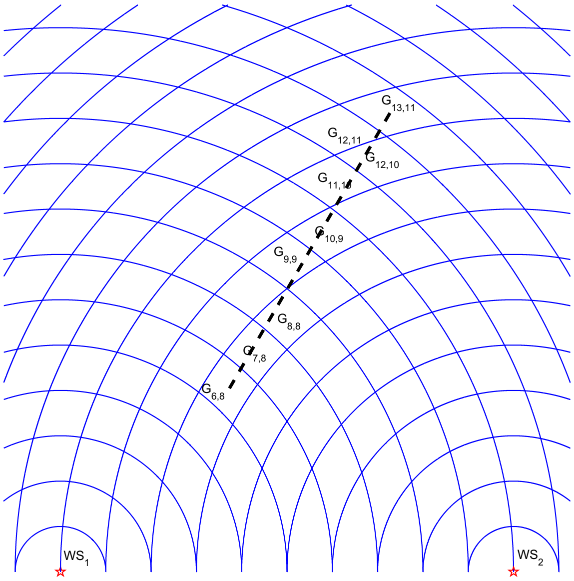

Fig. 5. Finding the group sequence according to the pattern of groups found in the ideal infinite density case.

WMC systems with infinite node density to determine the path of groups on this line analytically. In fact, the line can be uniquely defined by its end points which are the center points of the source and destination groups.

In the following, we first outline the calculation of the source and destination group centers in the hop-ID space to calculate the line of optimal path. We write the line equation in Cartesian coordinates after a change of coordinates from the hop-ID space to a Cartesian space. Since the unit distance in this Cartesian space is one hop distance, it is called a *hop-based Cartesian space*. Using the hop-based Cartesian coordinates of the source and destination group centers, the equation of the line of optimal path is obtained. Then, the groups that the line passes through are determined. This is achieved by finding the intersection points of the shortest path line with the boundaries of WMC regions. Then, intersection points are used to determine the path of groups between the source and destination groups. Finally, using the hop-ID space coordinates of these points, the group path is obtained. In the following sections, these procedures of the imaginary line approach are explained in detail.

4.2.1. Determining coordinates of a group center point

Due to the lack of exact geographic location information, the center point locations of groups should be defined in a way that uses the hop-ID space. Considering the ID-pairs of a group as its coordinates in the hop-ID space, the center of the group can be defined to be located at certain hop distances from the two wave sources.

The approximate hop distances of the center point C of a group $G_{\mathrm{ID1,ID2}}$ to the two source sensors can be computed as follows:

$$\begin{aligned} h_1 &= (\mathrm{id1} + (\mathrm{id1} - 1))/2, \\ h_2 &= (\mathrm{id2} + (\mathrm{id2} - 1))/2. \end{aligned} \tag{2}$$

In Eq. (2), id1 and id2 refer to the hop distance to source 1 and source 2, respectively. h_1 and h_2 are the approximate hop distances from the center of the region where group $G_{\mathrm{id1,id2}}$ is located to the wave sources WS_1 and WS_2, respectively. For instance, in Fig. 6, the center point C of the group $G_{13,9}$ has the coordinates $(h_1, h_2) = (12.5, 8.5)$ in hop-ID space.

4.2.2. Change of coordinates

After the hop-ID coordinates of the center points are obtained, the locations of the group centers of source and destination groups should be mapped from the hop-ID space to a hop-distance-based Cartesian space to calculate the line equation. A unit distance in such Cartesian coordinates corresponds to a distance of communication range R which corresponds to a unit hop distance when node density is infinite.

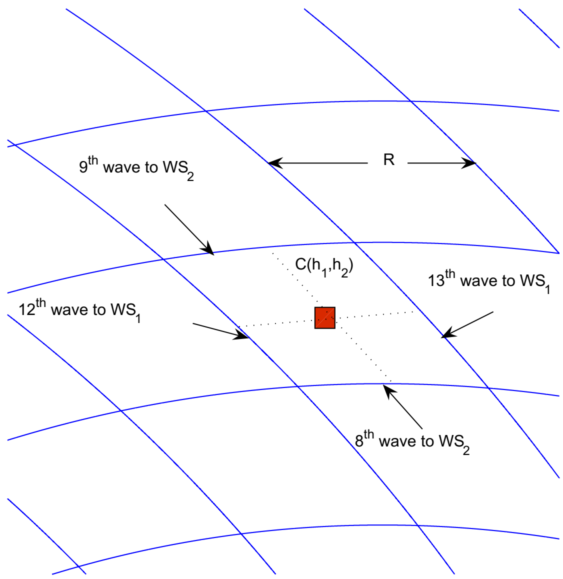

Fig. 6. Center point of a group.

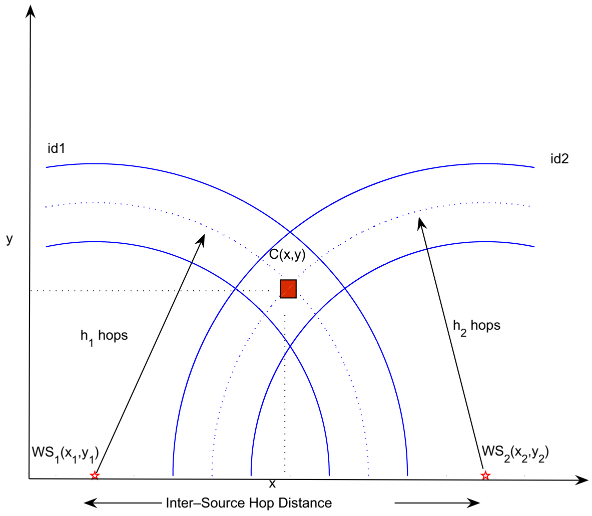

Fig. 7. The illustration of the variables for finding the approximate coordinates of the center point of a sample group.

The center of a group with the hop-ID coordinates (h_1, h_2) can be considered to be the intersection of two circles, as shown in Fig. 7. One of these circles is centered at WS_1 and has a radius of h_1 and the second circle is centered around WS_2 with a radius of h_2. The Cartesian coordinates of the intersection point $C(x, y)$ of the two circles in this figure can be found by using the equations of the circles:

$$\begin{aligned}(x - x_1)^2 + (y - y_1)^2 &= (h_1)^2,\\ (x - x_2)^2 + (y - y_2)^2 &= (h_2)^2.\end{aligned} \tag{3}$$

In Eq. (3), (x_1, y_1) denotes the Cartesian coordinates of the first wave source, while (x_2, y_2) is the Cartesian coordinate pair of the second wave source. The circle equations in Eq. (3) are solved for x and y which designate the Cartesian coordinates of the group center. The following is the expression to find the y coordinate of the intersection point.

$$y = \frac{-p \mp \sqrt{p^2 - 4r}}{2}, \tag{4}$$

where $p = \frac{2cd - 2dx_1 - 2y_1}{1 + d^2}$ and $r = \frac{c^2 - 2cx_1 + x_1^2 + y_1^2 - h_1^2}{1 + d^2}$. The variables c and d in these equations are given as follows:

$$\begin{aligned}c &= \frac{h_1^2 - h_2^2 + y_2^2 - y_1^2 + x_2^2 - x_1^2}{2(x_2 - x_1)},\\ d &= \frac{-(y_2 - y_1)}{x_2 - x_1}.\end{aligned} \tag{5}$$

Once y coordinate is calculated it is substituted in any one of the circle equations, equation set 3, to obtain the x coordinate of the center point C.

In order to have a consistent routing scheme, all nodes should use the same set of wave source coordinates while computing the Cartesian coordinates of the group center points. For ease of calculation, we assume that both wave sources are located on $y = 0$ line. The hop distance between the wave sources called the *inter-wave source hop distance* (IWSHD) can be disseminated by the second wave source during the network-wide broadcasting stage. Using this info, all nodes can make the same calculations. Note that x_1 and x_2 can be arbitrarily chosen as long as $x_2 = x_1 + IWSHD$.

4.2.3. Equation of the line of optimal path

After obtaining the Cartesian coordinates of the source and destination region centers, the equation of the line connecting them can easily be obtained in Cartesian coordinates. This equation can be defined in a parameterized way in Eq. (6). In this equation, (x_s, y_s) is the coordinate pair of the source group, and (x_d, y_d) constitutes the coordinate pair of the destination group.

$$\begin{aligned}x(t) &= (x_d - x_s)t + x_s,\\ y(t) &= (y_d - y_s)t + y_s.\end{aligned} \tag{6}$$

This line can be written in a non-parametric format, as well

$$y = \frac{(y_d - y_s)}{(x_d - x_s)}(x - x_s) + y_s. \tag{7}$$

When the x coordinates of the center points are equal, i.e., $x_d = x_s$, the following equation can be used to define the line:

$$x = \frac{(x_d - x_s)}{(y_d - y_s)}(y - y_s) + x_s. \tag{8}$$

In Eq. (6), the variable t is defined such that $0 \leqslant t \leqslant 1$. For $t = 0$, Eq. (6) gives the center point (x_s, y_s) of the source group, and for $t = 1$, the center point (x_d, y_d) of the destination group is obtained. For values of t between 0 and 1, the points on the line segment $[S, D]$ connecting the two center points S and D are obtained. Hence, t can be used to determine whether a point satisfying the line equation, Eq. (7) or Eq. (8), is located on the line segment between the center points of the source and destination groups. A point on the line is not in the line segment $[S, D]$ if $t < 0$ or $t > 1$.

4.2.4. Determining the inter-group path

The inter-group path is the sequence of groups from the source group to the destination group through which the line of optimal path passes. To determine the groups on this path, the intersection points of the optimal line of path with a group of wave circles are utilized. These wave circles are those whose hop distances to their centering wave sources are less than $\max(\mathrm{ID}i_s, \mathrm{ID}i_d)$. Here, $\mathrm{ID}i_s$ and $\mathrm{ID}i_d$ designate the hop distances of the source and destination groups to the wave source WS_i, respectively.

The Cartesian coordinates of the intersection points are substituted for $x(t)$ and $y(t)$ in the parameterized line equation, Eq. (6), to obtain the t value. Then, the points for which $0 \leqslant t \leqslant 1$ are selected and sorted in ascending order. The set of the selected intersection points are denoted as $P_1, P_2, P_3, \ldots, P_N$, where N is the number of intersection points. In Fig. 8, the points A–E are such intersection points.

The points in the interval $[P_i\ P_{i+1}]$ belong to a single region in a WMC system. Hence a common ID-pair designates these points. The ID-pair of this region can be obtained using the hop distances of points P_i and P_{i+1} to the wave sources. The hop distances h_{1_i} and h_{2_i} of a point P_i to the wave sources can be found easily by substituting the Cartesian coordinates of this point in Eq. (3).

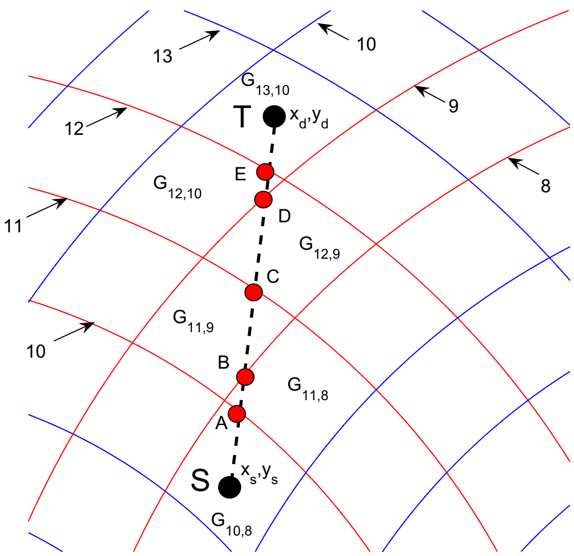

Fig. 8. An example set of intersection points in the line segment between two groups.

Denoting the hop distances of a point P_i by h_{1_i} and h_{2_i}, the points in the interval $[P_i\ P_{i+1}]$ have hop distances of values between h_{1_i} and $h_{1_{i+1}}$ to the first wave source, while their hop distances to the second wave source have values between h_{2_i} and $h_{2_{i+1}}$. Hence, the ID-pair of the region where these points are located is $(\lceil\max(h_{1_i}, h_{1_{i+1}})\rceil,\ \lceil\max(h_{2_i}, h_{2_{i+1}})\rceil)$.

As an example, in Fig. 8, the hop-IDs of the intersection points with ascending t values between $0 \leqslant t \leqslant 1$ are obtained as A: (10.0, 7.8), B: (10.3, 8.0), C: (11.0, 8.5), D:(11.7, 9.0), and E: (12.0, 9.2). Let the center of the source group be S and the center of the destination group be T. The intervals to consider are $[SA]$, $[AB]$, $[BC]$, $[CD]$, $[DE]$, and $[ET]$.

Considering the interval $[AB]$ between points A and B, the points in this interval have a common ID-pair that can be found by using the hop distances of the points A and B to the wave sources. Since the hop distance of point A to the first source is 10.0 while the hop distance of point B to this wave source is 10.3, the points in the interval have hop distances of values between 10.0 and 10.3 to the first wave source. Similarly, they have hop distances of values between 7.8 and 8.0 to the second wave source. Hence, the ID-pair of the group in between these two points is $(\lceil\max(10.3, 10.0)\rceil, \lceil\max(7.8, 8.0)\rceil) = (11, 8)$. Therefore, the group is $G_{11,8}$. Using this procedure, the group sequence from S to T is obtained as $P = [G_{10,8}, G_{11,8}, G_{11,9}, G_{12,9}, G_{12,10}, G_{13,10}]$.

4.2.5. Summary of the imaginary line approach

The imaginary line approach can be summarized in the following steps of operations:

1. The hop-ID space coordinates of source group center $S(h_{1s}, h_{2s})$ and destination group center $D(h_{1d}, h_{2d})$ are obtained using Eq. (2).
2. (h_{1s}, h_{2s}) is used in Eqs. (3) and (4) to find the Cartesian coordinates of the source center, (x_s, y_s). Similarly, (h_{1d}, h_{2d}) is used to find the Cartesian coordinates of the destination center, (x_d, y_d).
3. The line equation, Eq. (7) (or Eq. (8), if $x_s = x_d$) is used to obtain the Cartesian coordinates of the intersections of the line with a set of wave circles whose hop distances to their centering wave sources WS_i are less than $\max(\mathrm{ID}i_s, \mathrm{ID}i_d)$.
4. The Cartesian coordinates of the intersection points are substituted in Eq. (6) to obtain their corresponding t values.

5. All intersection points with $0 \leqslant t \leqslant 1$ are retrieved to form a set of intersection points found on the line segment connecting S and D. These points along with S and D are sorted in increasing order of t values. Hence, the set $\{S, P_1, P_2, \ldots, P_N, D\}$ is obtained, where $t_i < t_{i+1}$, $t_s = 0$ and $t_d = 1$, for $1 \leqslant i \leqslant N-1$.
6. The hop-ID space coordinates of P_i, for $1 \leqslant i \leqslant N$, are obtained by substituting their corresponding Cartesian coordinates in Eq. (3).
7. The hop-ID space coordinates of consecutive pairs of points in the set $\{S, P_1, P_2, \ldots, P_N, D\}$ are used to determine the ID-pair of the groups through which the line segment passes.

4.3. Combining the greedy and imaginary line approaches: inter-group routing

The grouping structure of the WMC system is designed for the case when node density is assumed to be infinite. Hence, the imaginary line approach outlined in Section 4.2 is derived using an *ideal group pattern*. However, when the node density is finite, group locations and shapes are not as regular as they are in the ideal infinite density case. Furthermore, some of the groups that are envisioned in Fig. 5 may not exist in the WMC system. For instance, if group $G_{3,4}$ has a neighbor group $G_{4,5}$ in the ideal infinite density case, there is no guarantee that these two groups are neighboring groups in case of finite node density. Moreover, either or both of the groups may not exist at all. Due to these reasons, the routing scheme of the WMC systems should be able to handle the irregularities that emerge as a result of finite node density.

4.3.1. Two types of WMC groups

When node density is finite, some extra groups may emerge other than the ones that are found in the infinite node density case. Since the inter-group routing scheme makes use of the regularity of the group pattern of WMC systems when node density is infinite, there should be mechanisms to deal with the irregularity induced by the existence of these extra groups. As a first step, the system should differentiate between two types of groups, namely, *regular* groups and *irregular* groups.

The following are the definitions of these two different group types that can be found in a finite density WMC system:

- *Regular group*: A group that exists in the WMC system in case of infinite node density.
- *Irregular group*: A group that cannot normally exist in the WMC system in case of infinite node density.

When the node density is infinite, the center point $C(h_1, h_2)$ of a group G is the intersection of two circles. One of these circles is centered at wave source WS_1 with a radius of h_1, while the center of the other circle of radius h_2 is wave source WS_2. Hence, the group center point C and the wave sources WS_1 and WS_2 are the corners of a triangle as illustrated in Fig. 9. Therefore, the type of a group can be determined by checking the triangularity condition of a triangle with side lengths h_1, h_2, and IWSHD. The check for the triangularity condition is provided in Algorithm 1.

Algorithm 1. Determines the type of a group G, with ID-pair (ID1, ID2), with inter-wave source hop distance IWSHD

```
if |ID1 − IWSHD| > ID2 OR |ID2 − IWSHD| > ID1 OR
|ID1 − ID2| > IWSHD then
    G is a Regular Group
else
    G is an Irregular Group
end if
```

As an example, for an IWSHD value of 15, the group $G_{13,7}$ is regular since it obeys the triangularity condition, while $G_{13,1}$ is an irregular group.

Algorithm 2. INTER-GROUP ROUTING

```
1: if PATH already exists in packet then
2:     Choose farthest group in PATH to be next
       group
```

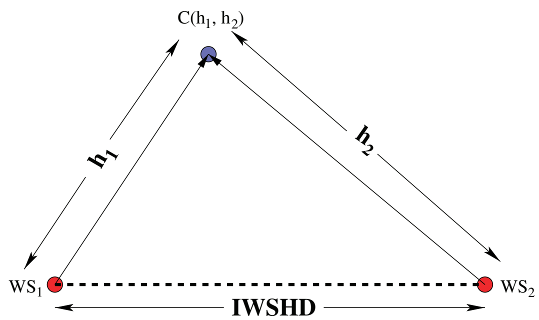

Fig. 9. Triangularity condition for the group G_{h_1,h_2}.

```
end if
if No PATH exists OR no neighbor group in PATH then
    Determine PATH with Imaginary Line Approach
    Choose farthest neighbor in PATH to be next group
    If no neighbor group in PATH, determine next group with Greedy Approach
end if
```

4.3.2. Inter-group routing in a regular group

In our proposed algorithm, a sequence of groups P between a source group S and a destination group D is created using a global view of the network topology. The imaginary line approach utilizes the ideal group pattern to determine this group sequence. Since the ideal group pattern is composed of regular groups alone, the group sequence is established by only regular groups.

Upon the reception of a packet, a regular group G performs the following operations: First, the packet is checked whether a sequence of groups P is contained in the packet. If not, G makes the calculations of the imaginary line approach to determine P. Otherwise, the existing sequence is kept. Then, the nearest neighboring group in P to D is selected to be the next group. To avoid sending a packet to a group that is already visited, the next group should not exist in the list of visited groups contained in the packet. As an example, consider a path of groups $P=[G_{3,4}, G_{4,5}, G_{5,5}, G_{5,4}, G_{5,6}]$ in a packet which is received by $G_{4,5}$. In path P, $G_{3,4}$ is the source group S, while $G_{5,6}$ is the destination group D. Suppose that the neighboring groups of $G_{4,5}$ are $G_{4,4}$, $G_{3,5}$, $G_{5,5}$, $G_{5,4}$, and $G_{5,3}$. Since the closest neighbor group to D in path P is $G_{5,4}$, it is chosen as the next group of Inter-Group Routing, provided that it is not previously visited.

Although a regular group G is supposed to set the sequence P of groups that lead to D, sometimes no neighboring nodes can be found in P. Furthermore, all neighboring groups that are found in P might be already visited. In such instances, G should use the greedy approach to choose the neighbor group that is closest to D in terms of hop distance in the hop-ID space.

The inter-group routing in a regular group is summarized in Algorithm 2, and further details are given in Algorithm 3. In these algorithms, PATH denotes the sequence of groups P contained in the packet.

4.3.3. Inter-group routing in an irregular group

When a node belongs to an irregular group, this means that it is not possible that an intersection point of two circles with the given radii of h_1 and h_2 exists. In this case, the group does not exist in the ideal infinite density group pattern. *Thus, the imaginary line approach cannot be used by an irregular group*. Hence, the greedy approach is used to forward the packet.

Fig. 10 illustrates an example experimental group path between the groups $G_{7,21}$ and $G_{24,24}$ with a sensor network of 3200 nodes in a 200×200 $unit^2$ field.

Algorithm 3. DETAILED INTER-GROUP ROUTING

```
Mark current group ID-pair in packet
if currentgroup = destination group then
    Check if unicast route exists to the destination node
    if yes then
        return 1
    else
        return 0
    end if
else
    if current group does not exist in ideal graph then
        Choose the unmarked neighbor group with smallest group distance to destination group
        if all neighbors are marked then
            return 0
        end if
        flag ← 1
    else
        if flag = 1 then
            PATH ← find new path of groups
        end if
        Choose neighbor group in PATH with largest index
        if flag = 2 AND no neighbor in PATH then
            PATH ← find new path of groups
            Choose neighbor group in PATH with largest index
        end if
        if neighbor group found in PATH then
```

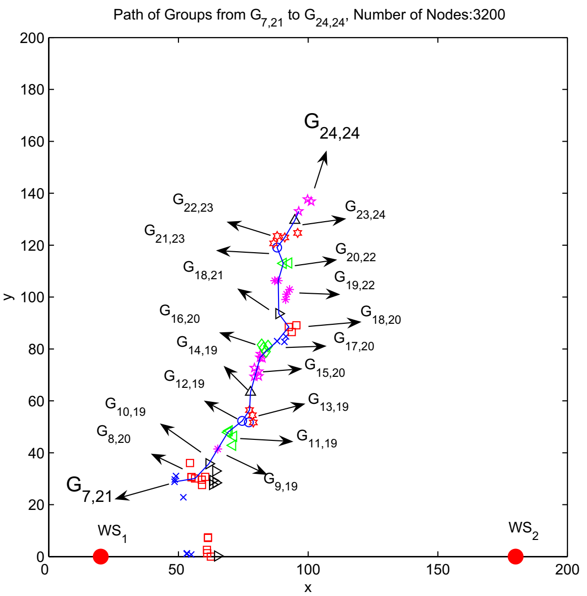

Fig. 10. Path of groups between two groups of an WMC system of 3200 nodes in a 200×200 unit^2 field.

Set PATH to exclude current group
flag ← 0
else
Choose the unmarked neighbor group with smallest group distance to destination group
if all neighbors are marked **then**
return 0
end if
flag ← 2
end if
end if
end if

5. Intra-group routing

Forwarding a packet to a node within a group is achieved by the intra-group routing scheme. At the end of group-wide broadcasting stage the nodes in a group *G* determine the shortest paths to other nodes of *G* using Dijkstra's algorithm and construct their forwarding tables. Using its forwarding table, the Initiator node determines a destination node within *G* who has a neighboring node belonging to the next group *N* determined by the inter-group routing scheme. Then, the packet is sent to the next node in the unicast path leading the destination node. The destination node forwards the packet to one of its neighbors in *N*. Fig. 11 illustrates an example of an intra-group routing path.

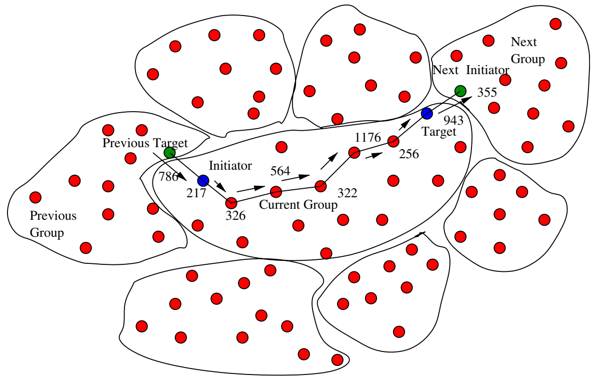

Fig. 11. Intra-group routing.

6. Node failures

Handling node failures is an important issue for correct operation of WMC systems. With the help of the grouping structure, the system is quite adaptive to node failure events. As explained in Section 2.2.2, WMC groups establish unicast paths during the group-wide broadcasting stage. These paths are used for intra-group routing. In case a node fails, the unicast paths through this node must be updated. Fortunately, the WMC system requires group-wide broadcast procedure to be performed for only the group where a node fails. Since a group is found to have small number of nodes as illustrated in Table 2, this procedure is simple. Furthermore, the updates are "event-driven", meaning that no periodic update procedures are required. Inter-group routing is not affected from node failures unless the transmitted packet is in a group which is updating its forwarding table. If a node *N* is going

Table 2
Network types for scalability tests and the resulting average number of nodes in a WMC group

Average number of nodes		
Number of nodes	Field size (units × units)	Average number of group nodes
12,800	400 × 400	4.5977
9800	350 × 350	4.4586
7200	300 × 300	4.4444
5000	250 × 250	4.1771
3200	200 × 200	4.1885
1800	150 × 150	4.0541
800	100 × 100	3.6364

to send a packet to a group, say G, and G is updating its forwarding table because of a node failure, then N stores the packet temporarily and sends it to G when the update procedure is over.

7. Comparative performance evaluation

In this section, the performance of the WMC system is evaluated in terms of the packet transmission success rate and the average path length. The performance results of WMC system are compared with those of greedy geographic routing (GGR) and the virtual coordinate scheme (GWL, geographic routing without location information) introduced in [10]. The comparisons are based on communication overhead, complexity, and routing performance. The effects of node density and the size of the sensor network field (scalability) on routing performance are investigated by changing the number nodes and/or the field size. Table 2 shows different types of networks used in scalability tests. The change of node density is studied using the set of networks as shown in Table 3.

The sensor nodes in the simulations have identical circular communication ranges with radius $R = 8$ units and symmetric communication links. The effects of fading, interference, and asymmetric links are not included in this study and can be investigated as a future research. Nodes can transmit/receive packets without error to/from within a communication range of radius R. Furthermore, sensor locations are random with a two dimensional Poisson distribution.

7.1. The geographic routing without location information scheme (GWL)

The GWL scheme [10] makes use of the neighborhood information of sensors to create a virtual coordinate space. In this way, although the sensors lack location information, greedy geographic routing can be performed over these new virtual coordinates. These coordinates are determined using the nodes in the perimeter of the network, called the perimeter nodes.

GWL proposes three schemes based on the information available in the nodes. In the first scheme perimeter nodes know that they are perimeter nodes and are aware of their true geographic coordinates. In the second scheme, perimeter nodes know that they are perimeter nodes but they do not know their locations. Finally, in the third scheme, perimeter nodes neither know their coordinates nor the fact that they are perimeter nodes. The results of these three different GWL schemes are labeled as GWL1, GWL2, and GWL3 in Figs. 12–15.

The procedure of GWL3, which is the GWL method with the least available location information, can be outlined as follows [10]:

1. Two designated bootstrap beacon nodes broadcast to the entire network. Nodes use their distances to one of these bootstrap nodes to determine whether they are perimeter nodes.
2. Every perimeter node sends a broadcast message to the entire network to enable every other node to compute its perimeter vector, i.e., the distances from that node to all perimeter nodes.
3. Perimeter and bootstrap nodes broadcast their perimeter vectors to the entire network.
4. Each node uses these inter-perimeter distances to compute the coordinates for both itself and the perimeter nodes.
5. Locations of the perimeter nodes are not changed while all non-perimeter nodes run a relaxation algorithm to determine their virtual coordinates. At each step of this algorithm, a non-perimeter node calculates the average of the x coordinates of its neighboring nodes and assigns this value to its x coordinate. The same averaging is performed for the y coordinate.

7.2. The comparison of the system set-up complexities of GWL and WMC

The GWL scheme is found to have lower success rates and comparable average path lengths when the results of GGR are considered. However, the GWL scheme has also the following drawbacks during its system set-up phase.

Table 3
Network types for tests of the effect of node density

Network types for density tests	
Number of nodes	Network size (unit^2)
3200	125×125
3200	150×150
3200	175×175
3200	200×200
3200	225×225
3200	250×250

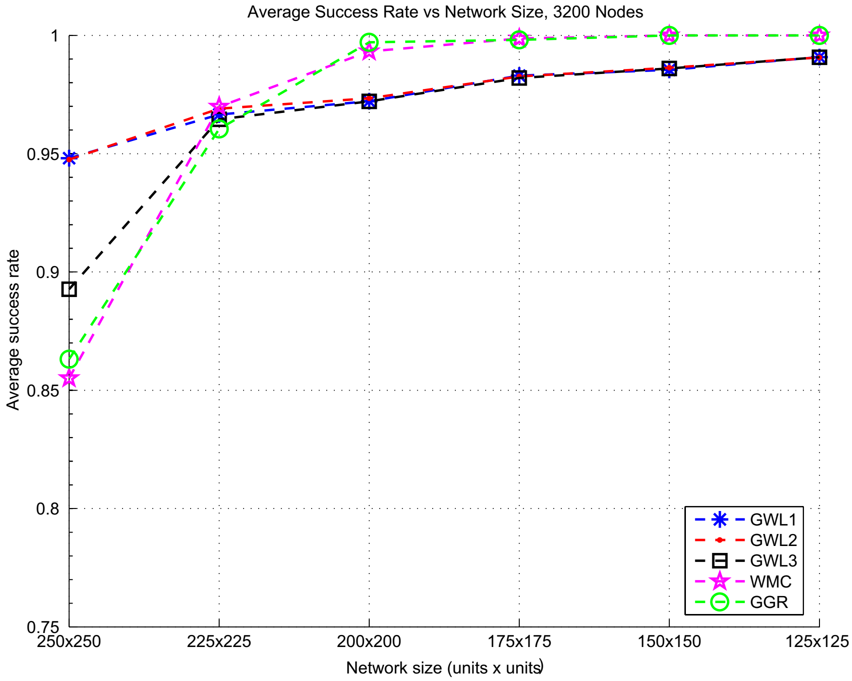

Fig. 12. Average success rates for decreasing network size for 3200 nodes.

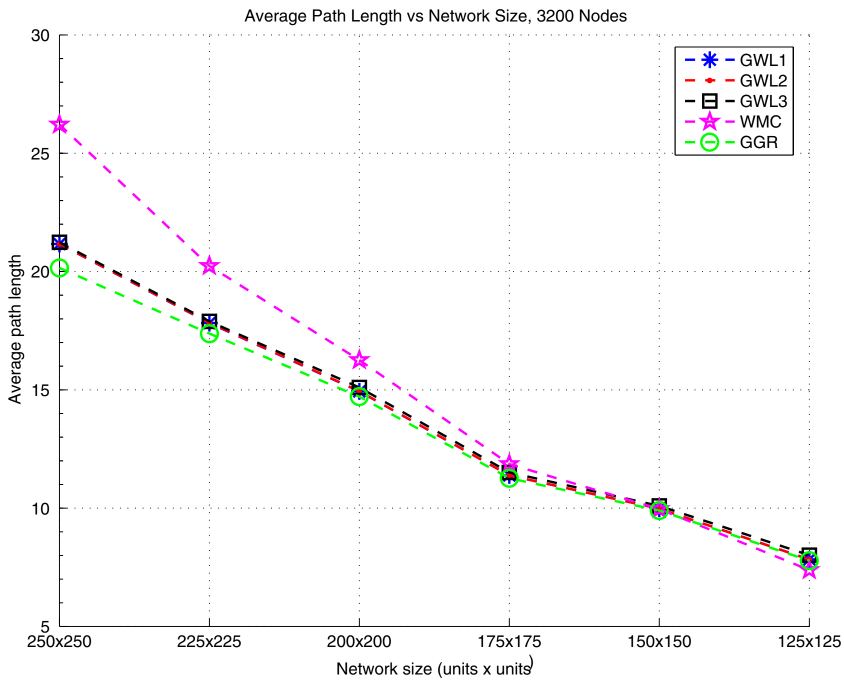

Fig. 13. Average path lengths for decreasing network size for 3200 nodes.

7.2.1. The system set-up comparisons of GWL and WMC

A major disadvantage emerges when the perimeter nodes in GWL are required to broadcast packets to the entire network. Since the number of perimeter nodes is in the order of $O(\sqrt{n})$, a large overhead occurs in terms of the message transmissions. For instance, 64 perimeter nodes are each required to

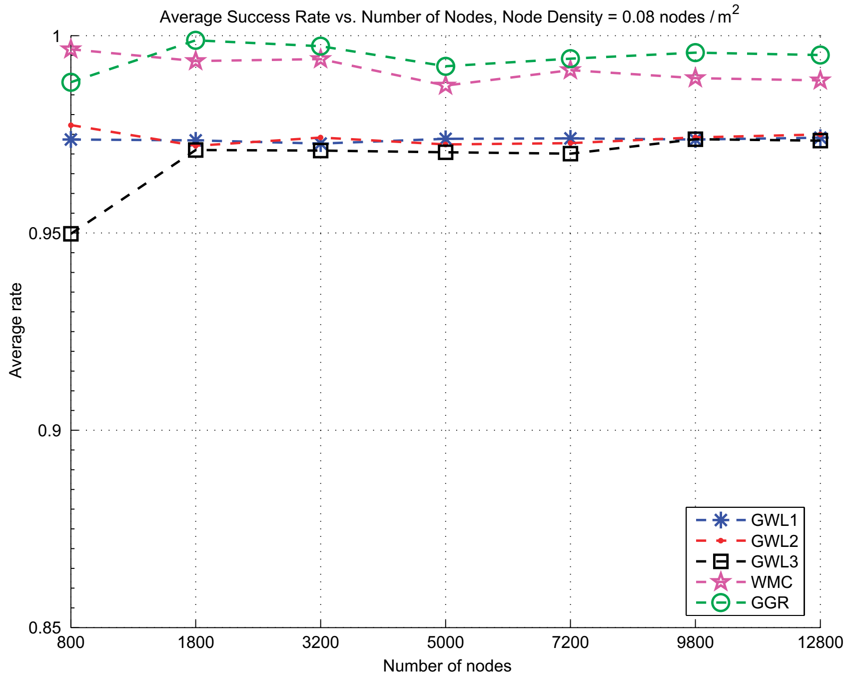

Fig. 14. Average success rates for increasing number of nodes. Node density: 0.08 nodes/m^2.

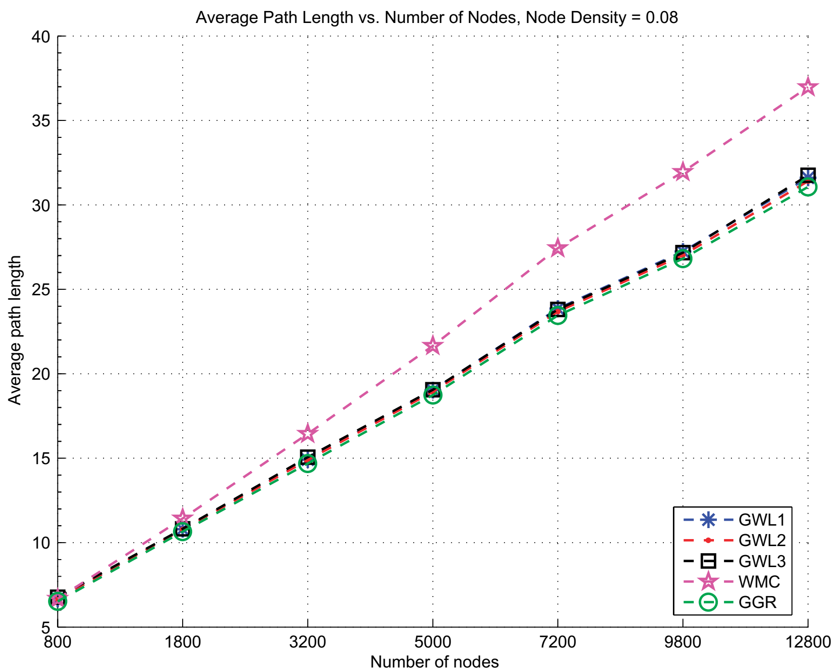

Fig. 15. Average path lengths for increasing number of nodes. Node density: 0.08 nodes/m^2.

broadcast a packet to the entire network. As a result of this network-wide broadcasts, the hop distances of each perimeter node to other perimeter nodes are determined and stored in a perimeter vector. The perimeter nodes must also broadcast their perimeter vectors, which makes a total of 128 network-wide broadcasts. Hence, the number of messages is in the order of $O(n\sqrt{n})$. This is a significant problem especially when the number of nodes in the network is large.

On the other hand, the WMC system needs only two network-wide broadcasts and only one or two forwardings are required within a group since a few nodes are included in a group as illustrated in Table 2 for a node density of 0.08 nodes/unit^2. Hence, the number of messages in WMC is in the order of $O(n)$.

7.2.2. The algorithm convergence delay in GWL relaxation step

The relaxation algorithm in GWL converges very slowly. When the relaxation process is applied without an initial triangulation procedure, around 1000 iterations are required for finding the virtual coordinates of the non-perimeter nodes. Furthermore, the number of relaxation iterations changes drastically for different sample networks of a certain network size and number of nodes. For instance, for a network of 5000 nodes it takes 620 iterations to obtain the virtual coordinates, while for another network of 5000 nodes with the same field dimensions 3111 iterations are required.

The triangulation algorithm, when applied as a preprocessing step, in GWL is claimed to decrease the number of relaxation iterations. However, such an improvement cannot be achieved for every sample network. For instance, triangulation is applied to two sample networks with 3200 nodes and 200×200 unit^2 field size. The number of relaxation steps is reduced from 1267 to 13 for one of the networks, while a reduction from 1191 iterations to only 573 iterations is achieved for the other.

Based on these observations, it can be concluded that the number of iterations in the relaxation step is highly dependent on the topology and has a large variation. This has an immediate effect on the time the system needs to stabilize, as each of the steps involve message exchanges between sensors. Hence, the GWL3 algorithm has a high communication complexity and a long convergence time.

7.3. Performance analysis of routing in WMC systems

The performance of routing in WMC systems is evaluated in terms of the packet routing success rate and the average path length of packet transmissions. *Success rate* is the fraction of times, scaled to a range of $[0, 1]$, that a packet is successfully delivered to its intended destination node. In order to evaluate the success rate and the average path length, 10,000 independent routes with independent source destination pairs are selected in various network topologies. The GGR and GWL schemes are also implemented and their routing performances on the same set of networks used for WMC are investigated. Different topologies are created by changing the following parameters that define a sensor network topology:

- Number of nodes.
- Network size.

7.3.1. The effect of the change in node density on routing performance

The two parameters, namely the number of nodes and the network size, are used to investigate the effect of density change on the routing success. In Table 3, the set of network topologies reflecting the effect of density change for a network with 3200 nodes is shown. The density change is obtained by changing the size of the sensor field while keeping the number of nodes fixed which is also used in [10].

Figs. 12 and 13 illustrate the density-effect on the transmission success rate and the average path length, respectively, of routing in networks of 3200 nodes. In Fig. 12, it can be observed that after for networks that are smaller than 225×225 unit^2, the rates of WMC are superior to those of GWL and are comparable to GGR rates. Despite its simplicity and very small number of packet exchanges, WMC provides higher success rates when compared with the more complex GWL scheme. Decreasing the field size, which is equivalent to increasing the density, decreases the average path length of WMC system, as seen in Fig. 13. Although the average path length of WMC is slightly longer than those of GGR and GWL, the average path lengths of the three methods are identical for high node densities.

7.3.2. Scalability in routing with WMC and GWL systems

The scalability of routing success is tested by changing the number of nodes and the network size while keeping the node density fixed. The simulations in this study use the set of network topologies shown in Table 2 to test the routing success of WMC, GWL, and GGR.

Results for the effect of network size (scalability) are similar to the results of the density effect on routing when the WMC and the GWL systems are compared. Despite the fact that increasing network size causes an increase in average path length, the routing success rates of WMC are much better than GWL and comparable to GGR. Figs. 14 and 15 illustrate these findings of average success rate and path length, respectively.

8. Conclusion

In this study, a simple and efficient coordinate system for dense sensor networks, the wave mapping coordinate system (WMC), is introduced. Furthermore, a highly successful and simple routing mechanism over WMC systems is designed. WMC system is aimed to provide approximate location information and is a scalable coordinate system for sensor networks without location information, any infrastructure support or complex and expensive hardware availability. The performance of routing over WMC systems is evaluated according to changing node density and sensor field size. The performance results are compared with the geographic routing without location information (GWL) scheme outlined in [10], and the geographic greedy routing scheme (GGR) which uses real coordinate information of sensors.

The GWL scheme requires a large number of packet exchanges, along with the need for solving complex optimization problems in each sensor node. The number of messages is in the order of $O(n\sqrt{n})$ in the initial stage of virtual coordinate construction, which creates a broadcast storm in WSNs. On the other hand, the WMC system needs only two network-wide broadcasts with a complexity of $O(n)$. Furthermore, group-wide broadcasts in WMC involve only the nodes of individual groups, which leads to a very small number of packet forwardings.

Another problem encountered in GWL Systems is the slow convergence of the relaxation algorithm, especially for networks with large number of nodes. Hundreds or even thousands of relaxation iterations occur and each sensor nodes is required to send a packet to its neighbors in each relaxation iteration. Hence, GWL needs hundreds of packet transmissions for each node during the system start-up, which is a high overhead for a sensor network.

From the perspective of system simplicity, message complexity, and routing success rate, the WMC system is found to be superior to the GWL scheme. The routing success rate of WMC is much better than GWL and comparable to GGR. Despite its simplicity and very small number of packet exchanges, WMC provides higher success rates when compared with the more complex GWL scheme.

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