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HVE-mobicast: a hierarchical-variant-egg-based mobicast routing protocol for wireless sensornets

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Abstract In this paper, we propose a new mobicast routing protocol, called the HVE-mobicast (hierarchical-variant-egg-based mobicast) routing protocol, in wireless sensor networks (WSNs). Existing protocols for a spatiotemporal variant of the multicast protocol called a "mobicast" were designed to support a forwarding zone that moves at a constant velocity, $\overrightarrow{v}$, through sensornets. The spatiotemporal characteristic of a mobicast is to forward a mobicast message to all sensor nodes that are present at time t in some geographic zone (called the forwarding zone) Z, where both the location and shape of the forwarding zone are a function of time over some interval (t_{start}, t_{end}). Mobicast routing protocol aims to provide reliable and just-in-time message delivery for a mobile sink node. To consider the mobile entity with the different moving speed, a new mobicast routing protocol is investigated in this work by utilizing the cluster-based approach. The message delivery of nodes in the forwarding zone of the HVE-mobicast routing protocol is transmitted by two phases; cluster-to-cluster and cluster-to-node phases. In the cluster-to-cluster phase, the cluster-head and relay nodes are distributively notified to wake them up. In the cluster-to-node phase, all member nodes are then notified to wake up by cluster-head nodes according to the estimated arrival time of the delivery zone. The key contribution of the HVE-mobicast routing protocol is that it is more power efficient than existing mobicast routing protocols, especially by considering different moving speeds and directions. Finally, simulation results illustrate performance enhancements in message overhead, power consumption, needlessly woken-up nodes, and successful woken-up ratio, compared to existing mobicast routing protocols.

Keywords Wireless sensor network · Spatiotemporal multicast · Mobicast · Cluster · Routing

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1 Introduction

A wireless sensor network (WSN) [1] is composed of a large number of small-sized, low-cost, low-power wireless sensor nodes/devices. Each sensor node/device has sensing, communicating, and data processing capabilities. One important research issue is the development of power-saving techniques to extend the network lifetime for WSNs with limited energy and scarce resources. Many techniques have been investigated for power-saving issues for WSNs, such as energy-efficiency MAC protocols [18], self-organization schemes [20], and directed diffusion protocols [11], energy-efficient routing protocols [7], and interest WSN applications, such as object tracking [8, 24, 26], human body and environmental monitoring [3], etc. These WSN applications need to send aggregated data, which are collected from many sensor nodes, to a sink node through efficient power-aware routing protocols in WSNs.

To support many WSN applications with an extended network lifetime, designing power-aware routing protocols is a very important research topic. Existing power-aware routing protocols are summarized as follows. Shiou *et al.* [23] proposed an energy-efficient routing protocol using the non-linear min-max programming technique to maximize the network life in sensor networks. Sabbineni *et al.* [22] presented a new data dissemination protocol based on a location-aided flooding scheme in WSNs. This protocol uses location information to reduce redundant transmissions, thereby saving energy. Many novel energy-efficient routing protocols [19, 29] have also been investigated in WSNs. In addition, multicasting in WSNs is a fundamental and important communication pattern to provide a sink node which can collect aggregated data from a set of sensor/destination nodes. Maleki *et al.* [17] proposed a lifetime-aware multicast routing algorithm in MANETs to maximize network lifetime. Furthermore, geocast routing is an important special case of multicast routing because all destination nodes are within a fixed geographical region. Existing geocasting protocols [2, 15] have been discussed in MANETs.

Recently, a new spatiotemporal multicast protocol, namely a mobicast, was presented in WSNs. The spatiotemporal characteristic of a mobicast is to forward a message to all nodes that will be present at time t in the forwarding zone, Z. The location and shape of the forwarding zone are a function of time over some interval (t_{start}, t_{end}). The mobicast is constructed by a series of message forwarding zones over different intervals (t_{start}, t_{end}). The sensor nodes in the forwarding zone in the time interval (t_{start}, t_{end}) are woken up for power-saving purposes. Huang *et al.* [21] presented a new energy-efficient spatiotemporal multicast in wireless sensor networks. There are many useful applications using mobicast routing protocols, such as object tracking [24, 26] and environmental monitoring [7, 8]. Observe that, Ji *et al.* [13] developed a dynamic cluster structure for object detection and tracking in WSNs. Acoustic target tracking [5] and push-and-pull discovery [16] have also been investigated in WSNs.

More recently, Chen *et al.* [6] proposed a variant-egg (VE)-based mobicast routing protocol in sensornets. The VE-mobicast protocol can adaptively and efficiently determine the location and shape of the message forwarding zone in order to maintain the same number of waken-up sensor nodes. To consider the path of a mobile entity which includes turns, variant-egg-based mobicast (VE-mobicast) routing protocol is investigated in [6] by utilizing the adaptive variant-egg shape of the forwarding zone to achieve high predictive accuracy. The message delivery method of VE-mobicast protocol is node-oriented. This method wastes unnecessary energy, e.g., by sending duplicate data. In existing protocols, when the prediction of the path of a forwarding zone is inaccurate, the nodes that were woken up earlier in the forwarding zone also waste much energy.

It is evident that the cluster-based approach offers benefits of power savings and low packet overhead. Many routing protocols are cluster-based schemes [14, 27, 28, 30], since only the cluster head is responsible for forwarding aggregated data. For example, Yu *et al.* [28] presented a clustering scheme for mobile ad hoc networks. Routing procedures are managed by the cluster head and cluster members do not be involved. So the packet overhead is confined to cluster head. Kwon *et al.* [14] proposed a passive clustering scheme in ad hoc sensor networks. An on-demand cluster construction scheme was developed by Kwon *et al.*, but it still had the same benefits as the cluster-based scheme. Efforts are made in this paper to develop a cluster-based variant-egg-based mobicast routing protocol in sensornets.

In this paper, we propose a new mobicast routing protocol, called an HVE-mobicast (hierarchical-variant-egg-based mobicast) routing protocol, in wireless sensor networks (WSNs). Existing protocols for a spatiotemporal variant of multicast called a "mobicast" were designed to support a forwarding zone that moves at a constant velocity, $\vec{v}$, through sensornets. The spatiotemporal characteristic of a mobicast is to forward a mobicast message to all sensor nodes that are present at time t in some geographic zone (called the forwarding zone), Z, where both the location and shape of the forwarding zone are a function of time over some interval (t_{start}, t_{end}). The mobicast routing protocol aims to provide reliable and just-in-time message delivery for a mobile sink node. To consider the mobile entity with the different moving speed, a new mobicast routing protocol is investigated in this work by utilizing the cluster-based approach. Message delivery by nodes in the *forwarding zone* of the HVE-mobicast routing protocol is accomplished by two phases; cluster-to-cluster and cluster-to-node phases. In the cluster-to-cluster phase, cluster-head and relay nodes are distributively notified to wake them up. In the cluster-to-node phase, all member nodes are then notified to wake up by cluster-head nodes according to the estimated arrival time of the delivery zone. The key contribution of the HVE-mobicast routing protocol is that it is more power efficient than existing mobicast routing protocols, especially by considering different moving speeds and directions. Finally, simulation results illustrate performance enhancements in message overhead, power consumption, needlessly woken-up nodes, and successful woken-up ratio, compared to existing mobicast routing protocols.

The rest of this paper is organized as follows. Section 2 presents the basic ideas and challenges of our routing protocol. Our proposed HVE-mobicast protocol is presented in Sect. 3. Section 4 gives the performance analysis. Finally, Sect. 5 concludes this paper.

2 Basic ideas and challenges

This section discusses the basic ideas and challenges of a special case of a "spatiotemporal multicast" protocol, where the spatiotemporal multicast provides sensing applications that need to disseminate the multicast message to the "right place" (or prescribed zone) at the "right time". A spatiotemporal multicast session is specified by $\langle m, Z[t], T_s, T\rangle$, which is formally defined in [10], where m is the multicast message, $Z[t]$ describes the expected area of message delivery at time t, and T_s and T are the sending time and duration of the multicast session, respectively. As the delivery zone $Z[t]$ evolves over time, and the set of recipients for m changes as well. A special case of a spatiotemporal multicast protocol, called a mobicast, was recently considered [6, 9, 10, 21].

In general, a mobicast routing protocol is composed of a delivery zone and a forwarding zone [6, 9, 10, 21]. The forwarding zone [10] is defined as every sensor node in forwarding zone $F[t+1]$ being responsible for forwarding the mobicast messages to guarantee that delivery zone $Z[t+1]$ at time $t+1$ can successfully receive the mobicast message. The size of forwarding zone $F[t+1]$ is always larger than the size of delivery zone $Z[t+1]$. One key problem of the mobicast routing protocol is how to predict and estimate the correct size and shape of forwarding zone $F[t+1]$ at time t.

More recently, Chen *et al.* [6] proposed a variant-egg-based mobicast (VE-mobicast) routing protocol. The VE-mobicast routing protocol develops an adaptive shape for the forwarding zone. VE-mobicast routing protocol can significantly improve the predictive accuracy of the delivery zone in [6]. An example of a VE-mobicast routing protocol is given in Fig. 1(a). The forwarding zone and delivery zone of VE-mobicast routing protocol are denoted as $F_{VE}[t]$ and $Z_{VE}[t]$ at time t. In the VE-mobicast routing protocol [6], the mobicast message floods the forwarding zone, $F_{VE}[t]$, at time t. The mobicast message also contains information on the direction and speed of the delivery zone. The information of direction and speed can acquire from the GPS device. Onemain purpose of the mobicast message is to adaptively and efficiently determine the location and shape of forwarding zone $F_{VE}[t+1]$ at time $t+1$. As illustrated in Fig. 1(a), all sensor nodes in forwarding zone $F_{VE}[t+1]$ at time $t+1$ are woken up to a wait the arrival of delivery zone $Z_{VE}[t+1]$ at time $t+1$. Observe that the message delivery mechanism of the VE-mobicast adopts node-to-node transmission in [6]. Efforts are made in this work to develop a cluster-based VE-mobicast routing protocol with greater power savings and higher predictive accuracy. From [6], the predictive accuracy is the percentage of the sensor nodes located in both $Z_{VE}[t+1]$ and $F_{VE}[t+1]$, therefore the predictive accuracy of the HVE-mobicast routing protocol is the percentage of sensor nodes which are located in both $Z_{HVE}[t+1]$ and $F_{HVE}[t+1]$. If most sensor nodes in $Z_{HVE}[t+1]$ are also in $F_{HVE}[t+1]$, then the predictive accuracy is high. Otherwise, the predictive accuracy is low.

To consider the mobile entity with the different moving speed, this paper mainly develops a new power-efficient mobicast routing protocol, called the HVE-mobicast (hierarchical-variant-egg-based mobicast) routing protocol. The forwarding zone and delivery zone of the VE-mobicast routing protocol are denoted as $F_{HVE}[t]$ and $Z_{HVE}[t]$ at time t. The forwarding zone $F_{HVE}[t]$ consists of a number of clusters. The cluster-head election algorithm can be used from [12, 27]. In this work, HEED protocol, which proposed by Younis et al. [27], considers the residual energy and degree of a node to determine which node can be the cluster-head, so the cluster-head can stably operate. Therefore, HEED protocol is adopted as our cluster-head election algorithm. All sensor nodes in forwarding zone $F_{HVE}[t]$ can be classified into groups I and II. Group I contains cluster-head nodes and gateway nodes, while group II contains all other sensor nodes. All sensor nodes in group I are initially woken up, and then all sensor nodes in group II are woken up after waiting for a period of time. Obviously, the HVE-mobicast routing protocol save power since the power consumption is lower during this period of time for all sensor nodes in group II. An example is given in Fig. 1(b).

The wake-up time-interval of the VE-mobicast routing protocol is denoted $T_{F_{VE}}$ in which all sensor nodes in $F_{VE}[t+1]$ are woken up. The wake-up time-interval of the HVE-mobicast routing protocol is denoted $T_{F_{HVE}} = T^{I}_{F_{HVE}} + T^{II}_{F_{HVE}}$ in which all sensor nodes in $F_{HVE}[t+1]$ are woken up. Let $T^{I}_{F_{HVE}}$ and $T^{II}_{F_{HVE}} = t_{i-1}$, where $1 \le i < T_{F_{VE}} - T^{I}_{F_{HVE}}$, denote the time cost to wake up sensor nodes of groups I and II in $F_{HVE}[t+1]$, respectively. Observe that $T^{I}_{F_{HVE}} + T^{II}_{F_{HVE}} < T_{F_{VE}}$, since the cluster advantage is used in the HVE-mobicast routing protocol. An example is shown in Fig. 1, where $T^{I}_{F_{HVE}} = t_{16} < T_{F_{VE}} = t_{30}$, and $T^{II}_{F_{HVE}} = t_{i-1}$. Therefore, the wake-up time interval of $F_{HVE}[t+1] = T^{I}_{F_{HVE}} + T^{II}_{F_{HVE}} = t_{16+i-1}$ < the wake-up time interval of $F_{VE}[t+1] = t_{30}$.

Observe that the result of wake-up time interval $T_{F_{HVE}}$ < wake-up time interval $T_{F_{VE}}$ is very important for handling the case of a variant speed for $Z_{HVE}[t+1]$. Existing mobicast routing protocols are considered a "constant velocity mobile mobicast". For example, using VE-mobicast routing, the moving speed of delivery zones from $Z_{VE}[t]$ to $Z_{VE}[t+1]$ is fixed as a constant velocity $\overrightarrow{v}$. As shown in Fig. 2(a), all sensor nodes in $F_{VE}[t+1]$ must be woken up before $T_{F_{VE}}$. However, if the moving speed becomes faster and is changed to $\overrightarrow{v'}$, where $|v'| > |v|$, then the delivery zone is moved from $Z_{VE}[t]$ to $Z'_{VE}[t+1]$ from time t to time $t+1$. Assume that the arrival times with $Z_{VE}[t+1]$

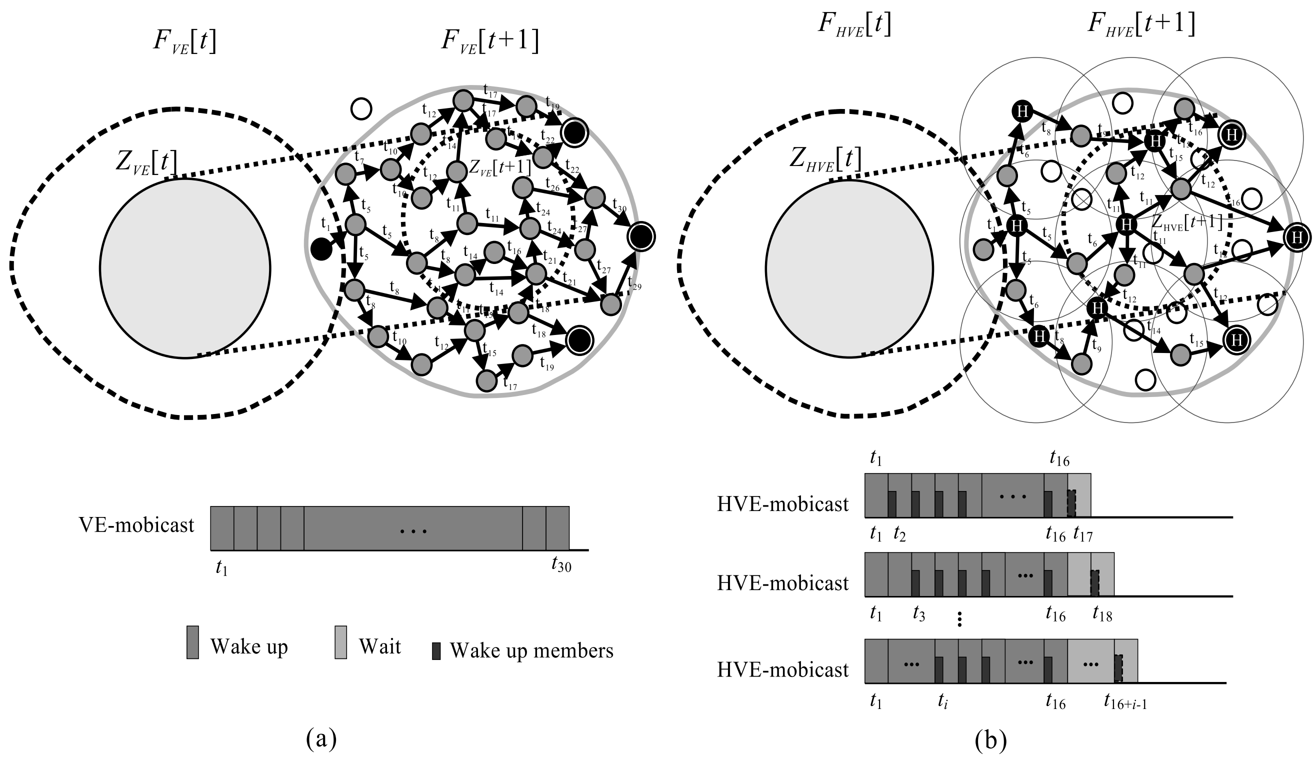

Fig. 1 Waking up process with the VE-mobicast and HVE-mobicast protocol

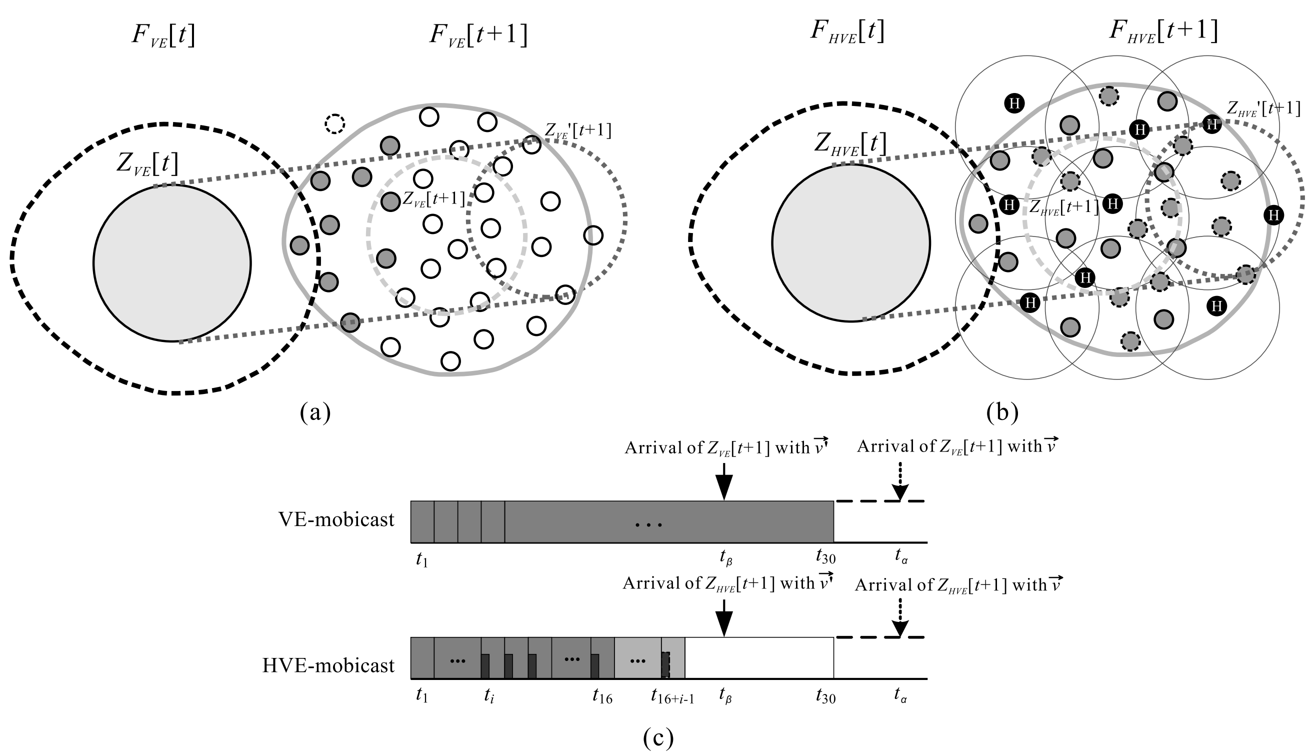

Fig. 2 Delivery zone with high speed in the VE-mobicast and HVE-mobicast protocols

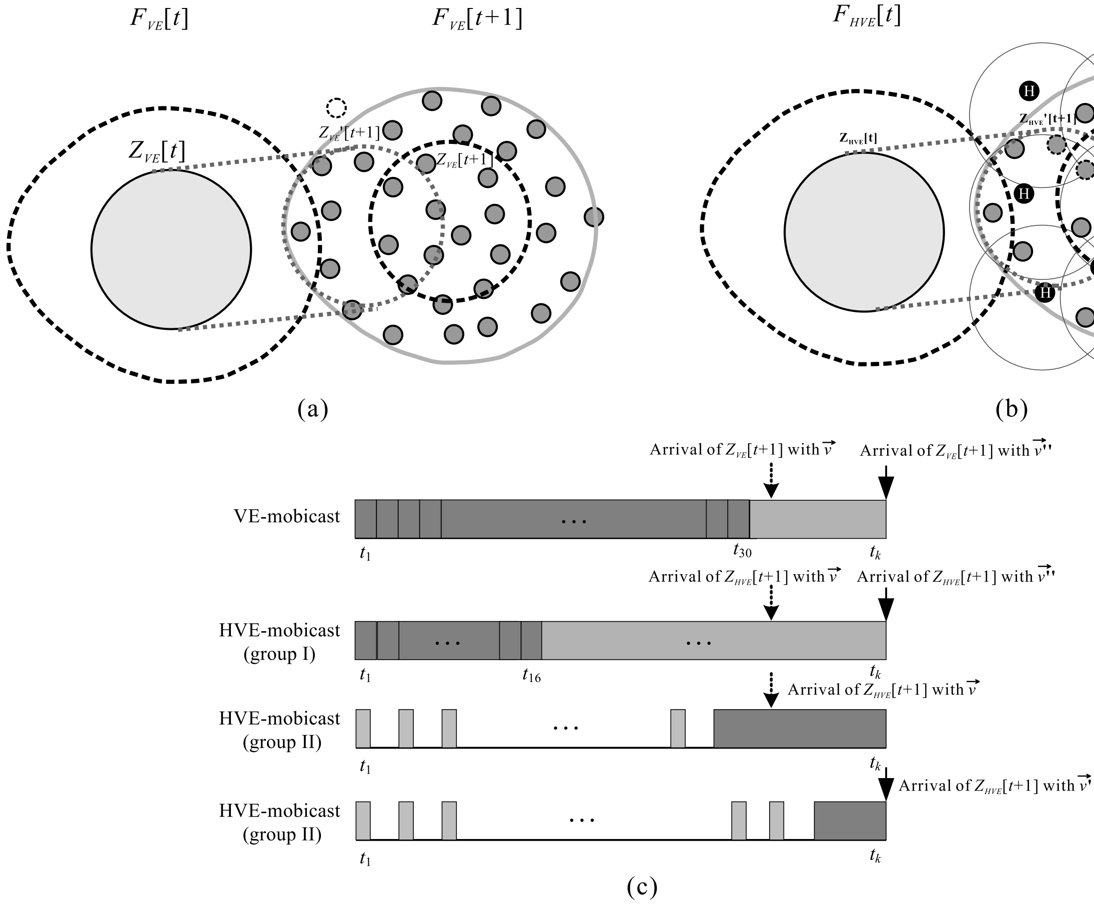

Fig. 3 Delivery zone with a slow speed in the VE-mobicast and HVE-mobicast protocol

of velocities $\vec{v}$ and $\vec{v'}$ are t_α and t_β. This resulting $t_\beta < T_{F_{VE}} < t_\alpha$. It thus takes less time to move from $Z_{VE}[t]$ to $Z_{VE}[t+1]$, and not all sensor nodes in $F_{VE}[t+1]$ can be woken up in time before $T_{F_{VE}}$. This causes an error condition in which inaccurate sensing data for the VE-mobicast routing are collected if a variable speed for the delivery zone is considered. This condition can efficiently be improved by using our new HVE-mobicast routing protocol, since $T_{F_{HVE}} < T_{F_{VE}}$. As illustrated in Fig. 2(b), assume that the arrival times of $Z_{HVE}[t+1]$ with velocities $\vec{v}$ and $\vec{v'}$ are t_α and t_β. Our scheme works well when $T_{F_{HVE}} < t_\beta < t_\alpha$ and $T_{F_{HVE}} < t_\beta < T_{F_{VE}}$. If the moving speed becomes slower and is changed to $\vec{v''}$, where $|v''| > |v|$, then the delivery zone moves from $Z_{HVE}[t]$ to $Z'_{HVE}[t+1]$ from time t to time $t+1$. An example is given in Fig. 3(a), (b). As shown in Fig. 3(c), the time period of the ready state for all sensor nodes in group II is obviously extended if $|v''| > |v|$. Therefore, our scheme actually saves power.

Another important contribution of our scheme is to reduce the power wasted if $Z_{HVE}[t]$ moves to $Z_{HVE}[t+1]$ along a different direction, from time t to time $t+1$. In VE-mobicasting, all sensor nodes in $F_{VE}[t+1]$ are woken up. In our scheme, all sensor nodes of group I in $F_{VE}[t+1]$ are woken up, but all sensor nodes of group II in $F_{VE}[t+1]$ are already in a ready state. Therefore, our scheme saves power if the factor of a different direction is considered. An example is given in Fig. 4. Improving the predictive accuracy of the forwarding zone and reducing the power consumption of WSNs are the main objectives of this work.

3 HVE-mobicast: hierarchical-variant-egg-based mobicast routing protocol

In this work, each node is assumed to be equipped with a location provider (*global position system*, GPS), and a cluster environment is pre-constructed as described in [14, 27, 28] before applying the HVE-mobicast routing protocol. The cluster head and relay nodes are identified by algorithms [27]. In this section, we present the hierarchical variant-egg-based mobicast routing protocol. While sensor nodes in a forwarding zone retransmit the message as soon as a sensor node receives it, the sensor nodes in the front of the forwarding zone enter a "hold-and-forward" state

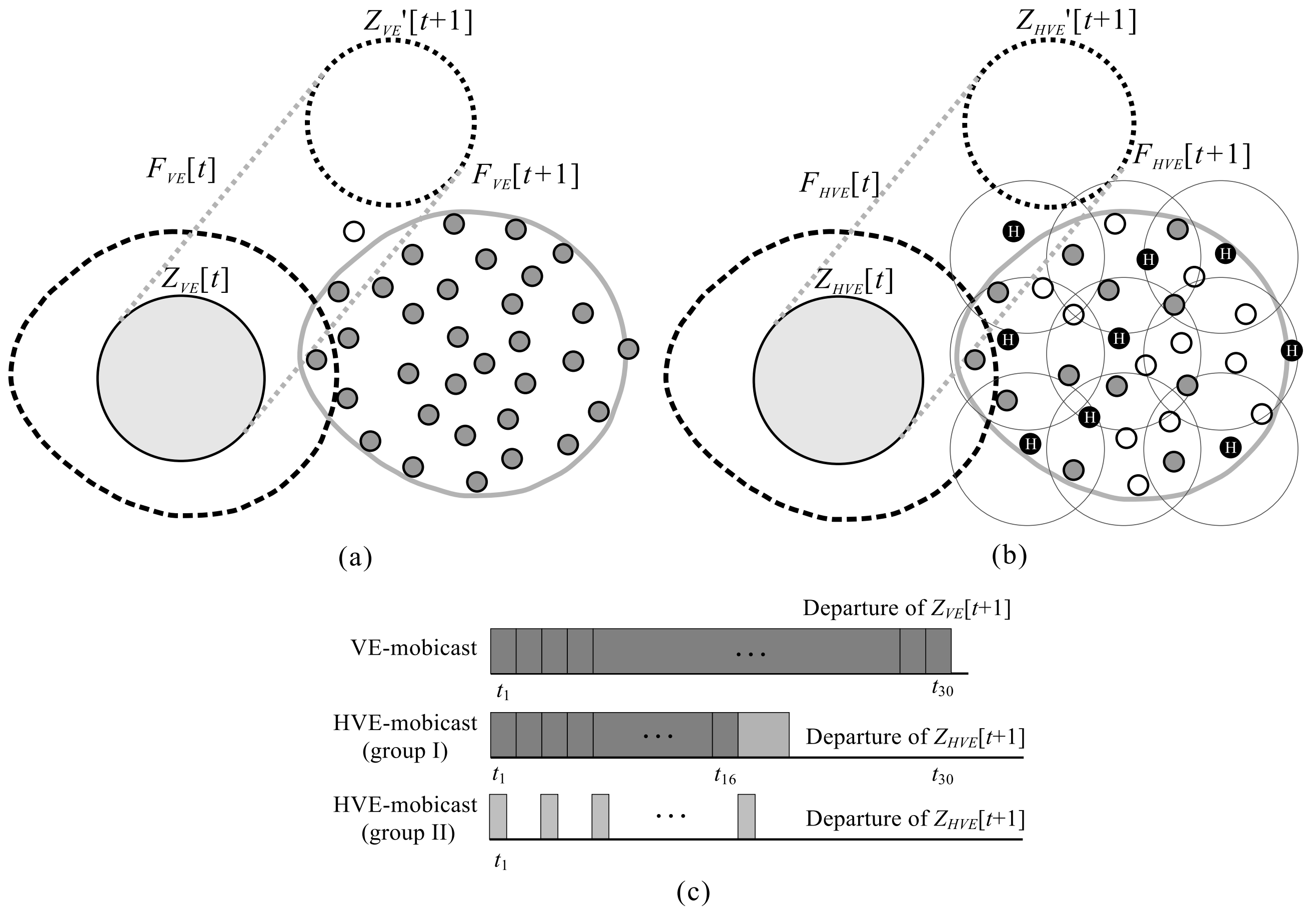

Fig. 4 Delivery zone which has changed direction with the VE-mobicast and HVE-mobicast protocol

whenever they hear the mobicast message [6, 9, 10, 21]. They retransmit the mobicast message only after becoming members of the forwarding zone. This area is denoted the hold-and-forward zone $H_{HVE}[t]$ at time t. In our HVE-mobicast approach, the hold-and-forward zone $H_{HVE}[t] = F_{HVE}[t] \cap F_{HVE}[t+1]$. An example of a hold-and-forward zone $H_{HVE}[t]$ is given in Fig. 5. The HVE-mobicast routing protocol is divided into two phases as follows.

(1) *Egg estimation phase*: The size of the variant-egg forwarding zone $F_{HVE}[t+1]$ at time t is estimated by sensor nodes in $H_{HVE}[t]$. The forwarding zone limits retransmission to a bounded space while ensuring that all nodes that need to get the message do so.

(2) *Distributed hierarchical-variant-egg-based mobicast phase*: With the estimated $F_{HVE}[t+1]$, a distributed algorithm of the HVE-mobicast operation is presented for all sensor nodes in $H_{HVE}[t]$. This operation can dynamically adjust the shape of the variant-egg forwarding zone $F_{HVE}[t+1]$ at time $t+1$. All sensor nodes in group I (including the cluster head and gateway nodes)are awoken by sensor nodes in $H_{HVE}[t]$, and then all other sensor nodes in group II are awoken by cluster head nodes.

3.1 Phase I: egg estimation

All sensor nodes in $H_{HVE}[t]$ at time t estimate the shape and size of variant-egg $F_{HVE}[t+1]$ for the incoming delivery zone, $Z_{HVE}[t+1]$. The shape of the variant-egg [6] is calculated by the equation of the *Cassini Oval*. The equation can be reduced to:

$$[(x)^2 + (y)^2]^2 - 2e^2[(x)^2 + (y)^2] = 0$$

The detailed formula of the variant-egg can be seen in [6]. Figure 5 shows an example of $F_{HVE}[t+1]$, where O_1 and O_2 denote two fixed points, O_2 is the center of the variant-egg forwarding zones, and $e = \pi^{1/2}R$. The term, R, is the radius of delivery zone $Z_{HVE}[t]$, D is the distance between delivery zone $Z_{HVE}[t]$ and forwarding zone $F_{HVE}[t+1]$, and r is the radius of the cluster head. One important task is deciding whether or not a sensor node (a, b) is located in a variant-egg forwarding zone $F_{HVE}[t+1]$. If $(x^2+y^2)^2 - 2e^2(x^2+y^2) = (a^2+b^2)^2 - 2e^2(a^2+b^2) \leq 0$, then (a, b)

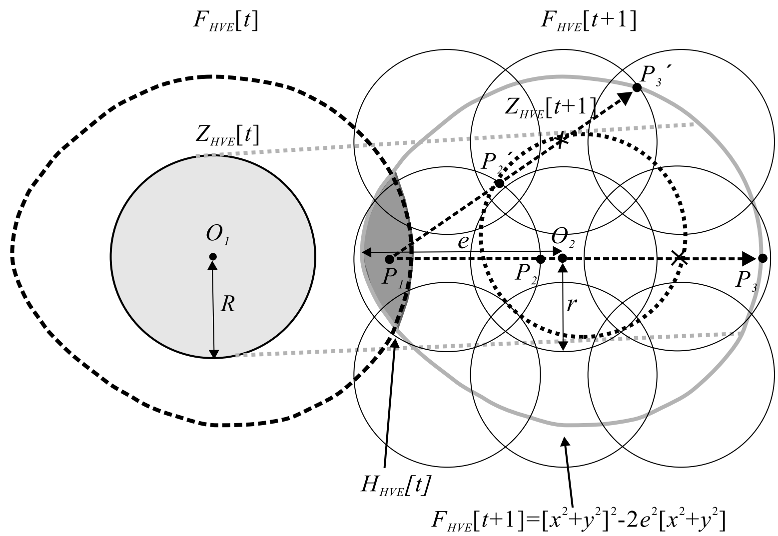

Fig. 5 Definition of the HVE-mobicast

is located in variant-egg forwarding zone $F_{HVE}[t+1]$. If $(x^2+y^2)^2 - 2e^2(x^2+y^2) = (a^2+b^2)^2 - 2e^2(a^2+b^2) > 0$, then (a, b) is not located in variant-egg forwarding zone $F_{HVE}[t+1]$. Given $F_{HVE}[t] = (x_t^2 + y_t^2)^2 - 2e_t^2(x_t^2 + y_t^2)$ and $F_{HVE}[t+1] = (x_{t+1}^2 + y_{t+1}^2)^2 - 2e_{t+1}^2(x_{t+1}^2 + y_{t+1}^2)$, an estimated hop count, H, is estimated as follows.

Step 1: The first task is to decide whether or not sensor node P_1 at (a, b) is located in the hold-and-forward zone $H_{HVE}[t] = F_{HVE}[t] \cap F_{HVE}[t+1]$. Sensor node P_1 is within $H_{HVE}[t]$ if P_1 is within $F_{HVE}[t]$ and P_1 is also within $F_{HVE}[t+1]$; that is, $(x_t^2 + y_t^2)^2 - 2e_t^2(x_t^2 + y_t^2) = (a^2+b^2)^2 - 2e^2(a^2+b^2) \leq 0$ and $(x_{t+1}^2 + y_{t+1}^2)^2 - 2e_{t+1}^2(x_{t+1}^2 + y_{t+1}^2) = (a^2+b^2)^2 - 2e_{t+1}^2(a^2+b^2) \leq 0$.

Step 2: An estimated hop count, H, is roughly calculated as follows. This estimated value is useful in phase II. Assume that a cluster covers the region of $H_{HVE}[t]$ which is called the *hold-and-forward cluster*. Let P_1 in $H_{HVE}[t]$ be a *hold-and-forward cluster head*. Given any relay node, P_2, path $\overleftrightarrow{P_1P_2}$ from P_1 to P_2 is considered, where point P_3 is the intersection of path $\overleftrightarrow{P_1P_2}$ with $F_{HVE}[t+1]$. An example is shown in Fig. 5. When $\overline{P_1P_3}$ is the distance from P_1 to P_3, the estimated hop count H is $\lceil \frac{\overline{P_1P_3}}{r} + 1 \rceil$ hops, where r is the communication radius of the cluster. An example is illustrated in Fig. 5, for which the estimated hop counts from P_1 to P_2 and P_2' are four and three, respectively.

3.2 Phase II: distributed hierarchical-variant-egg-based mobicast

Phase I mainly estimates the normal size and shape of a variant-egg-based forwarding zone, $F_{HVE}[t+1]$. In phase II, we develop a distributed algorithm based on a cluster approach to dynamically adjust the size and shape of variant-egg-based forwarding zone $F_{HVE}[t+1]$. The sensor nodes in $H_{HVE}[t]$ should forward a mobicast message to the *hold-and-forward* cluster head. Then, the *hold-and-forward* cluster head forwards the mobicast message to all other clusters in $F_{HVE}[t+1]$ to first wake up all sensor nodes in group I, and then wake up all other sensor nodes in group II after a calculated time. As mentioned before, all sensor nodes are divided into two groups; group I consists of cluster head nodes and relay nodes, while all other sensor nodes (member nodes in all clusters) are in group II. None of the nodes in group II relays flooding packets. This results in low packet overhead.

A simple control packet, denoted $P_{HVE}(\frac{h}{H}, N_{11}N_{12}\ldots N_{1i})t_x$ or P_{HVE}, is adopted in this work for developing the distributed algorithm, where $\frac{h}{H}$ is used to limit the number of packets forwarded, $N_{11}N_{12}\ldots N_{1i}$ keeps the path history, and the P_{HVE} packet is forwarded at time t_x. The value of H is calculated by $\lceil \frac{\overline{P_2P_3}}{r} + 1 \rceil$ from phase I, and the term, h, is increased if a P_{HVE} packet travels from one cluster to another cluster.

Assume that all sensor nodes are uniformly distributed in an area. This area is divided into three kinds of regions. Without loss of generality, we only consider the case of $Z_{HVE}[t]$ being adjacent to $Z_{HVE}[t+1]$, and a pair of $F_{HVE}[t]$ and $F_{HVE}[t+1]$ to explain the three regions.

- Region 1: A region along a path from $Z_{HVE}[t]$ to $Z_{HVE}[t+1]$, as shown in Fig. 6(a).
- Region 2: $F_{HVE}[t] \cup F_{HVE}[t+1]$ − Region 1, as illustrated in Fig. 6(b).
- Region 3: Inverse $(F_{HVE}[t] \cup F_{HVE}[t+1])$, as illustrated in Fig. 6(c).

The distributed algorithm of the HVE-mobicast operation is given here; *Steps 1–5* attempt to wake up all sensor nodes in group I, whole *Steps 6* and *7* are used to wake up all sensor nodes in group II.

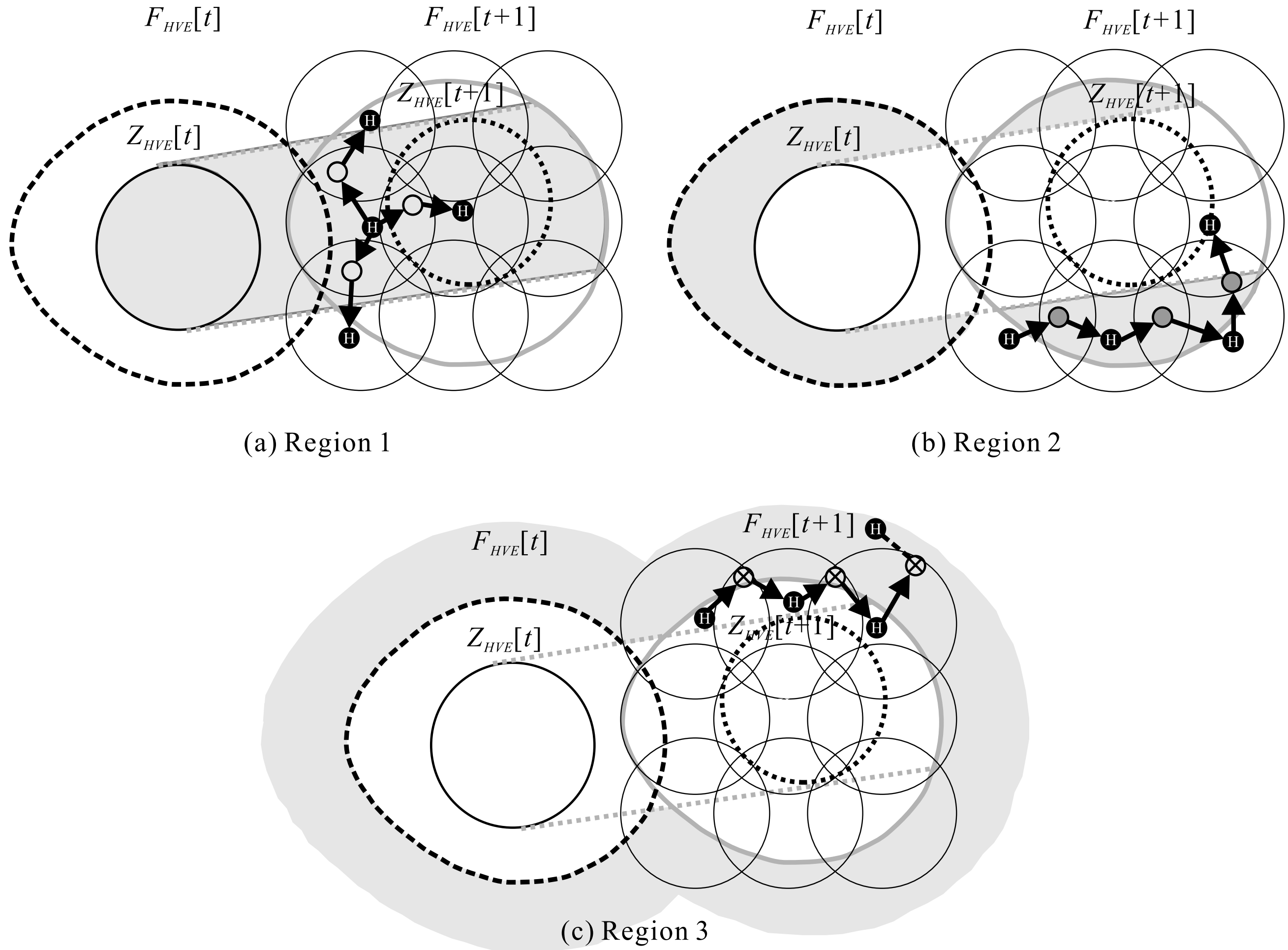

Fig. 6 Forwarding rules for relay nodes in three different regions

Step 1: Sensor nodes in $H_{HVE}[t]$ forward a mobicast message to the *hold-and-forward* cluster head at time t_1. Then, the *hold-and-forward* cluster head forwards the mobicast message to all neighboring cluster head nodes. Only cluster head P_i initiates and floods $P_{HVE}(\frac{1}{H}, P_i)t_x$ packets through relay nodes to neighboring cluster head P_j at time t_y, where H is the hop count calculated in phase I, $t_y = t_x + d + backoff\_time$, and d is the degree (number of neighboring relay nodes) of P_j. This means that the P_{HVE} packet received by P_j must wait for a period of time until t_y.

Step 2: Let cluster head H receive the $P_{HVE}(\frac{h_1}{H_1}, N_{1,1}N_{1,2}\ldots N_{1,i-1})t'_{x_1}$ packet from N_{1i-1} at time t'_{x_1}, where $t'_y = t'_{x_1} + d + backoff\_time$ and d is number of neighboring relay nodes of H. Cluster head H waits for a period of time until t'_y to receive any additional different P_{HVE} packets. A *waiting timer*, T_w, is set up, and this waiting timer is used to wake up all member nodes in the cluster before the arrival of delivery zone $Z_{HVE}[t+1]$, where *waiting timer* $T_w = T' - T''$, for which T' is the estimated arrival time of delivery zone $Z_{HVE}[t+1]$, and T'' is the minimum time which cluster head H receives the mobicast message.

Step 3: If relay node R receives the mobicast message, it is not forwarded to the next cluster head, H, if R and H are both in region 3. Otherwise, this mobicast message is forwarded.

Step 4: Assume that $P_{HVE}(\frac{h_1}{H_1}, N_{1,1}N_{1,2}\ldots N_{1,i-1})t'_{x_1}$, $P_{HVE}(\frac{h_2}{H_2}, N_{2,1}N_{2,2}\ldots N_{2,i-1})t'_{x_2}, \ldots,$ and $P_{HVE}(\frac{h_m}{H_m}, N_{m,1}\ N_{m,2}\ldots N_{m,i-1})t'_{x_m}$ packets are received at cluster head H before time t'_y, and m P_{HVE} packets are merged to one P_{HVE} packet, denoted as

$$P_{HVE}\left(\frac{h_{merge}}{H_{merge}}, \begin{bmatrix} N_{1,1}N_{1,2}\ldots N_{1,i-1}, P_i \\ \vdots \\ N_{m,1}N_{m,2}\ldots N_{m,i-1}, P_i \end{bmatrix}\right)_{t'_y}.$$

The merging operation, which depends on the position of cluster head H, is given here.

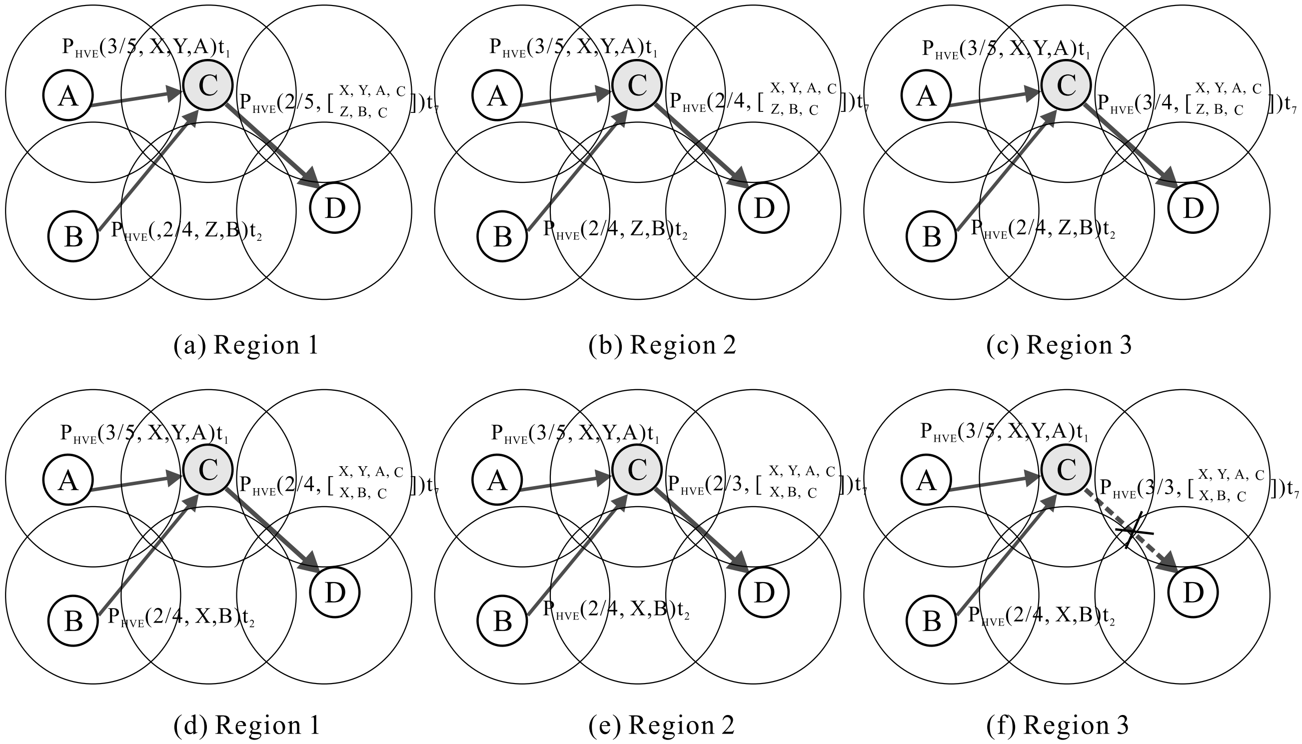

Fig. 7 Merging operations for cluster heads

1. Let $\frac{h_{merge}}{H_{merge}} = \frac{\underset{1\le i\le m}{\text{Min}}\ h_i}{\underset{1\le i\le m}{\text{Max}}\ H_i}$ if H is in region 1.
2. Let $\frac{h_{merge}}{H_{merge}} = \frac{\underset{1\le i\le m}{\text{Min}}\ h_i}{\underset{1\le i\le m}{\text{Min}}\ H_i}$ if H is in region 2.
3. Let $\frac{h_{merge}}{H_{merge}} = \frac{\underset{1\le i\le m}{\text{Max}}\ h_i}{\underset{1\le i\le m}{\text{Min}}\ H_i}$ if H is in region 3.

Step 5: If there are n identical predecessor cluster heads for all path histories of

$$\begin{bmatrix} N_{1,1}N_{1,2}\ldots N_{1,i-1},\ P_i \\ \vdots \\ N_{m,1}N_{m,2}\ldots N_{m,i-1},\ P_i \end{bmatrix},$$

then let $H_{merge} = H_{merge} - n$. After that, the

$$P_{HVE}\left(\frac{h_{merge}}{H_{merge}}, \begin{bmatrix} N_{1,1}N_{1,2}\ldots N_{1,i-1},\ P_i \\ \vdots \\ N_{m,1}N_{m,2}\ldots N_{m,i-1},\ P_i \end{bmatrix}\right)_{t'_y}$$

packet is forwarded if $\frac{h_{merge}}{H_{merge}} < 1$ at time t'_y.

Examples of the merging operation in *Step 4* are shown in Fig. 7. As shown in Fig. 7(a), if cluster head C is in region 1, cluster head C receives $P_{HVE}(\frac{3}{5}, X, Y, A)_{t_1}$ and $P_{HVE}(\frac{2}{4}, Z, B)_{t_2}$, and the merged packet is

$$P_{HVE}\left(\frac{2}{5}, \begin{bmatrix} X, Y, A, C \\ Z, B, C \end{bmatrix}\right)_{t_7}$$

since no identical predecessor cluster head exists. Figure 7(d) explains that cluster head C is in region 1, cluster head C receives $P_{HVE}(\frac{3}{5}, X, Y, A)_{t_1}$ and $P_{HVE}(\frac{2}{4}, X, B)_{t_2}$, and the merged packet is

$$P_{HVE}\left(\frac{2}{4}, \begin{bmatrix} X, Y, A, C \\ X, B, C \end{bmatrix}\right)_{t_7}$$

because X is identical to the predecessor cluster head. Four other cases can similarly be derived as shown in Figs. 7(c), (e), (f). In *Step 5*, it can be observed that $\frac{h_{merge}}{H_{merge}}$ is used to determine whether or not the P_{HVE} packet should be forwarded by the cluster heads, where h_{merge} denotes the estimated hop number over which the current P_{HVE} packet traverses and H_{merge} is the estimated hop count toward the boundary of $F_{HVE}[t+1]$. If the ratio of $\frac{h_{merge}}{H_{merge}} < 1$, the P_{HVE} packet should be forwarded since $h_{merge} < H_{merge}$. If the ratio of $\frac{h_{merge}}{H_{merge}} \geq 1$, the P_{HVE} packet can be forwarded since $h_{merge} \geq H_{merge}$. In the following, *Steps 5* and *6* are provided to wake up all sensor nodes in group II.

Step 6: Each cluster head maintains a *waiting timer*, T_w, then all sensor nodes in group II are woken up by the

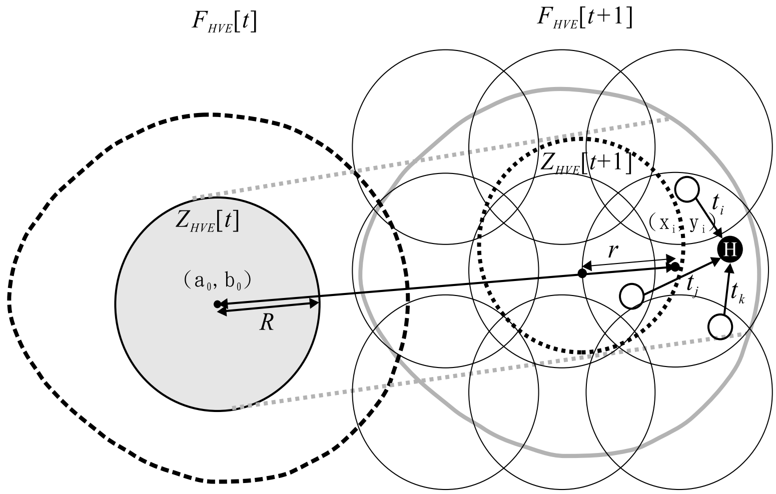

Fig. 8 Definition of the waiting timer in the HVE-mobicast protocol

cluster head if $T_w \leq 0$. Let *waiting timer* $T_w = T' - T''$, where T' is the estimated arrival time of delivery zone $Z_{HVE}[t+1]$, and T'' is the minimum time when cluster head H receives the mobicast message. An example can be seen in Fig. 8. The details of T' and T'' are given here.

- $T' = \frac{D((x_i, y_i), (a_0, b_0)) - r}{|v|}$, where (x_i, y_i) is the center of cluster i, (a_0, b_0) is the center of $Z_{HVE}[t]$, $D((x_i, y_i), (a_0, b_0))$ is the distance between points (x_i, y_i) and (a_0, b_0), r is the cluster radius, and $\overrightarrow{v}$ is the fixed moving speed of delivery zone $Z_{HVE}[t]$ at time t.
- $T'' = \text{Min}_{1<x<n} t_x$, where n is the number of relay nodes.

If *waiting timer* $T_w > 0$, the cluster head wakes up the nodes of group II while the *waiting timer* expires. Otherwise, if *waiting timer* $T_w \leq 0$ or the delivery zone has already arrived, the cluster head instantly wakes up the nodes of group II.

Step 7: In the beginning, the sensor nodes in $H_{HVE}[t]$ send a control signal to the cluster head of the *hold-and-forward* cluster at time t_1. The control signal, $P'_{HVE}((a_0, b_0), \overrightarrow{v})$, consists of the initial position (a_0, b_0), and the moving speed and direction $\overrightarrow{v}$ of $Z_{HVE}[t]$. The nodes of group I in $H_{HVE}[t]$ periodically check the moving speed and direction of $Z_{HVE}[t]$.

- If the moving speed of $Z_{HVE}[t]$ changes, the nodes of group I in the rear of $F_{HVE}[t]$ detect the arrival of the delivery zone before the waiting timer expires. These nodes then wake up the nodes of group II as soon as possible and inform the next neighboring cluster heads to adjust their waiting timers by sending control packet $P'_{HVE}((a'_0, b'_0), \overrightarrow{v'})$. The nodes of group I in $H_{HVE}[t]$ receive control packet P'_{HVE} and forward it to the cluster heads in $F_{HVE}[t+1]$. The cluster heads in $F_{HVE}[t+1]$ adjust their waiting timers according to P'_{HVE}. An example is shown in Figs. 11 and 12.
- If the moving direction of $Z_{HVE}[t]$ changes, the nodes of group I in the rear of $F_{HVE}[t]$ detect the departure of the delivery zone after the waiting timer expires. These nodes inform the nodes of group II to go back to sleep, send control packet $P'_{HVE}((a'_0, b'_0), \overrightarrow{v'})$ to the next neighboring cluster heads, and go back to sleep themselves. $H_{HVE}[t]$ receives the control packet which stops its waiting timer and forwards it to all cluster heads in $F_{HVE}[t+1]$. The cluster heads in $F_{HVE}[t+1]$ stop their waiting timers according to P'_{HVE} and go back to sleep. An example is shown in Fig. 13.

In the following, we give further examples of delivery zones from $Z_{HVE}[t]$ to $Z_{HVE}[t+1]$ from times t to $t+1$.

When the moving speed and direction of the delivery zone remains the same, there are two different cases. One case is the problem "with a hole" and another is "without a hole". These two example are shown in Figs. 9 and 10. The difference between Figs. 9 and 10 is the hole which is on the routing path in Fig. 10, and therefore on the egg-based forwarding zone in Fig. 10. The sensor nodes in $H_{HVE}[t]$ begin to forward the mobicast message to the cluster head of the *hold-and-forward* cluster. Then, the *hold-and-forward* cluster head broadcasts the mobicast message $(\frac{1}{2}, A)t_5$ through the relay node to the next neighboring cluster head B, C at time t_5 and the mobicast message $(\frac{1}{3}, A)t_5$ to the next neighboring cluster head D through a relay node at time t_5. Cluster head A forwards the P_{HVE} packet through B, C within 2 hops and E within 3 hops. Cluster head D has five relay nodes, and the P_{HVE} packet is sent at time t_{11}. If the cluster head receives only one mobicast message, both h and H of the mobicast message add one and send the message on. Cluster head E receives mobicast message $P_{HVE}(\frac{2}{3}, A, B)$ from cluster head B and mobicast message $P_{HVE}(\frac{2}{4}, A, D)$ from cluster head D. Since cluster head E is in region 1, the value of $\frac{h}{H}$ becomes $\frac{2}{4}$. But, one cluster head has same

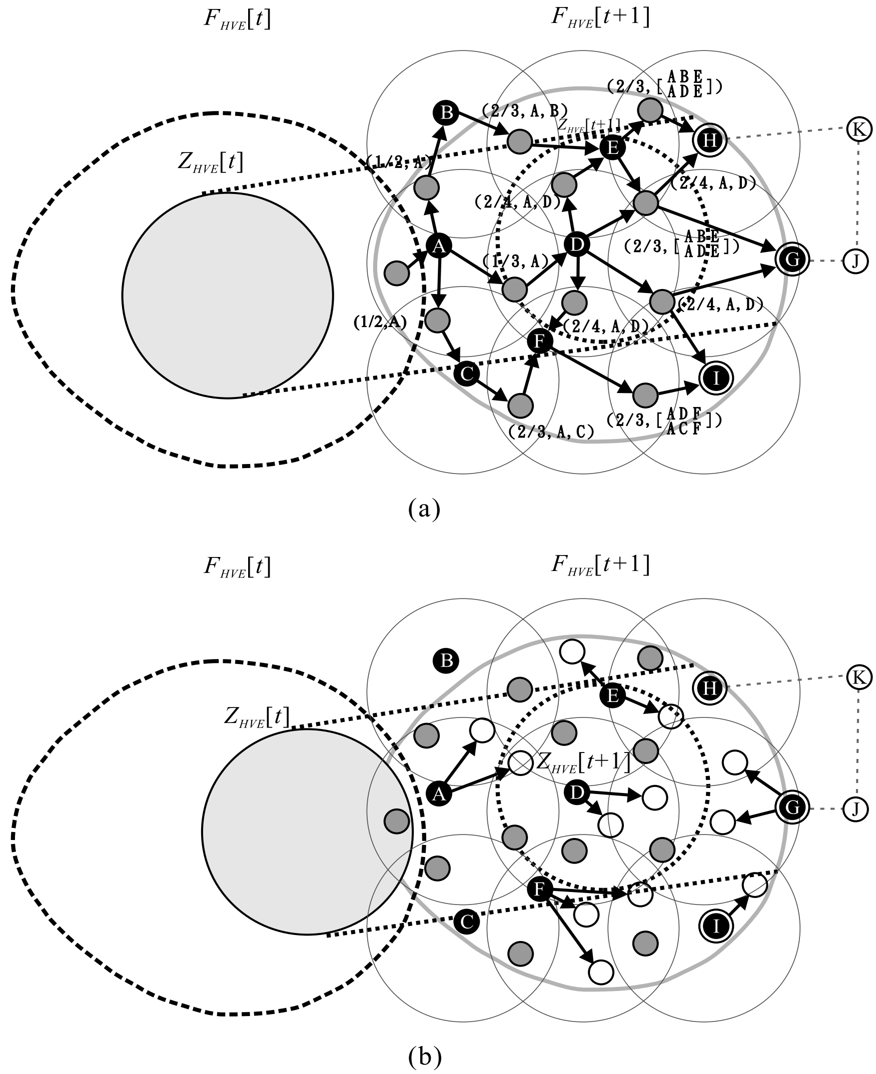

Fig. 9 Example of the "without a hole" problem in the HVE-mobicast protocol

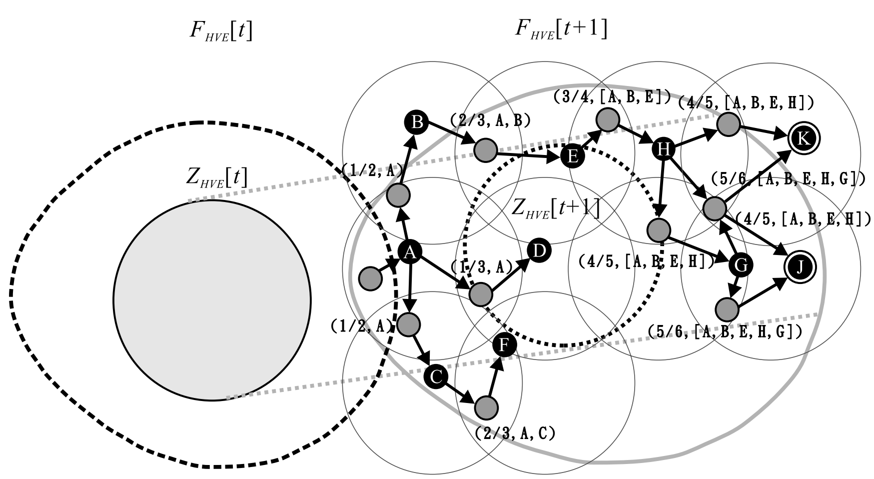

Fig. 10 Example of the "with a hole" problem in the HVE-mobicast protocol

path history of two P_{HVE} packets, and so the value of $\frac{h}{H}$ becomes $\frac{2}{3}$. The value of $\frac{h}{H} = \frac{2}{3} < 1$, and then the cluster head forwards this P_{HVE} mobicast message. Cluster head H receives two mobicast messages and stops forwarding it because the value of $\frac{h}{H} = \frac{2}{2} \leq 1$. As shown in Fig. 9(a), all cluster heads and relay nodes are woken up in this step. Be-

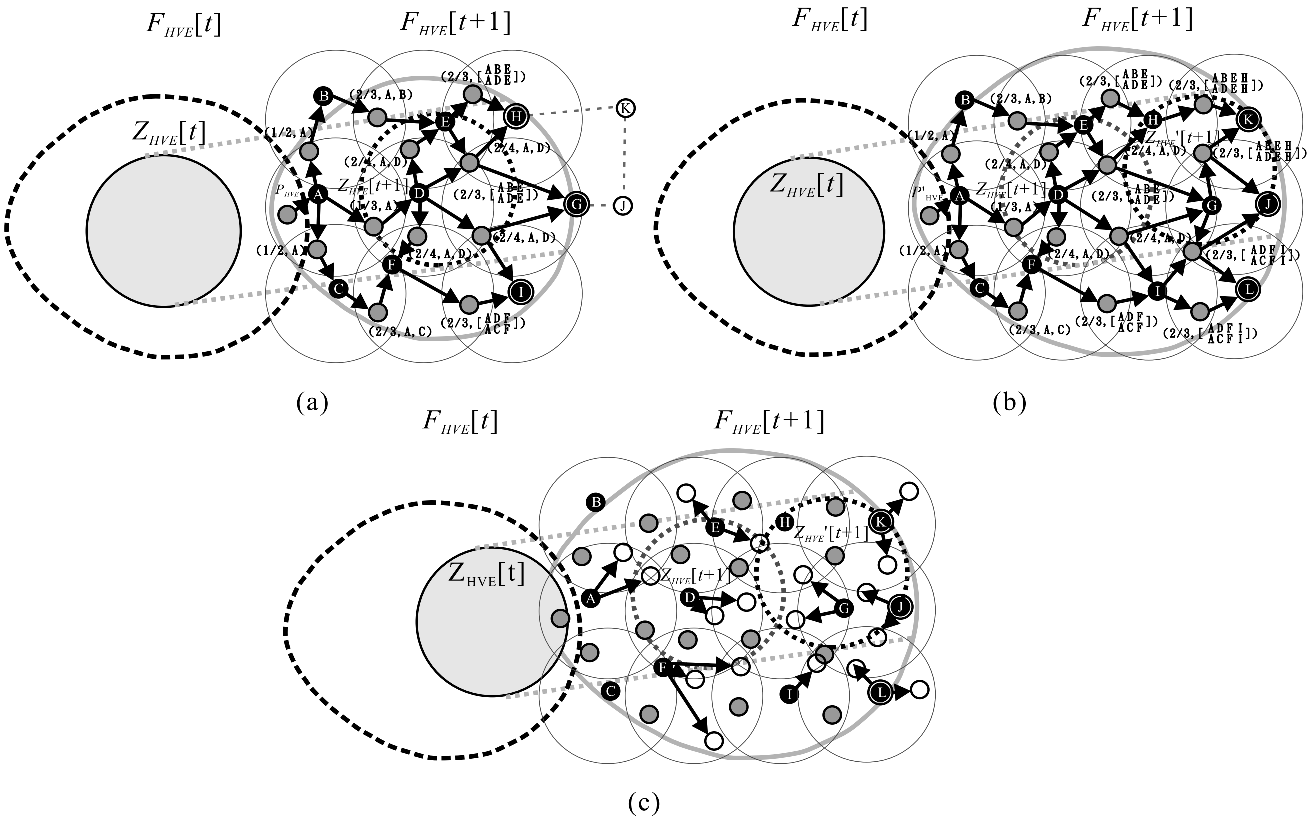

Fig. 11 Example of the "high-speed" problem in the HVE-mobicast protocol

fore the delivery zone arrives, the cluster heads wake up the members as the *waiting timer* expires. An example is shown in Fig. 9(b).

When a hole exists in WSNs, the HVE-mobicast routing protocol bypasses the hole and forwards the mobicast message to the delivery zone the next time. An example with a hole is shown in Fig. 10. Compared with Fig. 9(a), cluster heads D and F do not have relay nodes to flood the mobicast message to neighboring clusters, and the cluster which is the cluster head of I, disappears because its power is exhausted or terminated. In order to move across the hole, cluster heads G and H flood the P_{HVE} packet to cluster heads K and J. In other words, cluster head H floods $P_{HVE}(\frac{4}{5}, A, B, E, H)$ to neighboring cluster heads K and J, and cluster head G floods $P_{HVE}(\frac{5}{6}, A, B, E, H, G)$ to neighboring cluster heads K and J. Since cluster head K is in region 3, the value of $\frac{h_{merge}}{H_{merge}}$ is $\frac{5}{1} < 0$, and cluster head k stops forwarding the mobicast message. Cluster head J which is in region 1, also stops flooding the mobicast message because the value of $\frac{h_{merge}}{H_{merge}} = \frac{4}{2} < 0$. In Fig. 10, a hole makes the original routing path affect disappear, but this situation does not affect the result of the HVE-mobicast. The HVE-mobicast routing protocol forwards the mobicast message to a neighboring cluster head across the hole and has a mechanism to stop the forwarding.

The moving speed and direction of the delivery zone may change suddenly, so the forwarding zone should perform some corresponding action to adapt to different situations. Three situations are described as follows. First, when delivery zone $Z_{HVE}[t]$ suddenly increases speed, the sensor node resends control packet P'_{HVE} to enlarge $F_{HVE}[t+1]$ and informs the cluster heads to adjust the waiting timer. Cluster heads H, G, and I continue flooding the mobicast message. This is shown in Fig. 11(b). After adjusting the waiting timer, the nodes of group II are woken up early for just-in-time delivery. This is shown in Fig. 11(c). Second, when delivery zone $Z_{HVE}[t]$ suddenly decreases speed, the sensor node in H_{HVE} resends control packet P'_{HVE} to inform the cluster heads to adjust the waiting timer. The nodes of group II are woken up late to save some power. This example is shown in Fig. 12. Third, when the delivery zone $Z_{HVE}[t]$ suddenly changes direction, the sensor node in H_{HVE} resends control packet P'_{HVE} to inform the cluster heads to stop the waiting timer and command the cluster head to go back to sleep. This example is shown in Fig. 13.

Finally, when the delivery zone passes, the sensor nodes enter the idle mode. After the sensor nodes remain in the

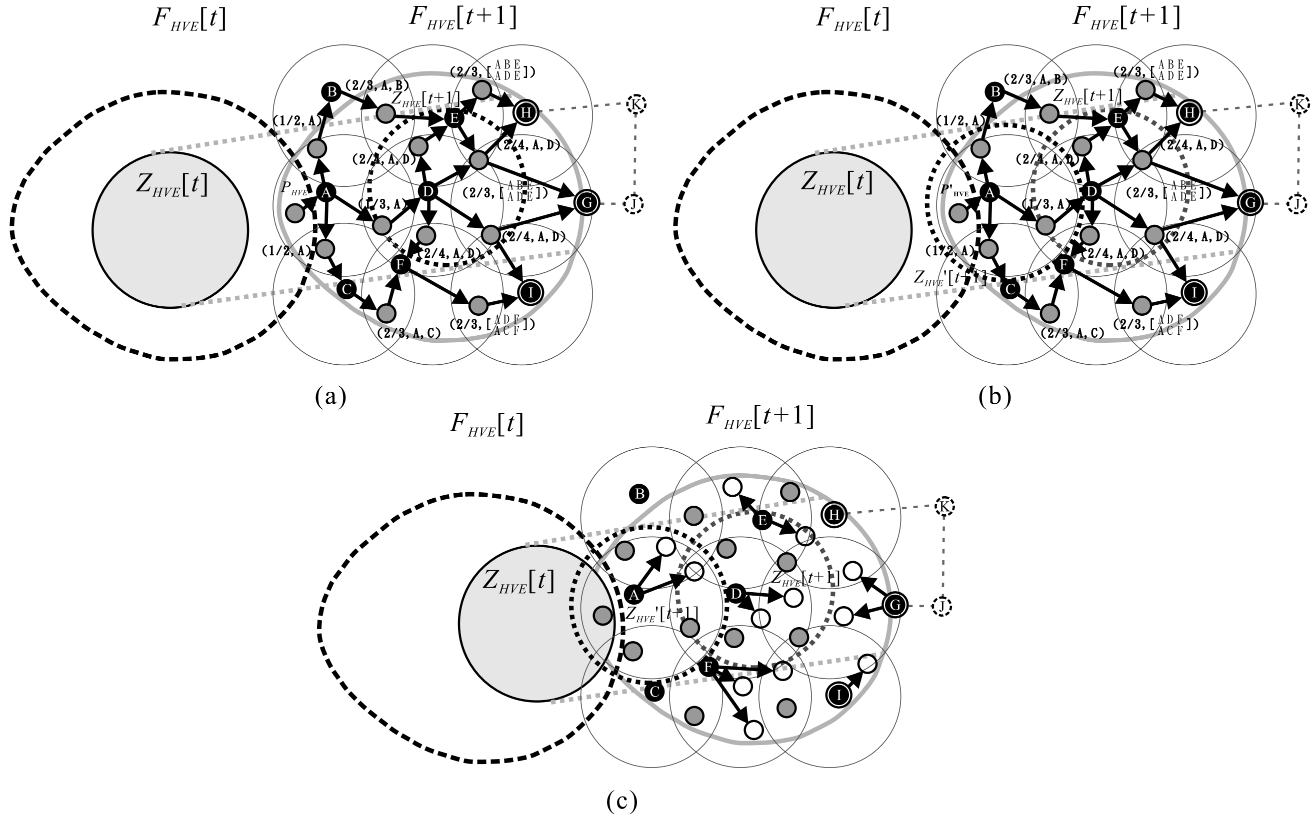

Fig. 12 Example of the "slow-speed" problem in the HVE-mobicast protocol

idle mode for a certain time, they then go back into the sleep mode.

4 Performance analysis and comparison results

In this section, we evaluate the performance of the HVE-mobicast routing protocol by using the NCTUns 2.0 simulator and emulator [25]. Through our developed Java program. To examine the effectiveness of our approach, three routing protocols, termed the "Mobicast" developed by Huang *et al.* [10], "FAR" developed by Huang *et al*. [21], and "VE-Mobicast" developed by Chen *et al*. [6], are compared with our HVE-mobicast routing protocol. To verify the HVE-mobicast routing protocol's analytic observations, some simulations are constructed. Java simulation programs were developed to achieve the four routing protocols which use Mobicast, FAR, VE-Mobicast and HVE-Mobicast requirements. The simulations were carried out for in nine different areas, 1000×400 m^2, 1000×500 m^2, 1000×600 m^2, 1000×700 m^2, 1000×800 m^2, 1000×900 m^2, 1000×1000 m^2, 1000×1100 m^2, and 1000×1200 m^2 with 800 sensor nodes which were set up at random. The communication radius of the sensor node is 35 m. The spatiotemporal application periodically broadcasts a mobicast message let the sensor nodes know the position with a 1-s period. The delivery zone where the spatiotemporal application takes place is circular, the velocity is 40 m/s, and the radius is 45 m. The communication radius of the cluster is 35 m. With the same power assumption model in [4], the power consumption of the sleeping mode for a sensor node is 130 mW (milliWatts). The power consumption of the active mode of a sensor node is 830 mW. The power consumption of the transmission/reception mode of a sensor node is 1400 mW. The simulation provides four parameters, *rotation frequency* (RF), *rotation angle* (RA), *network density* (ND), and *moving speed* (MV) to construct different sensornet models. The simulation executes for 1000 runs for different parameter.

- *Rotation angle* (RA): The spatiotemporal application can change the direction $\overrightarrow{v}$ of one angle for every simulation. In our simulation, the RA has nine different angles, from 5° to 45°.
- *Rotation frequency* (RF): The percentage of the spatiotemporal application changes the direction using $\overrightarrow{v}$ for every simulation.
- *Network density* (ND): A number of sensor nodes are located in a 100×100 m^2 area. In our simulation, we changed the size of network area to control the network density instead of changing the number of sensor nodes.

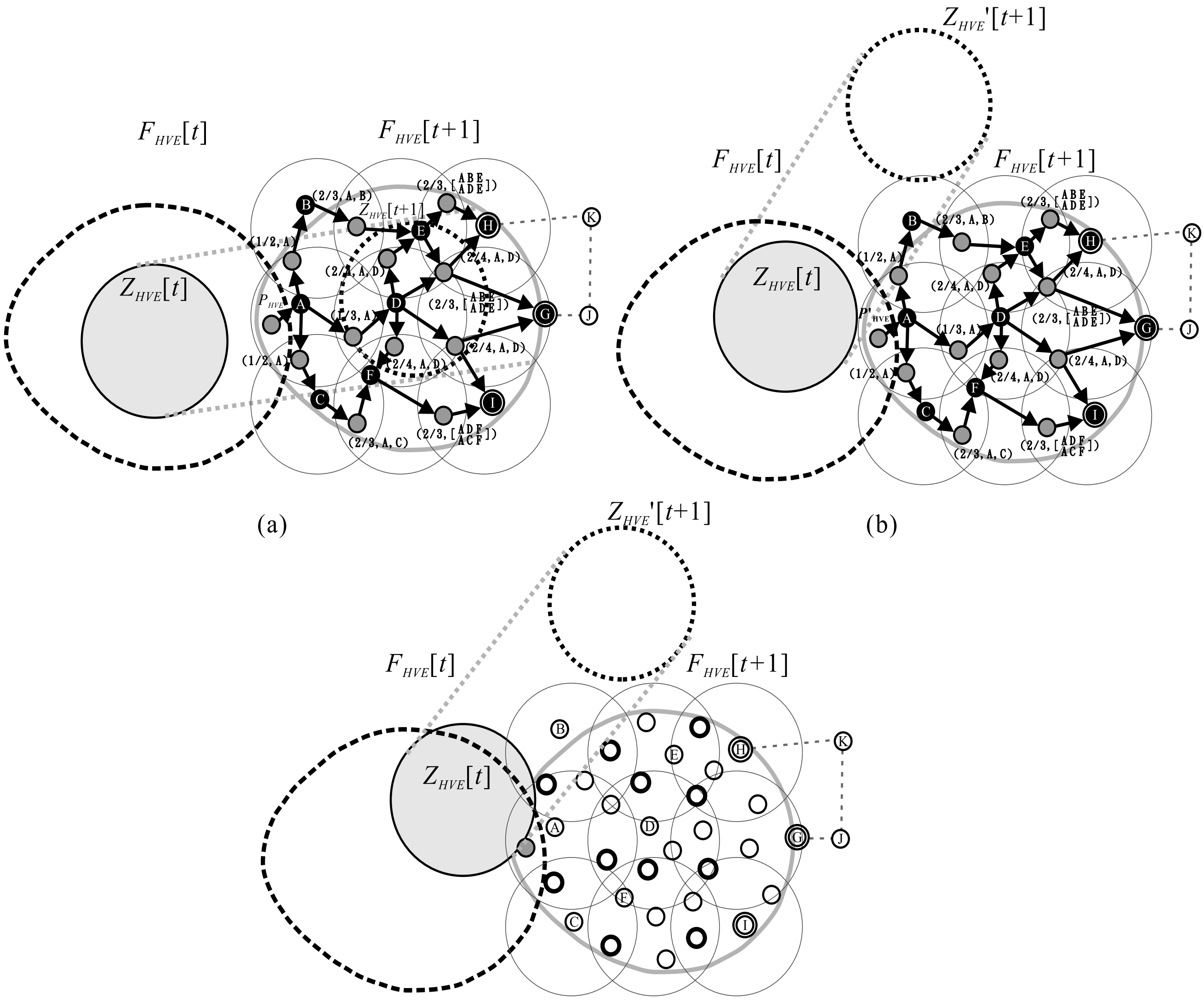

Fig. 13 Example of the "changed-direction" problem with the HVE-mobicast protocol

- *Moving speed* (MS): The moving speed of the delivery zone can dynamically change with time.
- *Moving speed variation* (MSV): This is the difference in the moving speed between the normal moving speed and the changed moving speed of the delivery zone.

We analyzed all simulated data of *packet overhead* (PO), *power consumption* (PC), *needlessly woken-up nodes* (NWNs), and the *successfully woken-up ratio* (SWR) from all sensor nodes in the sensornet. The performance metrics to be observed are:

- *Packet overhead* (PO): The total number of packets that every sensor node transmits, including the control and mobicast message.
- *Power consumption* (PC): The total power for all sensor nodes consumed for every simulation.
- *Needlessly woken-up nodes* (NWNs): The number of woken-up nodes in the forwarding zone through which the delivery zone did not pass.
- *Successfully woken-up ratio* (SWR): The number of woken-up nodes in $F_{HVE}[t+1]$ divided by the number of nodes which should have been woken up in $F_{HVE}[t+1]$.

A worthwhile mobicast routing protocol such as our HVE-mobicast routing protocol has a low packet overhead, low power consumption, few needlessly woken-up nodes, and a high successfully woken-up ratio. In the following, we illustrate the performance of PO, PC, NWNs and SWR.

4.1 Packet overhead

Figure 14 shows the results of packet overhead (PO), for four mobicast routing protocols and shows multiple

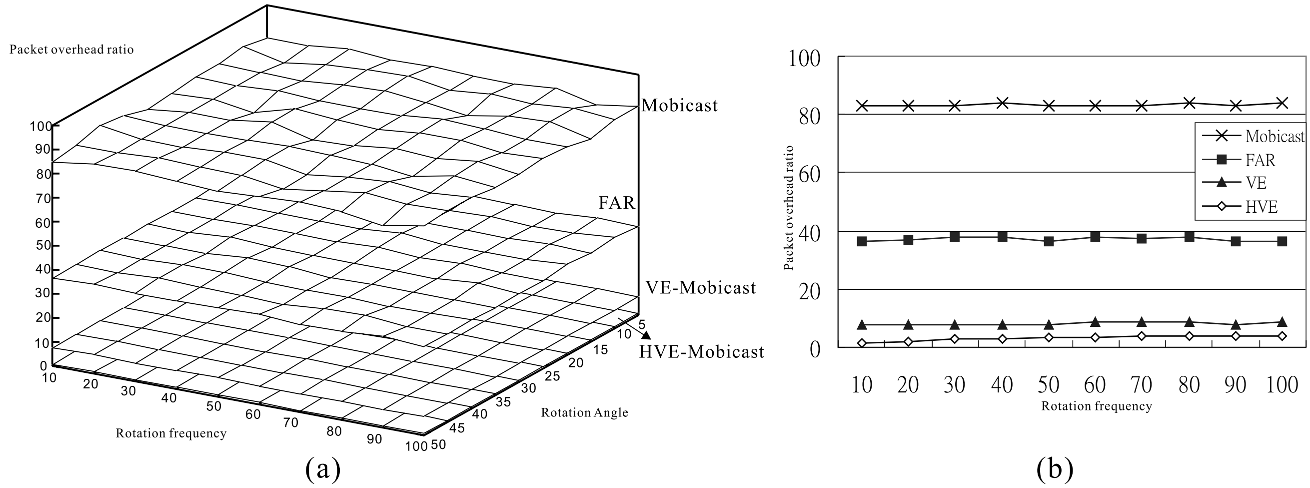

Fig. 14 Performance of the packet overhead ratio vs. the rotation frequency and rotation angle

relations. The high value of PO implies that the number of packets is very large. The Mobicast routing protocol is almost always bigger than the FAR, VE-mobicast and HVE-mobicast routing protocols at any time. Figure 14(a) shows the four routing protocols. Figure 14(b) shows an example of packet overhead with in two dimensions.

In Fig. 14, the Mobicast routing protocol always had a lot of packets in the sensornet for every simulation environment. The main cost of the PO is control packets which are used to construct the topology. The Mobicast routing protocol has to periodically broadcast to get the newest information about the local compactness to decide the forwarding zone, and this produces a lot of packets in the sensornet. When the local compactness is low, the Mobicast routing protocol may wake up additional sensor nodes to forward the mobicast message. The PO of the FAR protocol was lower than that of the Mobicast routing protocol, but still higher than that of the VE-Mobicast routing protocol. The main cost of the PO is control packets in the right-hand neighborhood discovery protocol. After constructing the spatial neighborhood. The FAR routing protocol uses a small number of sensor nodes to deliver the mobicast messages. VE-mobicast routing protocol has a low number of control packets that use local information from one-hop neighbors. Although the VE-mobicast routing protocol needs to wake up a few more sensor nodes than the Mobicast routing protocol, it does not have the cost of constructing the topology in advance. In the HVE-mobicast routing protocol, only the nodes of group I are involved with message routing instead of all nodes. Due to the hierarchical structure, the HVE-mobicast routing protocol can greatly reduce the message overhead. In particular, the HVE-mobicast routing protocol uses additional control packets to report the moving speed and direction of the delivery zone when they suddenly change. The PO of the HVE-mobicast is lower than that of the VE-mobicast routing protocol.

4.2 Power consumption

Figure 15 shows the results of power consumption (PC), for the four mobicast routing protocols and shows multiple relation. Figure 15(a–d) show the PC of the Mobicast, FAR, VE-mobicast, and HVE-mobicast routing protocols, respectively. The Mobicast routing protocol was almost always higher than the FAR, VE-mobicast, and HVE-mobicast routing protocols at any time.

The main cost of power consumption for sensor nodes is when they transmit packets. Due to high packet overhead, the power consumption is high. The Mobicast had the greatly PO resulting from more PC than the FAR, VE-mobicast, and HVE-mobicast routing protocols. Compared with Figs. 15, 16 shows the corresponding relations of these four mobicast routing protocols. When the moving speed of the delivery zone suddenly decreases, the woken-up nodes in the forwarding zone have to wait for a long time until the arrival of the delivery zone. This consumes more power than with a fixed moving speed. Figure 15(a–d) shows the moving speed from 40 to 5 m/s, the PC increases with a decreases in the moving speed. The PC of the HVE-mobicast routing protocol slowly increases because of the mechanism of the *waiting timer*. The cluster heads adjust the waiting timer to wake up the nodes of group II late in order to save power. When the rotation angle is between 0° and 90°, PC increases. As the predictive accuracy of the path of the delivery zone was worsens, the number of woken-up nodes in the forwarding zone grows. Therefore, the power consumption of these four mobicast routing protocols increases. Figure 16(e) shows an example of PC with moving speed. Figure 16(f) shows the amount of increased PC with variation in the moving speed. The PC of the HVE-mobicast

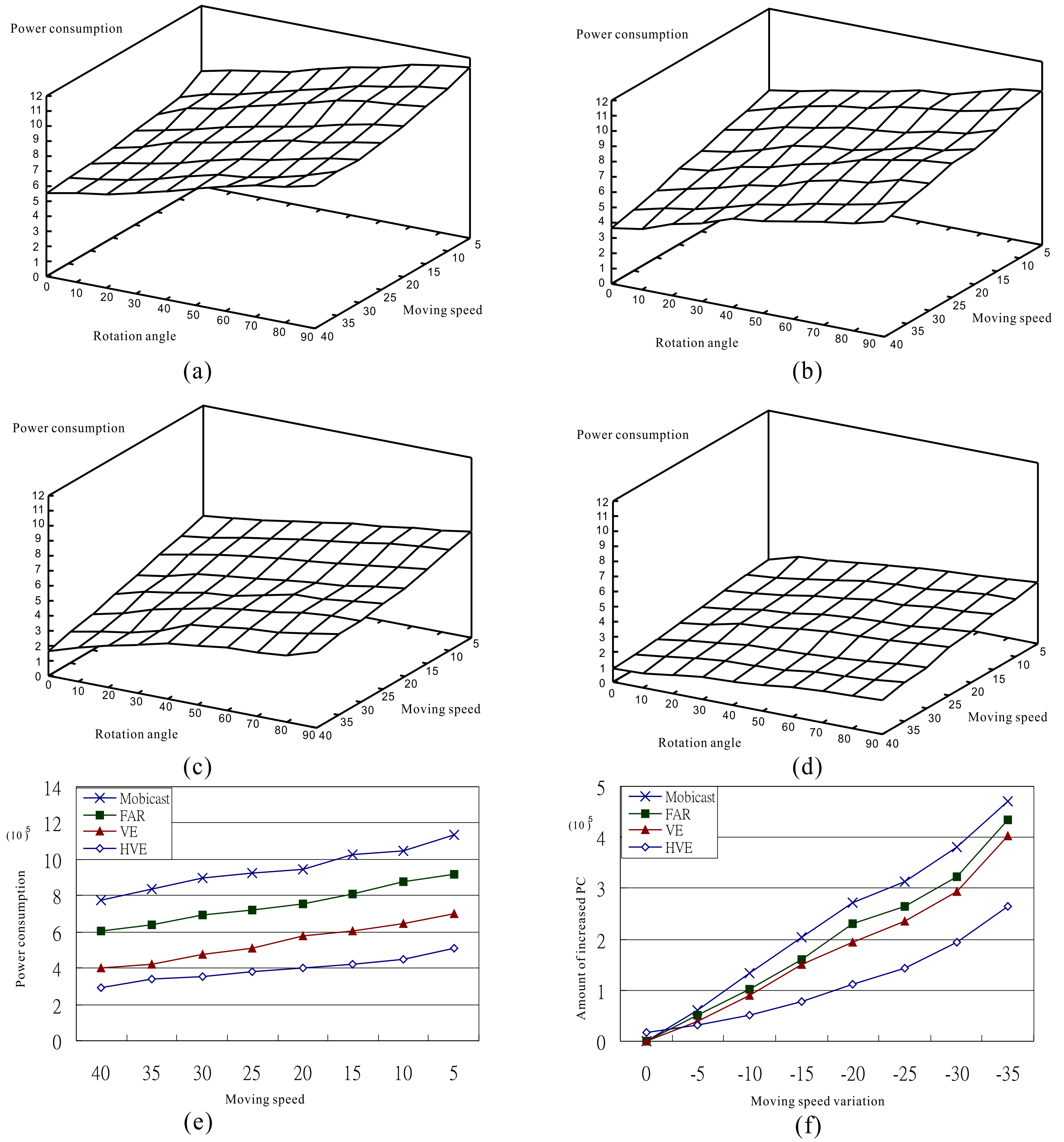

Fig. 15 Performance of power consumption (PC) in the (**a**) Mobicast, (**b**) FAR, (**c**) VE, (**d**) HVE, and (**e**) all schemes vs. the moving speed

increases by a smaller amount than those of the Mobicast, FAR, and VE-mobicast when the variation in moving speed decreases.

4.3 Needlessly woken-up nodes

Figure 16 shows the results of the needlessly woken-up nodes (NWNs), for the four mobicast routing protocols and shows multiple relations. These four mobicast routing protocols woke up about the same number of sensor nodes. In Fig. 16(a–c), when the moving direction of the delivery zone suddenly changes, the NWNs increase as the rotation angle increases. In Fig. 16(d), the NWNs increase with angles from 0° to 50°. When the angle is from 50° to 90°, the NWNs decrease. In HVE-mobicast routing pro-

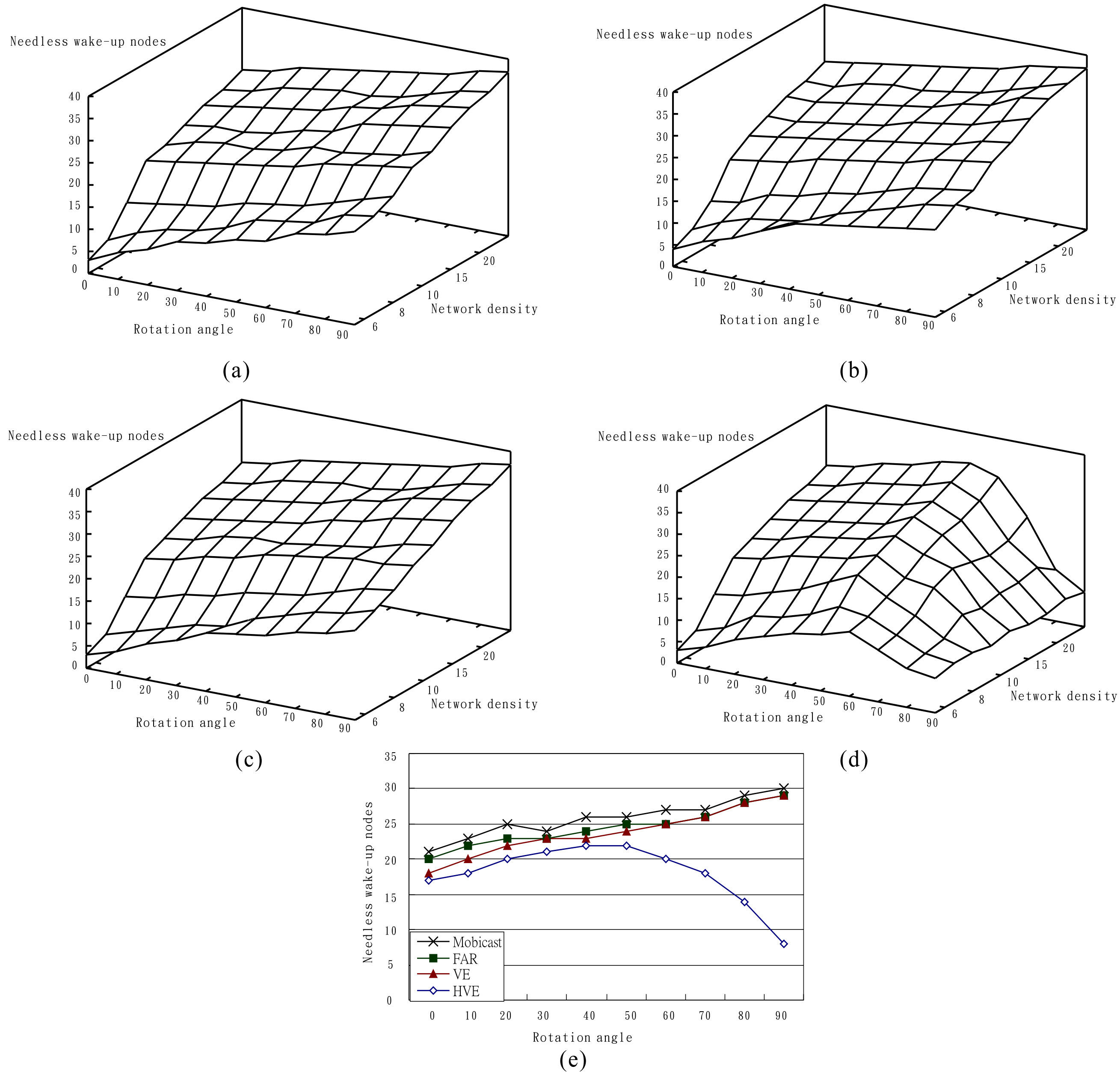

Fig. 16 Performance of needless wake-up nodes (**a**) Mobicast, (**b**) FAR, (**c**) VE, (**d**) HVE, (**e**) all schemes vs. rotation angle

tocol, control packets P' is forward to inform cluster heads in the forwarding zone when the moving direction of the delivery zone changes. The cluster heads that receives the control packets stop the *waiting timer* so as to prevent nodes of group II from being woken up. Then the cluster heads go back to sleep. The HVE-mobicast routing protocol reduces the NWNs due to its hierarchical structure and the mechanism of the *waiting timer*. When the network density increases, the NWNs increase. Figure 16(e) shows an example of power consumption with in two dimensions.

4.4 Successful woken-up ratio

Figure 17 shows the result of the successfully woken-up ratio (SWR) for the four mobicast routing protocols and shows multiple relations. The SWR of the HVE-mobicast was higher than those of the Mobicast, FAR, and VE-mobicast protocols.

When the moving speed of the delivery zone suddenly increases, the three mobicast routing protocols of Mobicast, FAR and VE-Mobicast show lower values for the SWR than the HVE-mobicast. Because the method of waking up nodes in these three routing protocols is node-by-node, it

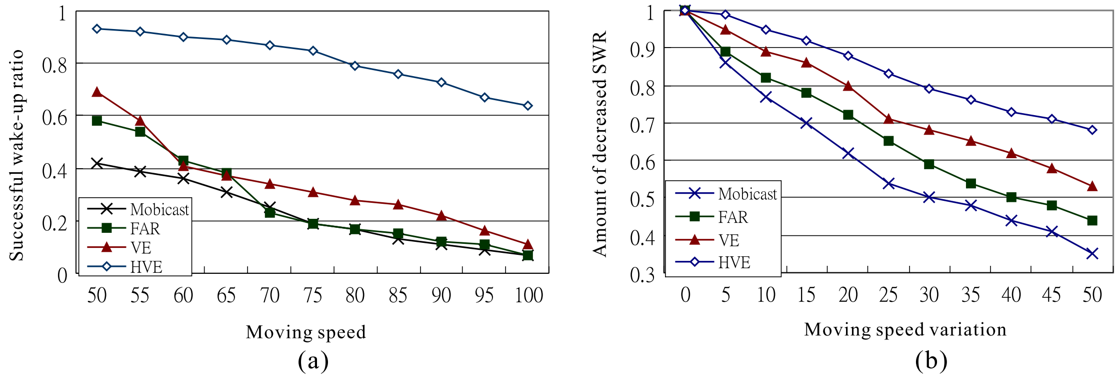

Fig. 17 Performance of the successfully woken-up ratio vs. moving speed

is inefficient, and these three routing protocols reveal low SWR when the moving speed changes from 50 to 100 m/s. The HVE-mobicast routing protocol wakes up the nodes in group I in a very short time. The control signal P' is forward to adjust the *waiting timer* to wake up nodes of group II early. Therefore, the HVE-mobicast routing protocol achieves a high SWR. Figure 17(a) shows an example of the SWR vs. moving speed. Figure 17(b) shows that the amount the SWR decreases is proportional to the variation in the moving speed. The SWR of the HVE-mobicast decreases a smaller amount compared to those of three Mobicast, FAR, and VE-mobicast protocols when the variation in the moving speed increases.

Finally, we know that the HVE-mobicast routing protocol provides low packet overhead, low power consumption, few needlessly woken-up nodes, and a high successfully woken-up ratio by the results of the performance analysis.

5 Conclusions

In this paper, we present a new mobicast routing protocol, called the Hierarchical-Variant-Egg-based Mobicast (HVE-mobicast) routing protocol, to improve the efficiency of message delivery in wireless sensor networks (WSNs). The HVE-mobicast routing protocol is a cluster-based approach. With the cluster advantage, HVE-mobicast protocol offers more power-saving results. The key contribution of the HVE-mobicast routing protocol is that it is more power efficient than VE-mobicast routing protocol, especially by considering different moving speeds and directions. Finally, simulation results illustrate performance enhancements in message overhead, power consumption, needlessly woken-up nodes, and successful woken-up ratio, compared to all existing mobicast routing protocols. Future work involves developing a multi-HVE-mobicast routing protocol which supports applications of multiple mobile sink nodes in a sensornet.

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