Mobile Robot Coordination and navigation with directional antennas in positionless Wireless Sensor Networks

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Abstract: Three schemes are proposed to coordinate and navigate mobile robots with directional antennas in a positionless wireless sensor network for the purpose of emergence rescue. The *k*-farthest-node forwarding scheme is for Waiting-for-Rescue (WFR) nodes to broadcast packets to ask mobile robots to come to help. The Mobile Robot Coordination (MRC) is to coordinate multiple mobile robots so that each WFR node is associated one nearby mobile node which is navigated by the Tree Assisted Navigation (TAN) scheme to fast reach the WFR node. The schemes' effectiveness is verified by the ns-2 simulator.

Keywords: mobile robot; directional antenna; wireless sensor network.

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1 Introduction

A Wireless Sensor Network (WSN) consists of many spatially distributed, small and inexpensive sensor nodes equipped with microcontrollers, short-range wireless radios, and analogue/digital sensors. It has been adopted in developing many military or environmental applications. In some working environments, such as a battlefield or a disaster field, automatic devices are more suitable than human to provide assistance. In such situations, it is favourable to use mobile robots (or mobile nodes) with mobility and automaticity to intelligently move and interact with the environment. The integration of mobile robots and the sensor network, called the *robot-sensor network*, simplifies robot design since the sensor network can take over the responsibility of sensing and help with decision-making. This opens up opportunities in new applications, such as sensors deployment (Chang et al., 2007), data collection (Sugihara and Gupta, 2010), sensors relocation (Teng et al., 2007), target tracking (Hwang et al., 2007), target detection (Arora et al., 2004), and search and rescue in harsh environments (Reich and Sklar, 2006; Severino and Alves, 2007).

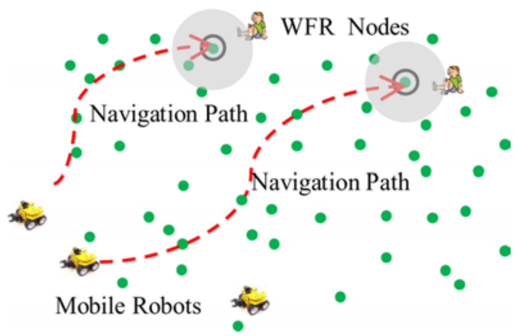
With the capabilities of the robot-sensor network, an emergency rescue system can be built. The robot-sensor network can be used to build the system for critical missions, such as emergently rescuing the wounded in the battlefield as shown in Figure 1. Building such a system has to efficiently coordinate and navigate the mobile robots to reach specific targets for providing assistance (Li et al., 2003). The system in practice has the following three requirements. First, it needs to notify all mobile robots about the existence of WFR entities. Second, it needs to allocate rescue tasks among mobile robots. Third, it needs to guide the mobile robots to reach the designated targets without location information.

In this paper, we study the problem about how to coordinate and navigate the mobile robots for the emergence rescue in the positionless WSN. We propose a suite of three schemes to solve the problem as follows.

The first is the *k*-FNF scheme. When a specific node, called the WFR node, detects the occurrence of an event, it broadcasts an event notification packet throughout the entire network for asking a mobile robot to come and help (refer to Figure 1). In many existent schemes, the broadcast is achieved by the flooding scheme and thus incurs many redundant forwarding packets. To eliminate the redundant forwarding packets, we propose the *k*-FNF scheme. The *k*-FNF scheme utilises RSS for a node to determine the backoff time of forwarding the broadcast packet. Farther nodes get weaker signals and have shorter backoff times. And, a node does not forward the packet if it hears *k* forwarded packets before the backoff time elapses. This can reduce a lot of redundant forwarding packets to save energy for prolonging the network lifetime. Furthermore, with the help of the *k*-FNF scheme, it is easy to establish a navigation tree, which is rooted at the WFR node and contains only packet forwarding nodes. The navigation tree will be used in the other two schemes to coordinate and navigate the mobile robots.

The second scheme is the MRC scheme, which is designed to coordinate multiple WFR nodes and multiple mobile robots. The scheme is distributed and greedy-based. Mobile nodes track all the recent notification packets from different WFR nodes. An available mobile node will reply to the packet with the minimum hop count via nodes in the navigation tree. Likewise, the WFR node will select the mobile robot whose reply packet has the minimum hop count and ask it to come and help. The selection decision is sent to all replied mobile nodes. If a mobile node is not selected, it can reply to another un-replied notification packet. The MRC is energy-efficient, since it causes only a small amount of control packets. It is also distance-efficient, since a WFR node is usually rescued by an available mobile node with the minimum hop count.

Figure 1 Navigation of mobile robots towards the Waiting-for-Rescue (WFR) nodes (see online version for colours)



The third is the TAN scheme, which guides a mobile robot with a directional antenna to move towards the designated WFR node with the aid of the navigation tree. On the basis of the navigation tree, there is a unique path from a mobile robot to the WFR node. When a mobile robot starts to move towards the WFR node, it continuously requests nodes in the path to take turn to issue navigation signals, and utilises the directional antenna to take proper direction to reach the WFR node hop by hop. In this way, the mobile robot can reach the WFR node without position information.

The rest of this paper is organised as follows. In Section 2, we introduce some related work. In Section 3, we describe the research problem and present the three schemes proposed. In Section 4, we present the simulation results of the proposed schemes and compared the results with those of other related methods. Finally, Section 5 concludes the paper.

2 Related work

In this section, we present the related work of the robot navigation and message-broadcasting schemes in the WSNs.

2.1 Mobile robot navigation

The mobile robot navigation schemes can be classified into two categories: navigation with position information (Verma et al., 2005) and navigation without position information (Reich and Sklar, 2006; Sheu et al., 2008).

Verma et al. (2005) proposed a scheme (called Verma's scheme for short) to guide the Mobile Sensor Nodes (MSNs) to move towards a goal by a network of sensor nodes. The scheme assumes every node in the network is equipped with a positioning device. It consists of two phases:

- finding phase
- navigation phase.

In the first phase, the goal node (the node nearest to the goal) broadcasts a request packet throughout the network. The MSN will reply the request packet when it is available.

The goal node will select one or more MSNs with the best metrics, such as coverage, power and proximity to the goal. In the second phase, a selected MSN broadcasts a navigation-request packet to its neighbours and waits for replies. Navigation is accomplished by credit-based field set-up. The MSN moves to the position that is calculated based on the virtual attractive force generated from high-credit neighbours' positions. This procedure will be repeated until MSN reaches the destination. This scheme does not require any prior maps of the environment.

Reich and Sklar (2006) proposed a positionless navigation scheme (called Reich's scheme for short) for search and rescue purposes. The goal is to search the mobile robots and then navigate them to rescue a target, which needs help. The basic idea is to assign 'low gradient' values to sensors close to the rescued target and 'high gradient' values to those far away from the target. Thus, the mobile robots can follow the path guided by the sensors in the order of high to low gradient values. Each mobile robot should move towards the unvisited sensor, which owns the largest gradient value in the mobile robot's neighbourhood. Such movement will be terminated when either

- the robot finds the rescued target or
- another robot finds the rescued target.

The scheme utilises flooding mechanism, and thus incurs a large number of packets. Furthermore, it does not provide robot coordination, so multiple mobile robots may move towards the same target simultaneously.

Sheu et al. (2008) proposed another positionless mobile robot navigation scheme for the purpose of replacing low-energy sensors. The scheme requires the sink node to dispatch mobile robots to install new sensors. Initially, the sink node floods the whole network so that every sensor learns of a path of sensor nodes, called guide nodes, from itself to the sink. When a sensor is running out of energy, it sends a request along the path to ask the sink to dispatch a mobile robot to install a new sensor. The navigation is based on the concept of receiving signal strength. The guide nodes periodically broadcast beacon packets. The mobile robot randomly selects a direction to move back and forth, and turns 90º when the RSS of a guide node reaches the maximum. It then moves along the direction in which the RSS of the guide node is increasing to move towards the guide node. In this way, the mobile robot can reach the low-energy sensor. In this scheme, the mobile robot needs to move back and forth, which wastes time and energy.

2.2 Message broadcasting

A broadcast mechanism is essential for navigation algorithms to disseminate messages throughout the whole network for the purpose of state notification or path construction. Here, we introduce some broadcast mechanisms. The flooding-based broadcast mechanism is widely used by navigation algorithms. For example, the notification designs in the above-mentioned algorithms (Reich and Sklar, 2006; Sheu et al., 2008; Verma et al., 2005) are all flooding-based. In the flooding-based mechanism, each node retransmits a packet once to increase the probability that the packet is received by all nodes. Flooding is simple, but easily leads to a lot of redundant packet forwarding, which consumes much energy and increases the possibility of packet collision.

There are some algorithms (Ni et al., 1999; Peng and Lu, 2000) proposed to improve the flooding mechanism. They can be classified into three categories: neighbour knowledge-based, probability-based and area-based. Peng and Lu (2000) proposed a neighbour knowledge-based Scalable Broadcast Algorithm (SBA) to reduce redundant forwarded packets. In SBA, nodes exchanges neighbour lists by sending 'hello' packets periodically so that each node knows of all its 2-hop neighbours. Upon receiving a new broadcast packet from a neighbouring node, node x should initiate a random backoff timer and keep on receiving packets from other neighbouring nodes. After the random backoff timer expires, node x should determine if it has any two-hop neighbours that are not covered by the one-hop neighbours having sent the packet. If so, x has to rebroadcast the packet. Ni et al. (1999) proposed a probability-based mechanism using counters. Each node maintains a counter to record the times of receiving the broadcast packet. After a certain waiting time, if the counter exceeds a predefined threshold value, then the node rebroadcasts the packet. Ni et al. (1999) also proposed an area-based algorithm. In that algorithm, each node uses the RSS to estimate the distance between itself and the sender. Only when the distance exceeds a pre-specified threshold, will the node forward the packet. All the above-mentioned mechanisms can eliminate unnecessary rebroadcast and reduce packet collision possibility.

3 The problem and the proposed schemes

In this section, we first describe the problem studied. We then propose a suite of three schemes to solve the problem.

3.1 Mobile robot navigation and coordination problem

We investigate the problem about how to coordinate and navigate mobile robots with directional antennas in a positionless WSN for the emergence rescue. A solution to the problem needs to satisfy the following three requirements. First, it requires a mechanism to notify a ll mobile nodes about the existence of WFR entities. Second, it requires a mechanism to allocate rescue tasks among mobile robots. Third, it requires a mechanism to guide mobile robots to reach designated targets. In a positionless WSN, sensor nodes have no position information. This increases the difficulty to meet the three requirements.

Aiming at this problem, we propose a solution consisting of three schemes: *k*-FNF scheme, MRC scheme and TAN scheme. The three schemes will be introduced one by one in the next three subsections.

3.2 k-FNF (k-Farthest Node Forwarding Scheme)

When a specific node, called the WFR node, detects the occurrence of an event, it broadcasts an event notification packet throughout the entire network by *k*-FNF scheme to ask a mobile robot to come and help. A node determines, with the help of RSS, the backoff time of forwarding the packet when it receives the packet for the first time. Nodes farther from the sender get weaker signals and have shorter backoff times. On the contrary, nodes nearer to the sender have longer backoff times. A node does not forward the packet if it hears *k* nodes forwarding the packet before the backoff time elapses. As we will show, *k*-FNF scheme can reduce the redundancy of packet forwarding and achieve high reachability. Its details are described in the following:

- When a sensor node detects a specific event that needs mobile robot to come and help, it becomes a WFR node. The WFR node will broadcast the notification packet NOTICE<RID, ID, HC> to its neighbouring nodes where RID is the identity of WFR node, ID is the sender identity (RID = ID in this step) and HC is the hop count, which is initially 0.
- On receiving NOTICE<*w*, *x*, HC> from a node *x*, a node *y* just drops the packet if it has ever received *k* NOTICE packets originating from the WFR node *w*.
- On receiving the first NOTICE<*w*, *x*, HC> packet originating from *w*, a node *y* performs the following three sub-steps.
  - Node *y* calculates the distance *D* between itself and the upstream sender *x* by the received signal power P_{rcv} of the NOTICE packet by the following equation:

    $$P_{rcv} = P_{tx}(C_1/D)^{\alpha}C_2, \quad (1)$$

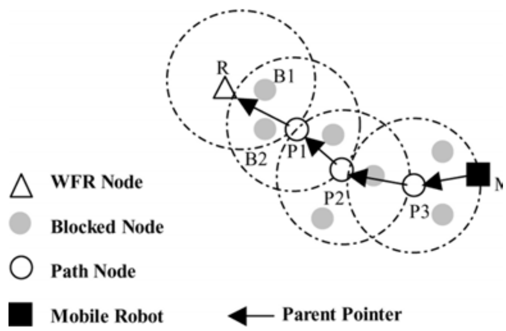
    where P_{tx} is the transmitting power of the sender (we assume all nodes transmit packets with a pre-specified power P_{tx}), and C_1, C_2 and α represent the gain of the antenna, the wavelength and the propagation exponent factor ($2 \le \alpha \le 5$).
  - Node *y* then calculates the backoff time T_Backoff by the following equation:

    $$\text{T\_Backoff} = ((L - D)/L)B, \quad (2)$$

    where *L* is the maximum transmission distance of sensors, and *B* is the maximum backoff time. (The reader can check that the backoff time is shorter when *D* is longer. This implies that the farthest node has the shortest backoff time and thus the highest probability to forward the packet first.)
  - Node *y* waits for T_Backoff time to elapse. If node *y* receives totally *k* NOTICE packets originating from *w* before T_Backoff time elapses, it stops the backoff timer and will not forward the packet. Otherwise, node *y* sets itself as *w*'s *path node* of hop count HC′ + 1 and forwards the packet by sending out NOTICE < *w*, *y*, HC′ + 1>, where HC′ is the minimum hop count value among those of the received NOTICE packets originated from *w*. Let node *s* be the sender node sending the packet with the minimum hop count value HC′. Node *y* sets node *s* as its *parent node*, and stores the identity of *s* and the hop count value HC′. For such a case, we say that there is a *parent pointer* from *y* to *s*.

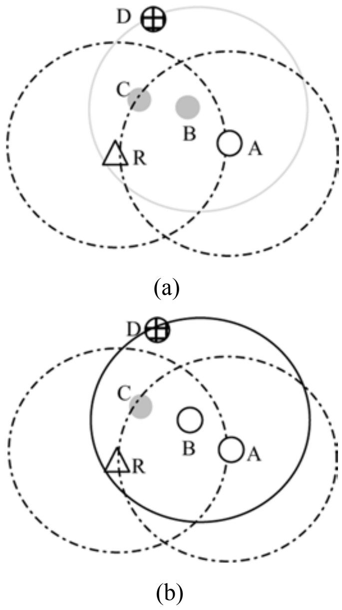
Figure 2 illustrates the execution of the *k*-FNF scheme for the case of *k* = 1. In the example shown in Figure 2, the WFR node *R* broadcasts a NOTICE packet. The nodes that possibly receive the packet are B1, B2 and P1. Since P1 is the node farthest away from *R*, it has the shortest backoff time. Thus, P1 will forward the packet first, mark itself as a path node, and set *R* as its parent node. Nodes B1 and B2 will not forward the packet since they have longer backoff time than P1 and hence they are supposed to hear P1 forwarding the packet before the backoff time elapses. Similarly, P2 and P3 will forward the packet and mark themselves as path nodes. Eventually, the mobile node *M* will receive the NOTICE packet. Note that P1, P2 and P3 are parent nodes of P2, P3 and *M*, respectively.

Figure 2 The illustration of *k*-FNF scheme for the case of *k* = 1



The *k*-FNF scheme uses fewer nodes to broadcast packets when *k* is smaller. There is a trade-off between the number of broadcasting nodes and the reachability. For the case of a small *k*, we can image that some nodes may not receive packets when node density is low. For example, in Figure 3(a), there are three candidate nodes A, B, C to forward the broadcast packet sent by node R. Since only node A forwards the packet, node D does not receive the packet for the case of *k* = 1. However, as shown in Figure 3(b), node D will receive the broadcast packet since nodes A and B will forward the packet for the case of *k* = 2. Note that in the extreme case of *k* = ∞, the *k*-FNF scheme becomes the flooding scheme in which every node forwards the broadcast packet once. Obviously, k-FNF has the highest reachability and the largest number of rebroadcasts for the case of $k = \infty$. On the contrary, k-FNF has the lowest reachability and the smallest number of rebroadcasts for the case of $k = 1$.

Figure 3 The illustration of k-FNF scheme for: (a) $k = 1$ and (b) $k = 2$



By the k-FNF scheme, a WFR node can broadcast an event notification packet throughout the entire network for asking a mobile robot to come and help. By the parent pointers, there is a unique path from a mobile node to the WFR node. Note that the parent pointer will not form a cycle since the pointer is going from a node of hop count HC + 1 to a node of hop count HC. Therefore, the pointer can be used to construct a navigation tree, which consists of only path nodes and is rooted at the WFR node, whose hop count value is 0. The navigation tree plays an important role in the coordination and navigation schemes, whose construction details will be described in the next two subsections.

3.3 Mobile Robot Coordination (MRC) scheme

The MRC scheme is designed to coordinate multiple WFR nodes and multiple mobile robots. In the MRC scheme, the mobile nodes track all recent notification packets originated from different WFR nodes. An available mobile node will reply to the notification packet with the minimum hop count via a sequence of path nodes in the corresponding navigation tree. Likewise, a WFR node will select the mobile robot whose reply packet is with the minimum hop count to come and help. The selection decision is sent to all replied mobile nodes. If a mobile node is not selected, it can reply to another un-replied notification packet after knowing of the selection decision.

The details of MRC are described in the following

1. On receiving a NOTICE packet, a mobile robot should add a new record in its own request table T_REQ. Each record in T_REQ contains the SN, SBit, HC and ID fields. The SN (source node) field represents the WFR node that initially sends this NOTICE packet. The SBit (served bit) field represents if the associated WFR node has been served by the mobile robot. And, the HC field is one plus the received NOTICE packet's HC. The ID field represents the upstream sender of this notification packet. Table 1 is one simple instance of the request table.
2. When a mobile robot starts to serve, it first chooses from T_REQ the record with the minimum HC among those with SBit being 0. It then sets variable SN_{MIN} to be the SN value of this record. Afterwards, the mobile robot sends the MOVE<SN_{MIN}, MID, MHC, PID> packet to the SN_{MIN} node along a path in the navigation tree, where MID is the mobile robot's identity, MHC is the hop count distance between the mobile robot and SN_{MIN} WFR node, and PID is the identity of the mobile node's parent node.
3. On receiving the MOVE<SN_{MIN}, MID, MHC, PID> packet, a path node p whose ID is PID will forward this packet by sending out MOVE<SN_{MIN}, MID, MHC, PID′>, where PID′ is p's parent node. (Many path nodes execute Step 3 and the WFR node will eventually receive the MOVE packet.)
4. When a WFR node receives multiple MOVE packets from different mobile nodes, it first selects the mobile robot of the MOVE packet with the smallest MHC value. It then sends the RESB<RSN, MID> packet to all mobile robots that have sent MOVE packets along paths in the navigation tree, where RSN is the WFR node's identity and MID is the identity of the selected mobile robot.
5. On receiving the RESB<RSN, MID> packet, every mobile robot will set the SBit as 1 in the record whose SN is RSN in the T_REQ. And the selected mobile robot (the one whose identity is MID) starts to move towards the WFR node whose identity is RSN. On the other hand, unselected mobile node should execute Step 2 for checking the T_REQ table to choose the record with the minimum HC among those with SBit being 0 to send the MOVE packet to a WFR node.

Table 1 An example of a request table (T_REQ)

SN	*SBit*	*HC*	*ID*
25	0	7	63
136	0	9	4
251	1	19	116

3.4 Tree Assisted Navigation (TAN) scheme

When MRC is finished, the selected mobile robot will start to move. The TAN scheme will guide a mobile robot to move towards the designate WFR node with the aid of a directional antenna. On the basis of the navigation tree, there is a unique path from a mobile robot to the WFR node. Each mobile robot is assumed to be equipped with one omni-directional antenna and one directional-antenna. The former is used to send/receive control packets, whereas the latter is used to find the direction of path nodes. The details of TAN scheme are described in the following:

1 When the mobile robot starts to move, it will send out REQNAV<SN, MID, PID> packet where SN, MID and PID are, respectively, the identity of the target WFR node, the identity of the mobile robot and the identity of the mobile robot's parent node. All neighbouring path nodes of the mobile robot will receive the REQNAV packet.

2 On receiving REQNAV<SN, MID, PID> packet, the path node whose identity is PID will take the responsibility to navigate the mobile robot by continually sending NAV signal for a time period of length *Tx*. To prevent interference, the other nodes, which overheard the NAV signal, should keep silent for a time period of length *Tx*. It is noted that to prevent interference, the nodes overhearing the REQNAV packet should also keep silent for a time period of length *Tx*.

3 When the mobile robot receives NAV signal from a path node, it calculates the direction towards this path node as follows. The mobile robot first rotates its directional antenna from 0° to 360° to find the strongest signal strength. The mobile robot will record the received time and the RSS in each rotation step (say rotation degree unit is 15°). After rotating 360°, the mobile node can figure out the rotation angle that has the maximum RSS.

4 After the mobile robot successfully calculates the direction to a path node, it starts to move towards the node until reaching the path node *p* (or approaching the path node *p* within a threshold distance). Afterwards, the mobile robot sends out REQNAV<SN, MID, PID′>, where PID′ is the identity of *p*'s parent node (note that *p*'s parent node can be embedded in a specific NAV signal).

The mobile robot and associated path nodes will execute Steps 1–4 continually. In this way, the mobile robot can reach the WFR node along a path in the navigation tree.

4 Performance evaluation

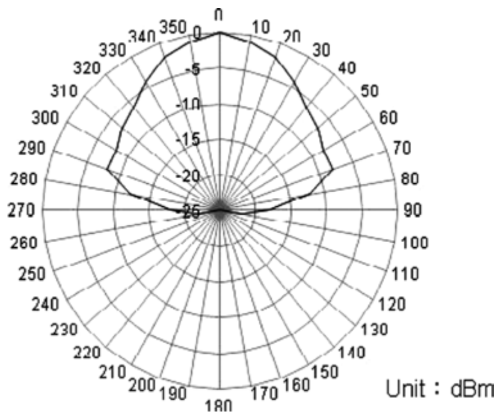
We present the performance evaluation results in this section. We report the experimental result of feasibility of navigation by directional antenna in Subsection 4.1. We also perform simulation experiments by the ns-2 simulator (ns-2, 2009) to compare the effectiveness of our proposed schemes with other related ones. The notification effectiveness is reported in Subsection 4.2. The coordination and navigation effectiveness is reported in Subsection 4.3. The comparison summary is reported in Subsection 4.4.

The setting of simulations in ns-2 is as follows. The simulation experiments assume 300, 500, …, or 1100 sensors are randomly deployed in a 300 m × 300 m area. The transmission power is the same for each sensor and the transmission range is 25 m.

4.1 Experimental result of RSS on directional antenna

To validate the feasibility of our idea, we design an experiment to measure the effect of the RSS on different receiving angles of directional antenna. We use two T-Mote Sky (2009) sensors in the experiment, one for transmitting packets and the other for receiving packets. The transmitting sensor is equipped with an omni-directional antenna, and the receiving sensor is equipped with a directional antenna. The distance between two sensors is 20 m. As shown in Figure 4, the RSS will be the strongest when the angle is zero (i.e., when the receiving sensor straight confronts the transmitting sensor).

Figure 4 The RSS of a directional antenna

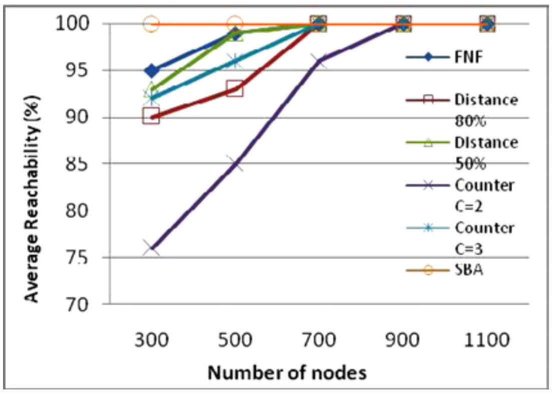


4.2 Evaluation of notification effectiveness

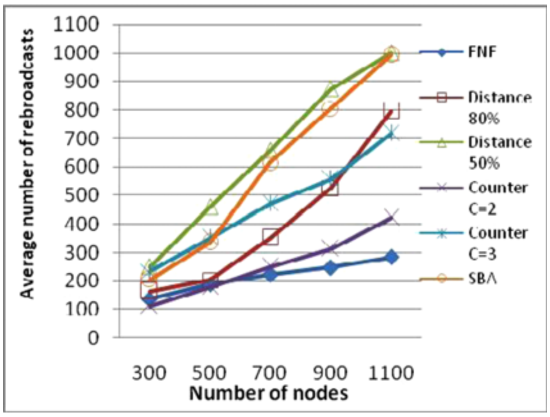
We evaluated the reachability and the packet cost of *k*-FNF scheme (with $k = 1$) and other representative broadcast schemes: SBA (Peng and Lu, 2000), counter-based (with $C = 2$ and $C = 3$) (Ni et al., 1999) and distance-based schemes (with threshold = 0.8 transmission_range and threshold = 0.5 transmission_range) (Ni et al., 1999), which are introduced in Section 2. Note that the reachability stands for the ratio of nodes in the network that receive the broadcast packet.

The simulation experiments are conducted in the different cases for 300, 500, 700, 900 and 1100 sensors. Figure 5(a) shows the reachability of different schemes. As can be seen, *k*-FNF scheme with $k = 1$ (or FNF for short) maintains a steady reachability of near 100%, which is very close to the reachability of SBA. Figure 5(b) shows the number of rebroadcast packets of different schemes. As can be seen, *k*-FNF scheme causes comparably few rebroadcast packets. From the above-mentioned results, we can see that FNF scheme (k-FNF scheme with $k = 1$) achieves comparably high reachability with very few rebroadcast packets when compared with other schemes.

Figure 5 Comparison of FNF (k-FNF with $k = 1$) scheme and others: (a) reachability and (b) average number of rebroadcast packets (see online version for colours)



(a)



(b)

4.3 *Evaluation of coordination and navigation effectiveness*

For the sake of comparison, we perform experiments to evaluate the moving distance of our schemes, Verma's scheme (Verma et al., 2005) and Reich's scheme (Reich and Sklar, 2006) with one mobile robot and one WFR node (or goal node). We measure the moving distance ratio (RD) for WSNs with 300, 500, …, 1100 nodes, where RD = ((sum of moving distances of robots to WFR nodes)/(sum of shortest distances from robots WFR nodes)). Figures 6 and 7 show the trajectory of the mobile robot and RD for different schemes. We can observe that the moving distance ratio RD of our schemes is very close to position-based Verma's scheme. Furthermore, our schemes have smaller RD than positionless Reich's scheme for some cases. Besides, Reich's scheme does not consider how to coordinate multiple mobile robots to move towards multiple targets. Compared with Reich's scheme, our proposed scheme has higher capability in the sense that more targets can be served simultaneously.

We also simulate our schemes for the following settings:

- multiple WFR nodes and multiple mobile robots
- one WFR node, one mobile robot and one obstacle
- one WFR node, one mobile robot and multiple obstacles.

It is noted that we assume large convex-shaped obstacles, which no wireless communication link can penetrate through. Examples of such obstacles are large lakes or hills. Figures 8–10 show the trajectories of mobile robots for different settings. We can see that mobile robots can be successfully navigated to WFR nodes by our schemes for all simulated scenarios.

Figure 6 Trajectories of the mobile robot in different schemes (the left one is for Reich's scheme, the right one is for Verma's scheme, and the middle one is for our schemes) (see online version for colours)

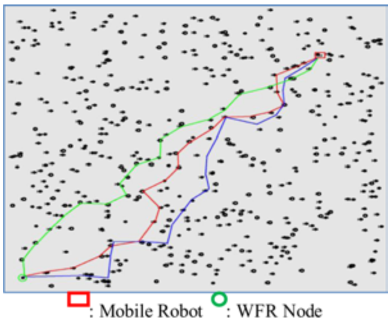


Figure 7 Moving distance ratio of mobile robots in different schemes (see online version for colours)

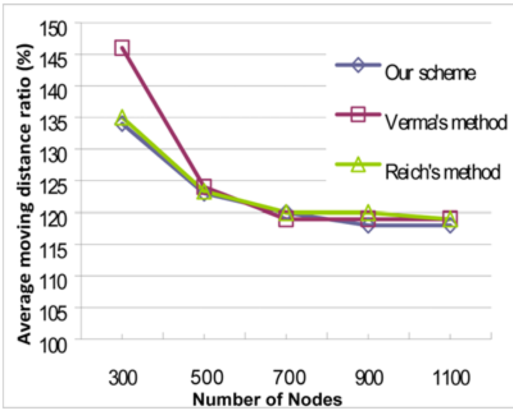


Figure 8 Trajectories of mobile robots for the scenario of 3 WFR nodes and 3 mobile robots (see online version for colours)

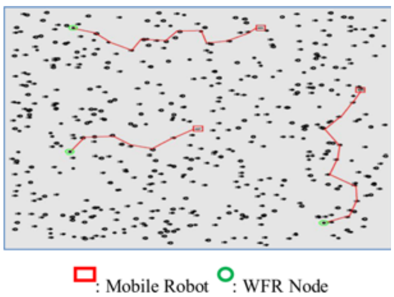


Figure 9 Trajectory and result of the mobile robots for the scenario of 1 WFR node, 1 mobile robot and 1 obstacle (see online version for colours)

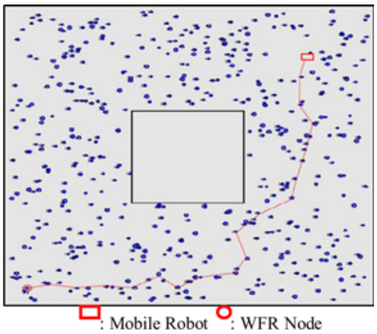
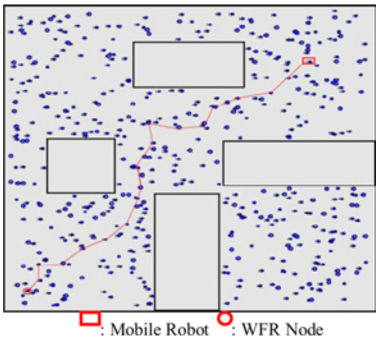


Figure 10 Trajectory and result of the mobile robot for the scenario of 1 WFR node, 1 mobile robot and 4 obstacles (see online version for colours)



4.4 *Comparison of navigation schemes*

We compare the proposed schemes with Verma's scheme and Reich's scheme in Table 2 in terms of basic ideas and some performance metrics. Our schemes do not need position information and they have relatively low broadcasting redundancy, relatively high reachability, and the ability to coordinate multiple mobile robots. Furthermore, our schemes have about the same moving distance of mobile robots as Reich's scheme, and our schemes have shorter moving distance of mobile robots than Verma's scheme. By the comparison results, we can see that our proposed schemes are suitable for the coordination and navigation of mobile robots in positionless WSNs.

Table 2 Comparison of navigation schemes in robot-sensor networks

	Our schemes	*Verma's scheme*	*Reich's scheme*
Position information	Not needed	Needed	Not needed
Broadcasting mechanism	*k*-FNF	Flooding	Flooding
Coordination mechanism	Greedy-based coordination	None	None
Navigation mechanism	Tree-assisted navigation	Credit-based navigation	Gradient-based navigation
Broadcasting redundancy	Low	High	High
Reachability	High	High	High
Moving distance of mobile robots	Shorter	Longer	Shorter

5 Conclusion

Coordination and navigation of mobile robots are important and challenging design issues in robot-sensor networks. In this paper, we propose a suite of three schemes, called *k*-FNF, MRC and TAN, for coordination and navigation in positionless wireless robot-sensor networks. We also simulate our schemes by ns-2 simulator and compare the simulation results with those of related schemes. *k*-FNF scheme utilises the RSS for a node to make k farthest node have the highest possibility to forward a broadcast packet. As we have shown, *k*-FNF scheme can reduce a lot of redundant forwarding packets, while achieving good reachability. With the help of *k*-FNF scheme, we can construct navigation tree rooted at the WFR node to facilitate our coordination scheme MRC and our navigation scheme TAN. As we have shown, MRC and TAN schemes can successfully guide mobile robots to move towards the WFR nodes with short moving distances.

Navigating mobile robots in the situation with obstacles is challenging, especially in the positionless sensor network without map information. As we have shown in the simulation experiments, the proposed schemes might work well with large convex-shaped obstacles. However, it might have problems when encountering obstacles of any shapes. In the future, we plan to solve the problems by adding new devices, like compass or an anti-collision instrument, to mobile robots, or by integrating position information into our schemes.

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