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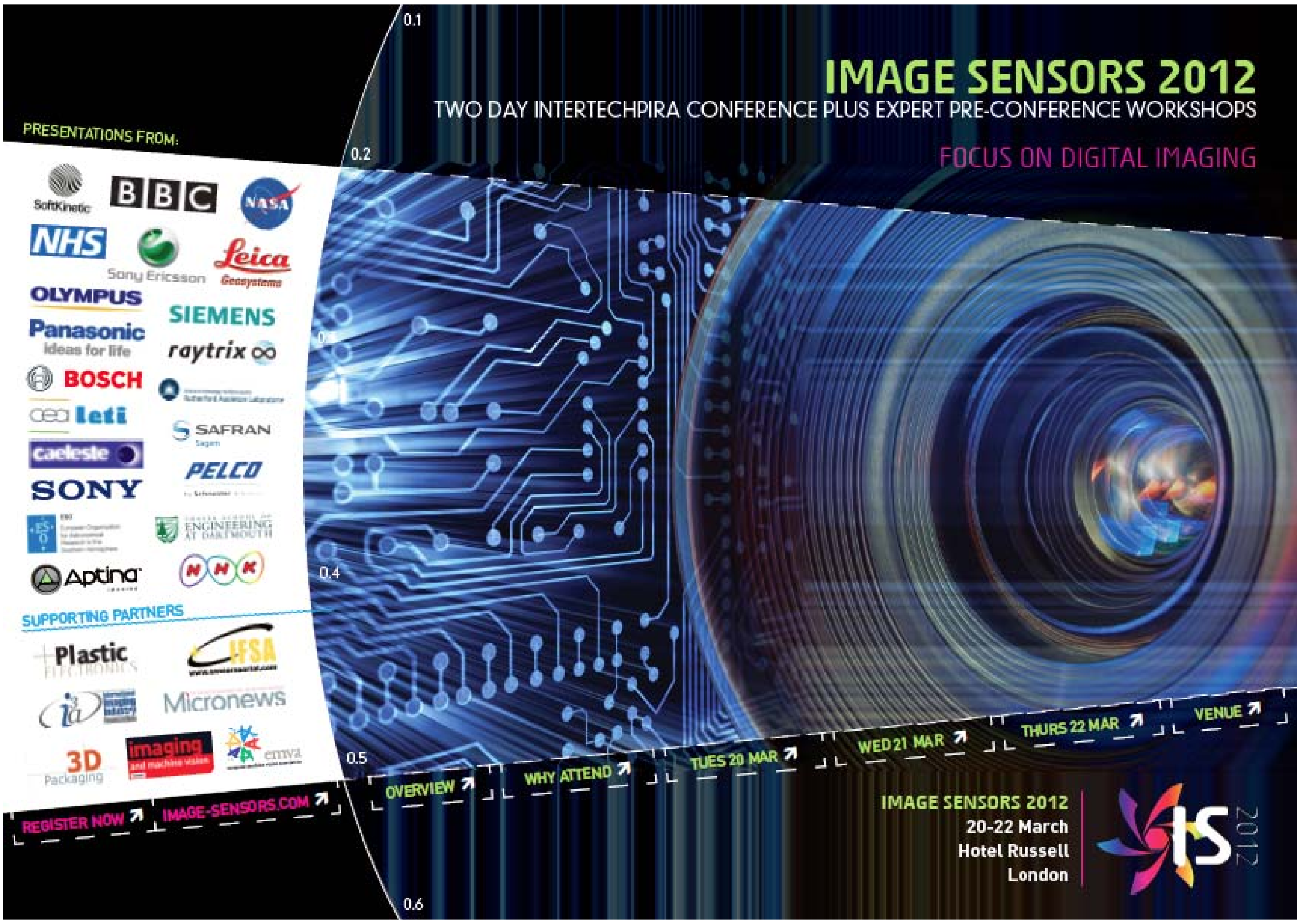

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An Effective Approach for Handling both Open and Closed Voids in Wireless Sensor Networks

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Abstract: Closed voids are created within a deployed wireless sensor network (WSN), but open voids are often formed on the boundary of this network. Geographical routing protocols must handle these voids where packets fall into local minima. To contribute on resolving this problem, we propose in this paper an effective void-tolerant routing approach based on two mechanisms for handling any kind of void. Our approach uses simple and effective algorithms ensuring discovery and maintenance of voids in a WSN. Contrary to existing void-handling techniques, our proposal uses information of all voids for better orienting data packets toward their destination in optimal paths around the voids. Proposed approach has good performances in terms of packet delivery ratio, average routing path length, control packets overhead, energy of network and boundary nodes consumed per delivered packet, and average residual deadline of delivered packets. *Copyright © 2012 IFSA*

Keywords: Sensor networks, Geographical routing, Routing voids, Void-handling techniques.

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1. Introduction

The mission of a WSN is generally to supervise a phenomenon, to take measures regularly and to send alarms to a sink node. Many applications using WSN exist in different fields such as defense, safety, health, agriculture and smart houses. Due to several economic and deployment considerations, sensor nodes have small size with limited resources of storage and computation. They use batteries, thus energy conservation becomes a big challenge. Since they communicate by radio with short range, the multi-hop routing becomes necessary so that captured information reaches the sink node. A simple approach would be to use the geographical routing, which guarantees a good scalability and a positive progression of forwarded packets toward the sink node. Each sensor node forwards the current data packet to its neighbor, which is nearest that itself to the sink node. The fact that no routing information is to maintain, other than tables of neighbors, routing paths adapt to any topological change.

Nevertheless, the geographical routing has two problems. Firstly, it is not applicable when sensor nodes do not have the possibility of knowing their geographical locations. Virtual coordinates systems, such as NoGeo [2], GEM [3], and BVR [4], can be used in this case. Virtual coordinates require nodes to know the distances from its neighbors to certain points of reference by using periodic messages. Secondly, there can be voids between a source node and a sink. A void is an area without any active node. It can be located inside the network (closed void) or on the network boundary (open void). A geographical routing path toward a sink is interrupting when relay nodes for avoiding voids are absent.

Existing solutions present insufficiencies in handling voids [5-18], particularly the open voids, so we propose to combine two simple routing mechanisms for handling any kid of void that can appear in a WSN. Since this paper in an extended version of our conference paper [1], the first mechanism handling open voids was proposed in [1] but the second mechanism handling closed voids was proposed in our previous work [19]. In the present paper, we combine the two mechanisms in a simple and effective approach of avoiding all voids in a WSN. Our void-avoiding approach can be associated with any geographical routing protocol.

The rest of the present paper is organized as follows. Section 2 presents the problem of voids in geographical routing. Section 3 proposes our void-tolerant routing approach that handles open and closed voids in a WSN. Section 4 proposes two simple algorithms to discover and to maintain each void that can appear inside a deployed WSN or on its boundary. Section 5 proposes two complementarily void-avoidance mechanisms, the first one handles open voids on a boundary of a deployed WSN and the second one handles closed voids that can appear inside the network. Section 6 evaluates performances of our void-tolerant routing approach when associated with the well-known real-time routing protocol SPEED [15]. Section 7 concludes the paper.

2. The Void Problem in WSN

A void is an area where sensor nodes are unable to route packets or straightforwardly inalienable. It appears when using a random deployment of nodes or because of node breakdown due to various reasons, such as circuit breakdown, destruction or energy exhaustion of some nodes. The problem of geographical routing is that stuck nodes, located on a void boundary, can receive packets destined to the sink. Let us consider the example of Fig. 1, where black nodes are located on the void boundary and node *i* must forward a packet to the destination node *d*. In this case, node *i* is stuck because there is any forwarding neighbor closer to node *d*. Once received by node *i*, the packet cannot have a positive progression toward node *d*. This packet will be directed toward node *j* (or node *k*) in a negative progression around the void. The node where a packet may get stuck is called a local minimum. Without an efficient void-handling approach, data packets are dropped, wasting the network resources and communications can be lost between a few pairs of nodes. Such a behavior is strongly undesirable in WSNs and the loss of some critical information can harm the network mission.

To reduce the negative impact of voids on the geographical routing effectiveness in WSNs, particularly in case of real-time applications, several void-handling techniques exist in the literature. They gather in two classes (Fig. 2): right-hand rule [5-14] and backpressure rule [15-18].

The techniques belonging to the first class use boundary nodes to route any stuck packet toward its destination. In [5], the geographical routing algorithm GPSR is proposed. On a non-stuck node, the packet is forwarded by GPSR to the nearest neighbor to the destination node (greedy forwarding mode). Consequently, the destination is approximate hop by hop until reached by the packet. When this mode fails, the current node uses the face routing to overcome the meted void (perimeter forwarding mode). Boundary nodes apply the right-hand rule until the packet arrives at a node closer to the destination. Several other algorithms using the face routing were proposed later [6-10]. However, [20] showed that planarisation algorithms used to obtain a planar graph, such as Gabriel graph [5], reduced the number of usable links in a network. However, sensor networks deployed for real-time applications cannot admit this reduction because of its negative impact on exploring multiples paths toward the packet destination (load balancing and network fluidity).

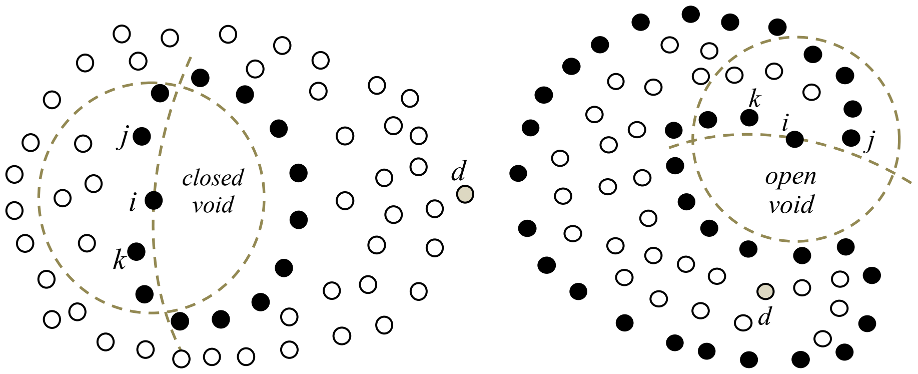
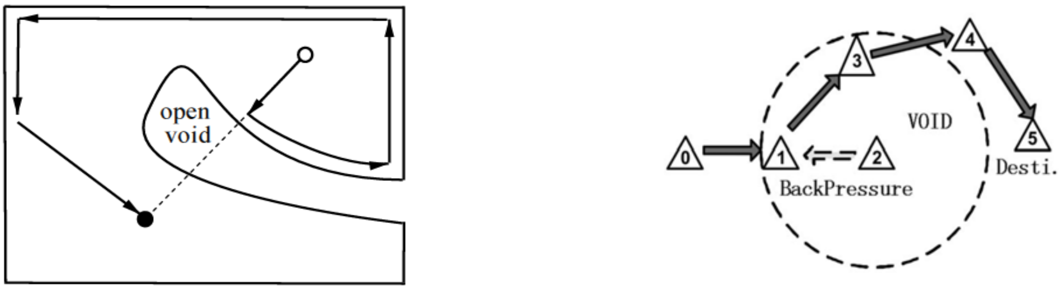


Fig. 1. The void problem: *i* is a stuck node according to the destination node *d*.



(a) Right-hand rule [5];

(b) Backpressure rule [15];

Fig. 2. Classes of techniques handling routing voids in WSNs.

On the other hand, the techniques belonging to the second class exploit the backpressure beacons broadcasted by the boundary nodes. When receiving these messages, upstream neighbors get alternative paths around the met void for next data packets. SPEED [15] is a spatiotemporal communication protocol proposed for WSN. It assures an end-to-end soft real-time for data parquets, requires each node to maintain information on its neighbors and employs the geographical forwarding to choose routing paths. Moreover, SPEED maintains a desired delivery speed across sensor networks with a two-tier adaptation included for diverting traffic at the networking layer and locally regulating packets sent to the MAC layer [15]. It considers a routing void as a permanent congestion. In SPEED, a stuck node drops the received packet and sends out a backpressure beacon informing its neighbors about its final incapacity to forward the next packets. When its forwarding neighbors are stuck nodes, the current node drops the packet and broadcasts a backpressure beacon. This process is repeated until an alternative path is found or the source node reached by the beacons. To improve QoS guarantees, former works [16, 17] proposed extensions to SPEED but they not changed the technique for handling routing voids.

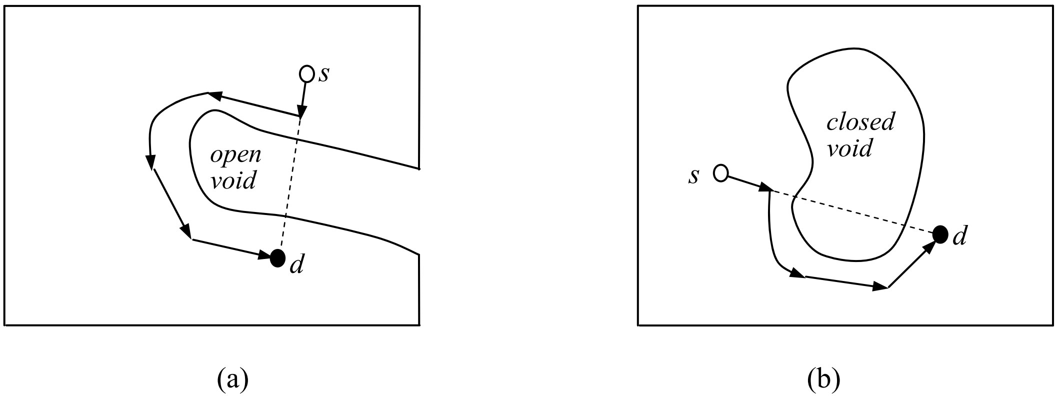
3. Proposed Void-Tolerant Routing Approach

As described in section 2, the right-hand rule is less effective when handling open voids. It excessively uses boundary nodes and consumes rapidly their energy. In this case, several sessions can use a same boundary, where the problems of collisions and delays of packets. In the same way, the backpressure rule generates many control packets and drops packets in concave zones of voids. Routing paths are long because of backpressure beacons, from where links are overloaded and packets delayed. These packets will be dropped after their deadline expires, a non-desirable situation in real-time applications.

To mitigate these insufficiencies, we propose an effective approach based on two mechanisms for handling voids in WSNs. The first mechanism, called OVA-nb (Oriented Void-Avoidance on network boundary) and proposed in Section 5, orients each stuck packet on the network boundary toward its destination node. It uses the geographical coordinates of the current node, those of the network center and those of the packet destination node to compute the packet orientation around an open void. It is based on two simple and effective algorithms described in Section 4: NBD (Network Boundary Discovery) and NBM (Network Boundary Maintenance). The first algorithm identifies nodes forming the network boundary just after its deployment and the second one maintain this boundary in a reactive manner. The second proposed mechanism, called OVA-0h (Oriented Void-Avoidance on zero hops from closed-void network boundary), consists of void-discovery, void-announce and packet-rerouting steps. The first step uses the VD algorithm to locate the closed void and to calculate its center-point *v*. The second step is used to announce v and to periodically maintain the void. The third step is used by each sender node *s* to forward each data packet *p* toward the destination *d*. This is done by choosing the appropriate forwarding region around the closed void. Note that when several closed voids exist in the network a sender node will, in the first place, avoid the nearest void. Note that OVA-0h and its several algorithms was proposed in our previous work [20].

Unlike existing techniques using long routing paths (Fig. 2), our void-avoidance approach, based on the mechanisms OVA-nb and OVA-0h, uses short routing paths to avoid voids that can appears in a WSN (Fig. 3). To forward a packet *p* toward the destination *d*, a sender node *s* in our approach executes one of the three following rules:

1. If node *s* is on boundary of the network then it uses the mechanism OVA-nb to orient the packet *p* to inside the network and toward the destination node (Fig. 3 (a)).
2. If node *s* is on a boundary of a closed void then it uses the mechanism OVA-0h to orient the packet in an optimal path around the void (Fig. 3 (b)).
3. If *s* is not a boundary node then it selects the next-hop neighbor to receive the packet *p* according to the implemented protocol metric, such as the distance metric used by the protocol GPSR [5] or the relay speed metric used by the protocol SPEED [7]. Note that our void-avoidance approach can be associated with any geographical routing protocol.



(a) (b)

Fig. 3. A short routing path used by our void-avoidance mechanisms.

4. Network-Boundary Discovery and Maintenance

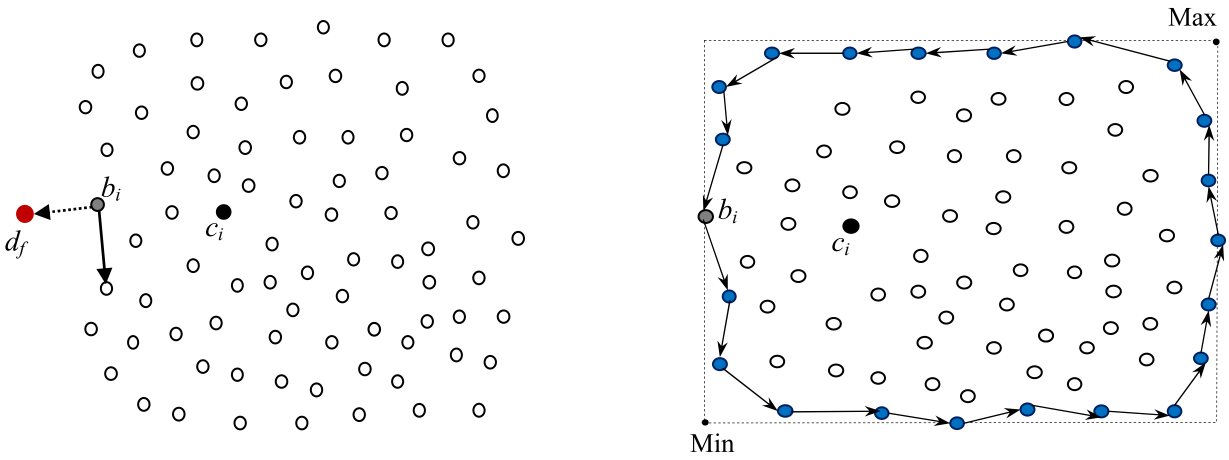
Existing algorithms to discover and maintain voids, such as BOUNDHOLE [11] and the right-hand rule [12-14], inserts information about each boundary node in the VD (Void-boundary Discovery) packet, increasing the node memory requirements and reducing the algorithm scalability. Moreover, these algorithms periodically check an eventual failed node and rediscover the entire void if a boundary node fails. It would be interesting to rediscover only the affected local section of the void. The VD packet size grows whenever it moves forward on the boundary of a void to discover. Therefore, existing algorithms [11-14] deplete a significant portion of boundary nodes energy. The same drawback is true for the void maintenance procedure used by these algorithms. BOUNDHOLE [11] does not address the open void as a special case. The outside of the network deployment scope, including the open void shown in Fig. 2 (a), is considered as a great void. For each stuck packet on the network boundary, the algorithm uses a long routing path formed mainly by boundary nodes. At the same time, the right-hand rule does not consider an open void as a particular problem. It handles only the closed voids located inside a deployed sensor network.

To overcome these limits, we propose two simple and efficient algorithms. The NBD algorithm brings back all the nodes forming the boundary of a deployed WSN and then calculates and communicates its center. The NBM algorithm detects and then updates any topology change that can occur on the network boundary during its mission.

4.1. NBD Algorithm

A designed sink (node c_i in Fig. 4) initiates the NBD algorithm when deploying a WSN. The algorithm operation is based on the GPSR protocol [5] to find the node closest to a virtual point located at one end of the network field. This node will complete the process of exploring the network boundary. The NBD algorithm takes place in three phases: initial phase, intermediate phase and final phase.

a) Initial phase: the sink c_i selects the nearest border of a network field; i.e., the line which passes by one of the points B1, B2, B3 or B4 in the Fig. 5. Then c_i projects its geographical location on the selected border. The resulting point (B1 in our example) represents the fictitious destination d_f used by the NBD algorithm to discover the nodes forming the network boundary.



(a) Fictitious destination d_f.

(b) Nodes forming the network boundary.

Fig. 4. Discovery process of the network boundary.

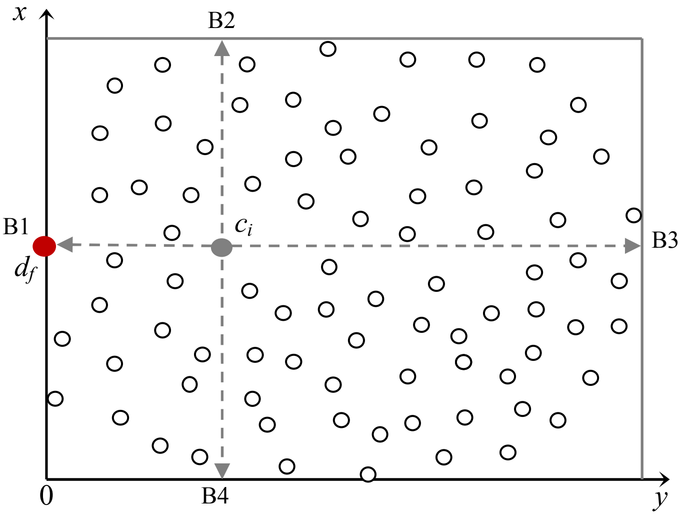


Fig. 5. Fictitious destination d_f for the NBD algorithm.

b) Intermediate phase: the sink c_i sends to the fictitious node d_f a new packet ND (Network-boundary Discovery), whose header fields are summarized in Table 1, to identify the fields Min and Max of the network boundary. The packet ND is routed by using greedy and perimeter modes of the GPSR protocol. When node b_i receives the packet ND, it launches the perimeter mode on the network boundary (Fig. 4 (a)). During this process, the fields N1Up (1-hop upstream boundary node), N1Down (1-hop downstream boundary node) and N2Down (2-hops downstream boundary node) of each intermediate node are updated. When b_i (node that initiated the last perimeter mode) receives the packet ND for a second time, it deduces that it is the closer node to d_f. Thus, b_i executes the final phase of the NBD algorithm.

Table 1. The header fields of the packet ND.

Field	Mission/Content
PerimID	Identifier of the node having lance the last perimeter mode
DestID	Coordinates of the fitifious destination d_f
Mode	Forwarding mode of the packet ND: Greedy or Perimeter
Distance	Distance from d_f to the last node initiated a perimeter mode
Min	Coordinats of the minimum point on the network boudary
Max	Coordinats of the maximum point on the network boudary
NodeUp	Identifier of the boundary node having sent the packet ND

c) Final phase: when receiving the packet ND, node b_i compute the network center (the midpoint of segment [Min, Max]), drops the packet ND and sends a new packet NU (Network-boundary Update), marked by its identifier, to browse the network boundary in the opposite direction of the packet ND. The header fields of the packet NU are summarized in Table 2. Each boundary node b_i, that receives the packet NU, updates its boundary information (NBorder=1 and NCenter=NU.NCenter) and verifies the field NodeUp of packet NU. If this field identifies a neighbor of b_i then node b_i updates its field N2Up by NodeUp, otherwise N2Up receives N1Up. Note that N1Up and N1Down are used to maintain the network boundary, N2Up (2-hops upstream boundary node) and N2Down to route packets using two hops on the network boundary. This routing technique reduces energy consumption and minimizes end-to-end delays of the routed packets.

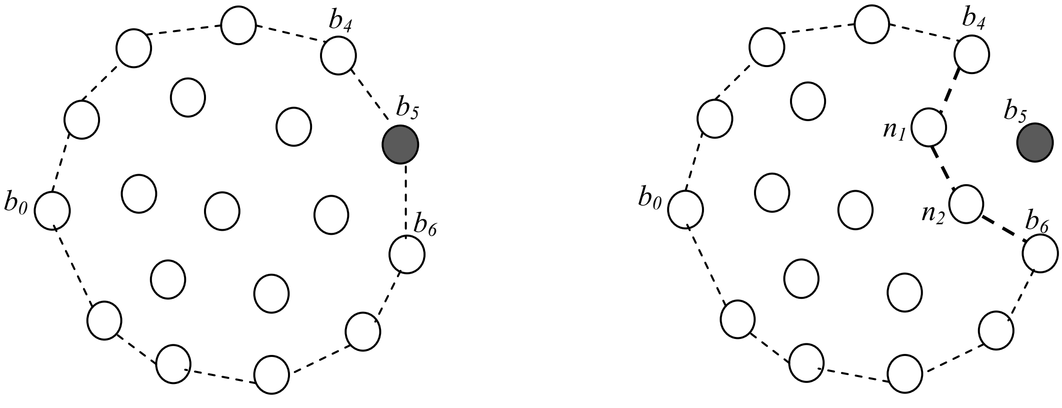
Table 2. The header fields of the packet NU.

Field	Mission/Content
NCenter	Coordinates of the network center
NodeUp	Identifier of a node having sent the pauqet NU

4.2. NBM Algorithm

Some network-boundary nodes may stop working because of insufficient energy or hardware failure. The network boundary can also change shape following the redeployment of nodes on the outside the network. For information usable by any routing process, the algorithm NBM distinguishes two different cases: (a) Failed node on the network boundary, (b) Redeployed node outside the network but near its boundary.

a) Failed node on the network boundary: through its field N1Up, each boundary node b_i can detect the absence of its direct upstream boundary node b_{i-1}. On expiry of the validity time of b_{i-1} in its neighbors table, node b_i discovers a new boundary segment to connect to the old one. Following the failure of boundary node b_5 in Fig. 6 (a), node b_6 discovers the new segment $b_6n_1n_2b_4$ that connects to the old segment $b_4b_0b_6$ of the network boundary (Fig. 6 (b)). For this discovery, b_i considers b_{i-1} as fictitious destination, sets forwarding mode to perimeter in the packet ND and executes the intermediate phase of the algorithm NBD. The discovery of new nodes is completed in the first node encountered in the old boundary segment (node b_4 in Fig. 6 (b)). This node is recognized by its field N1Up that is different from the default value. Once the two segments connected, the packet ND will continue its travel to restore the full information of the new network boundary. Upon receiving the packet ND, b_i (node b_6 in Fig. 6 (b)) executes the final phase of the NBD algorithm updating fields of nodes on the network boundary.

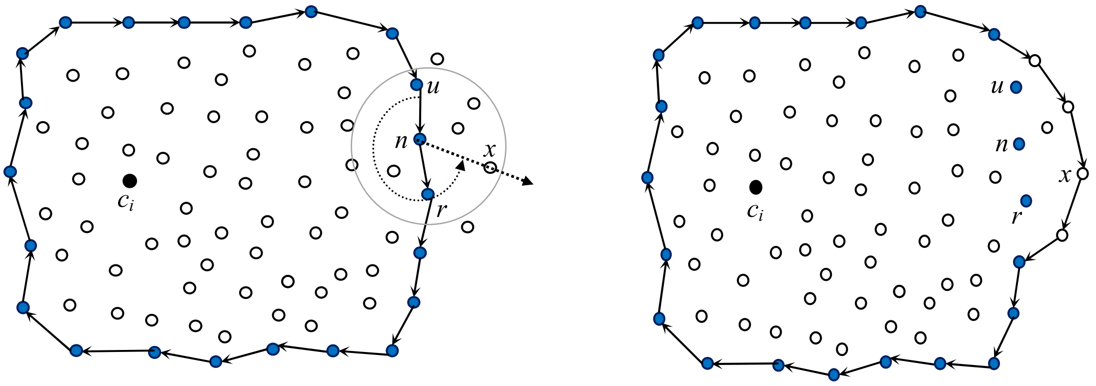


(a) Boundary node b_5 failed.

(b) Network boundary updated.

Fig. 6. Network boundary updating after a node failure.

b) Redeployed node outside the network: upon receiving a location beacon from a neighbor x, boundary node n checks its neighbors table. If x is outside the network, node n sends a new packet NS (Network-boundary Suppression), marked by its identifier, on the actual network boundary. Its mission is removing the information concerning this boundary. When receiving the packet NS, each intermediate node b_i resets the fields concerning the network boundary (NBorder, N1Up, N2Up, N1Down and N2Down). At the end, node n drops the packet NS and executes the NBD algorithm to discover the new network boundary. Having the updated fields N1Up and N1Down, node *n* uses its 1-hop boundary neighbors *u* and *r* to perform the following rule (angles' value in radian): if $\widehat{unx} > \widehat{unr}$ then node *x* is outside the network (Fig. 7 (a)).



(a) Node *x* deployed outside the network.

(b) Network boundary updated.

Fig. 7. Network boundary updating after a node deployment.

5. Proposed Void-Avoidance Mechanisms

Our void-tolerant routing approach combines two effective void-avoidance mechanisms: OVA-nb for avoiding open voids and OVA-0h for avoiding closed voids.

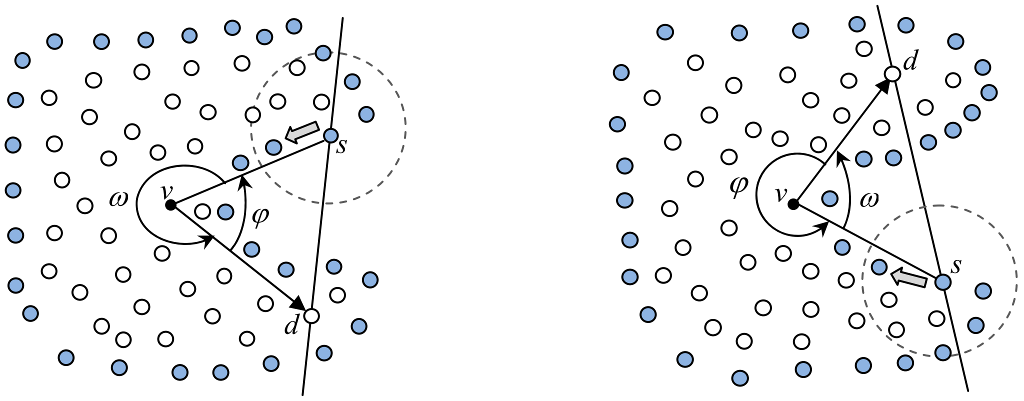
5.1. Mechanism OVA-nb

The mechanism OVA-nb orients toward the sink all packets arriving on the network boundary. Its role is to prevent these packets from drops by nodes located on boundaries of open voids. Having the network center and the updated fields NCenter, N2Up and N2Down, boundary node *s* (*s*.NBorder=1) forwards any received packet *p* to its destination node *d* by using the angles $\varphi=\widehat{dvs}$ and $\omega=\widehat{svd}$, shown in Fig. 8. When receiving *p*, node *s* performs one of the following rules:

1. If $\varphi<\omega$ (Fig. 8 (a)) then *p* is forwarded at right of line (*sd*). Thus, node *s* updates the orientation field in *p* if necessary, constructs its set R (greedy forwarding neighbors of *s* located at right of line (*sd*)) and executes the following rule: if R is empty the next-hop node *n* of *p* is identified by the field *s*.N2Down, otherwise *n* is chosen from R.

2. If $\varphi\geq\omega$ (Fig. 8 (b)) then *p* is to forward at left of line (*sd*). In this case, node *s* updates the orientation field of *p* if necessary, constructs its set L (greedy forwarding neighbors of *s* located at of line (*sd*)) and executes the following rule: if L is empty the next-hop node *n* of *p* is identified by the field *s*.N2Up, otherwise *n* is chosen from L.

Note that the next-hop node *n* is chosen from the set R (or L) according to the routing strategy of the implemented protocol that uses the mechanism OVA-nb. Associated with SPEED for performance evaluation, OVA-nb uses the neighbor relay speed as a criterion to choose the next hop of the packet *p*. Also, when *s* is not a network-boundary node (i.e., *s*.NBorder=0), it executes the routing strategy used by the implemented protocol for choosing the next hop of each data packet *p*.



(a) Forwarding at right of line (*sd*)

(b) Forwarding at left of line (*sd*)

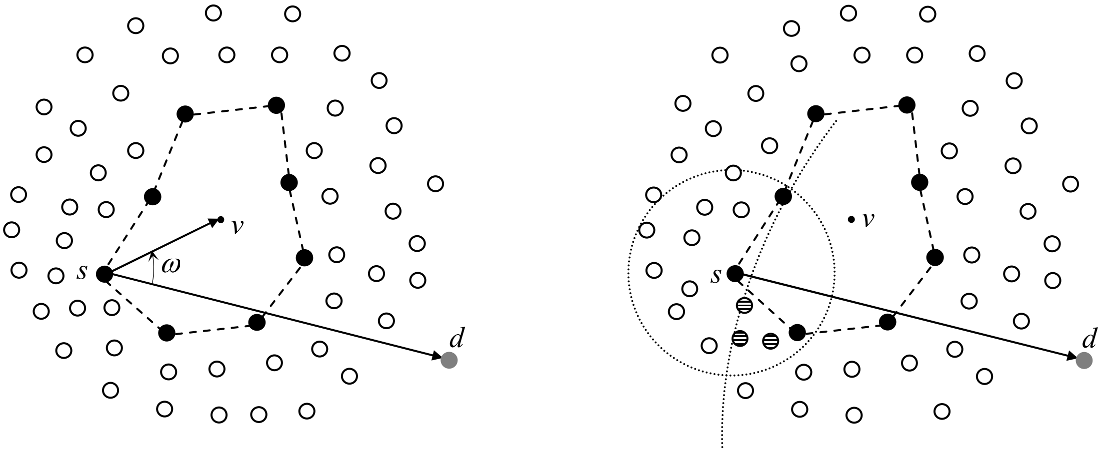
Fig. 8. Packet orientation in the mechanism OVA-nb.

5.2. Mechanism OVA-0h

The mechanism OVA-0h orients each packet arriving on boundary of a closed void in an optimal path toward its destination. Having fresh information about the void, a sender node *s* forwards any received packet *p* to its destination node *d* by using the angle ω shown in Fig. 9 (a). To forward a packet *p*, boundary node *s* performs the two following steps:

1. If node *d* is located at right of vector $\overrightarrow{sv}$ (i.e., $sin(\omega)>0$ in Fig. 9 (a)) the node *s* builds its RFS (Reduced Forwarding candidate neighbors Set) by its neighbors in FS and located at right of $\overrightarrow{sd}$; i.e., the hatched nodes in Fig. 9 (b). But if node *d* is located at left of $\overrightarrow{sv}$ (i.e., $sin(\omega)\leq 0$) then node *s* builds its RFS from its neighbors located at left of $\overrightarrow{sd}$.

2. Nodes *s* removes all boundary nodes from its RFS and execute the following rule: if RFS is empty, node *s* forwards the packet *p* to the next-boundary node located at right (or left) of $\overrightarrow{sv}$ according to the location of the destination *d* (Fig. 9 (a)), else it forwards the packet *p* to a neighbor *n* selected from RFS according to the implemented routing metric, such as the relay speed metric used in SPEED [7] or the distance metric used in GPSR [5].



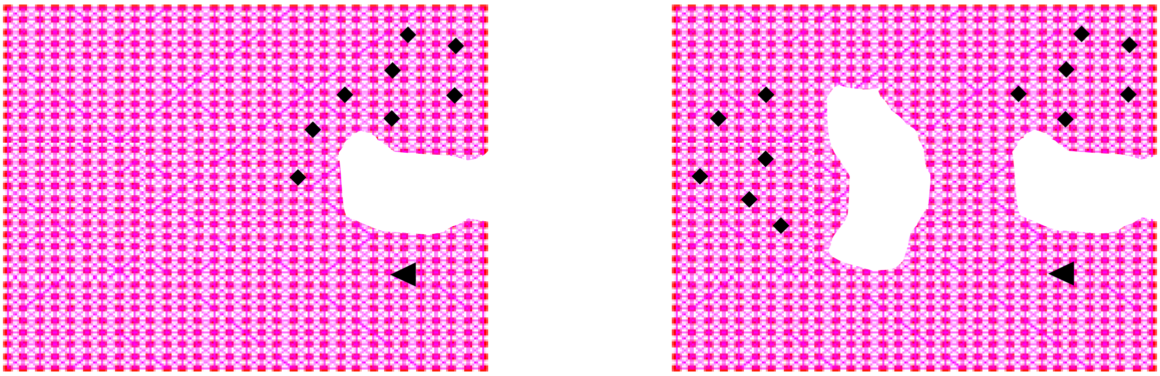
(a)

(b)

Fig. 9. Mechanism OVA-0h: (a) Oriented geographic forwarding based on the locations of *s*, of *v* and of *d*, (b) Forwarding candidate nodes of *s* (the three hatched nodes).

6. Performance Evaluation

Since we are interested by critical applications using WSNs, we first implemented the well-known real-time routing protocol SPEED [15] by using the network simulator ns-2 [21]. Then, we associate the mechanism OVA-nb with SPEED and the resulting protocol is called SPEED-nb. Finally, we associated the two mechanisms OVA-nb and OVA-0h with SPEED and the resulting protocol is named SPEED-ab (SPEED for any boundary). To evaluate performance of our void-tolerant routing approach, we use two simulation scenes shown in Fig. 10, with a grid distribution of nodes, in order to create voids with controlled sizes. The first scene shown (Fig. 10 (a)) is used to evaluate performance of SPEED-nb and the second scene (Fig. 10 (b)) to measure performance of SPEED-ab. For all our simulations, we use the parameters summarized in Table 3.



(a) (b)

◀: destination node ◆: source node ■: other node

Fig. 10. Simulation scenes: (a) both open and closed void, (b) open void only.

Table 3. Simulation parameters.

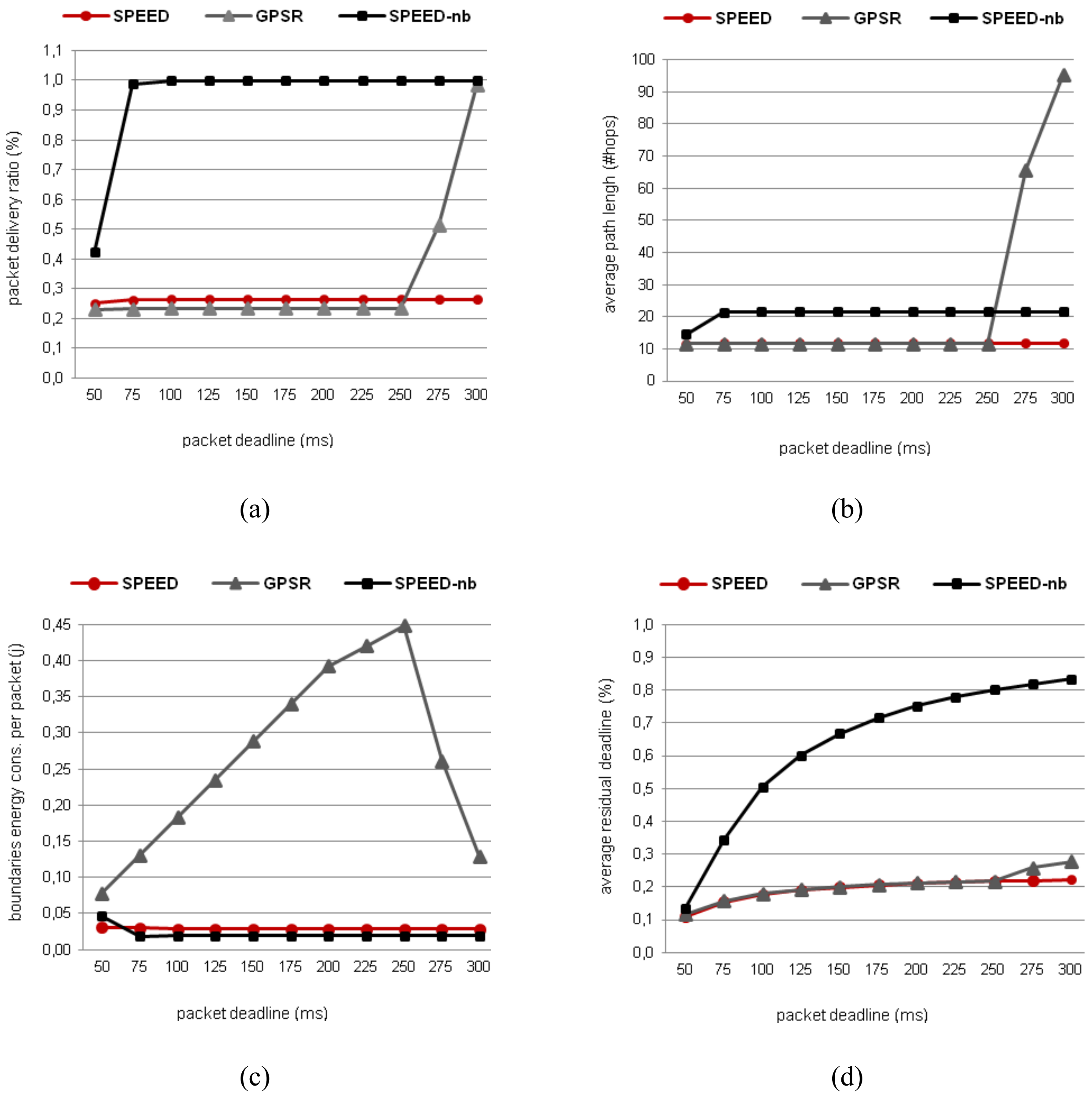
MAC layer	IEEE 802.11
Radio model	RADIO-NONOISE
Propagation model	TwoRayGround
Antenna model	OmniAntenna
Queue model	Queue/DropTail/PriQueue
Size of the queue	50 packets
Canal de transmission	WirelessChannel
Wireless interface	WirelessPhy
Bandwidth	200 Kb/s
Size of data packets	32 bytes
Energy model	Energymodel of ns-2
Radio range	40 m
Transmission power	0.666 W
Reception power	0.395 W

6.1. Performance of SPEED-nb

We compare SPEED-nb performance to those of traditional protocols SPEED and GPSR. Our objective is to show the inadequacy of existing techniques in handling open voids. The used scene has a size of

800 m × 800 m and contains 925 nodes, as shown in Fig. 10 (a). It contains an open void with 120 m as radius, located on the right boundary of the scene. Six source nodes, selected randomly and located at the top of the void, periodically send data packets to a destination node located at the bottom of the void. Note that to enable a minimum of forwarded packets to the same destination node by the evaluated protocols, two other source nodes are selected from the left side of the void.

We evaluate performance of the protocols SPEED-nb, SPEED and GPSR at packet rate of 2 p/s. We vary the packet deadline between 50 ms and 300 ms. At the end of each simulation and for each protocol, we measure the packet delivery ratio, the average routing-path length, the average boundary-energy consumed and the average gain in deadline for each received packet. Each point from our graphs represents the average results of 15 simulations, with random source nodes for each simulation, performed under same conditions and during 221 s. The obtained results are shown in Fig. 11.



(a)

(b)

(c)

(d)

Fig. 11. Open void impact on performance of the evaluated routing protocols.

Fig. 11 (a) shows that 75 ms of packet deadline is sufficient for SPEED-nb to route successfully all the packets because it proposes to take a short path toward the destination node as shown in Fig. 11 (b). To reach the same performance, GPSR needs 300 ms as packet deadline. This is because the face routing of GPSR which uses many boundary nodes before reaching the sink. Therefore, too long and busy routing paths are used by GPSR, as shown in Fig. 11 (b), and many packets are dropped because their deadline expires.

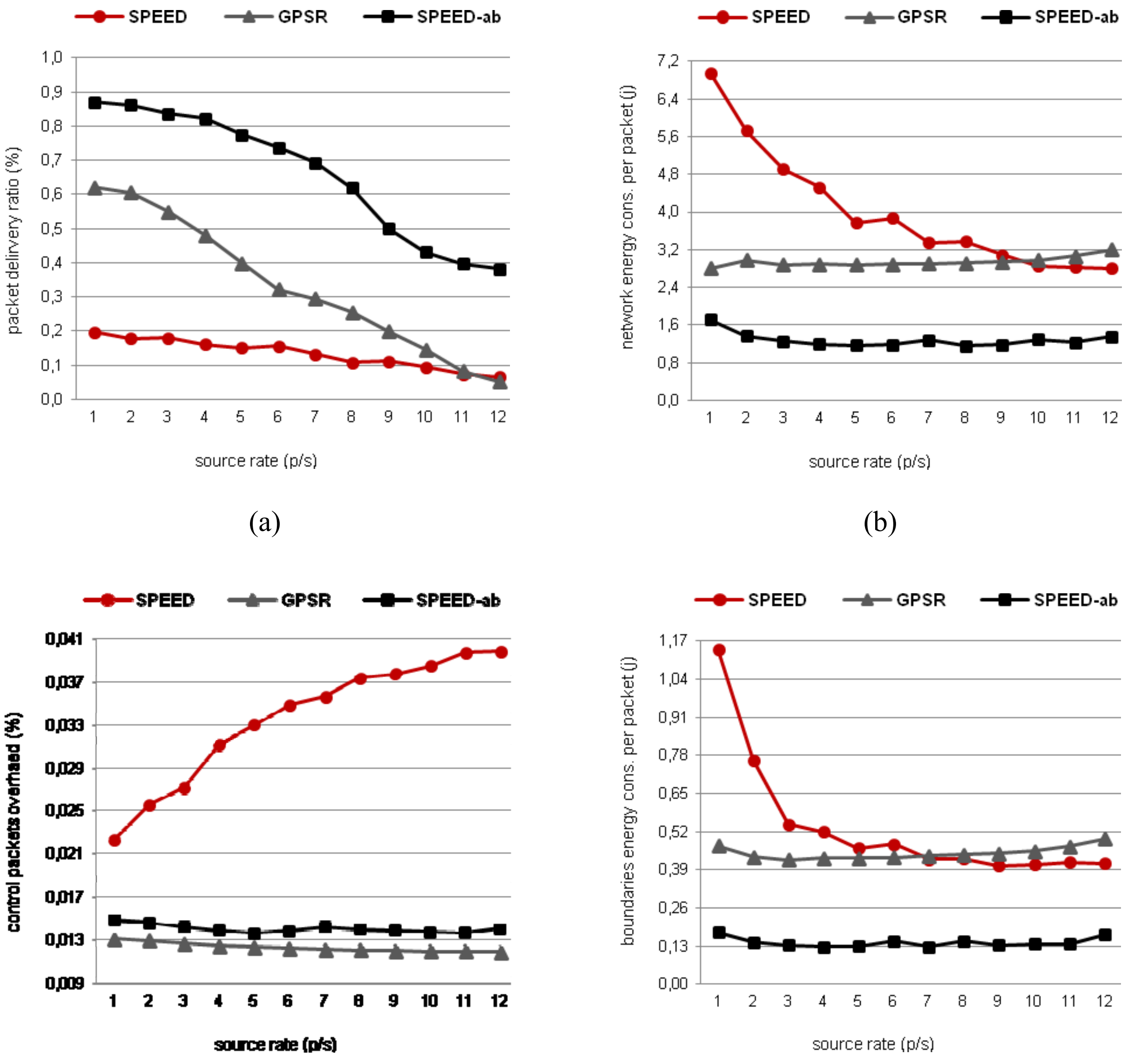
SPEED also removes many data packets, as shown in Fig. 11 (a), because backpressure beacons that generate stuck nodes delay the next packets in their progression and block definitely some source nodes. For this reason, packet delivery ratio of SPEED remains weak despite the growth of packet rate (Fig. 11 (a)). For packet deadline exceeding 250 ms, GPSR uses long routing paths to deliver the maximum number of packets, but the protocols SPEED and SPEED-nb use short paths for all delivered packets, as shown in Fig. 11 (b). Also, Fig. 11 (c) shows that excessive use of boundary nodes in GPSR has led to large energy depletion in these nodes, but SPEED-nb consumed less energy of boundary nodes because it uses short routing paths. Consequently, SPEED-nb delivers data packets with significant residual deadline (i.e., reduced end-to-end delays), as shown in Fig. 11 (d).

6.2. Performance of SPEED-ab

To measure the source rate impact on performance of the protocols SPEED, GPSR and SPEED-ab, we use the simulation scene shown in Fig. 10 (b). The scene has a size of 800 m × 800 m and contains 825 nodes. Two voids with 120 m as radius are created in the scene: the first one is open and located on the right boundary of the scene, but the second one is closed and located at the scene center. Six source nodes, selected randomly from the top of the open void and six other source nodes, selected randomly from the left of the closed void, send data packets to a destination node located at the bottom of the open void. We fix the packet deadline to 110 ms and we vary the source rate between 1 p/s and 12 p/s. At the end of each simulation and for each protocol, we measure the packet delivery ratio, network energy consumed per delivered packet, control packets overhead and energy of boundary nodes consumed per delivered packet. Each point from our graphs, shown in Fig. 12, represents average results of 15 simulations, where the source nodes are chosen randomly for each simulation. All these simulations are performed under same conditions and during 221 s.

The graphs in Fig. 12 show that performance all protocols decreases each time the sources' rate grows. They use longer and loaded routing paths around the voids. Therefore, the deadline of some packets expire rapidly before reaching the destination node and are thus removed in the network because we suppose the case of a critical application.

In Fig. 12 (a) shows that SPEED is the worst protocol in delivering packets. This protocol overloads the upstream nodes of a routing path by many backpressure messages broadcasted by each stuck node around the voids. In concave areas of these voids, these messages are also received by some source nodes. These sources are then blocked definitively and each generated packet for the same destination will be automatically dropped because all there forwarding candidate neighbors are stuck nodes. When sources' rate is less than 11 p/s, GPSR performs better than SPEED. This is due the perimeter mode, based on the right-hand rule, used to forward packets on boundaries of the voids. By cons, GPSR becomes less efficient when the sources' rate reaches 12 p/s because the protocol uses a single path from a source to a destination. Therefore, some packets spend much time in queues of nodes belonging to these routes, consuming a significant part of their deadline and then causing their removal in the network. However, SPEED-ab delivers more packets than GPSR and SPEED in the presence of open and closed voids, even for large sources' rate. This performance is due to the proposed void-avoidance mechanisms.



(a)

(b)

(c)

(d)

Fig. 12. Impact of both open and closed voids on performance of evaluated routing protocols.

Fig. 12 (b) shows that SPEED-ab is rational in managing energy of nodes. For one delivered packet, our protocol consumes less energy than the protocols GPSR and SPEED. For few packets received by the destination node, SPEED consumes much energy of both network nodes (Fig. 12 (b)) and boundary nodes (Fig. 12 (d)). This excessive energy consumption is due to the high number of backpressure messages broadcasted by SPEED near the voids and its useless forwarding of delayed packets. GPSR is more efficient than SPEED in managing energy of network nodes when the sources' rate in less than 7 p/s, and in conserving energy of boundary nodes when the sources' rate is less than 9 p/s. In fact, when the rate is important, most of the sources are definitively blocked in SPEED and then only some packets are forwarded in the network consuming less energy. But GPSR always attempts to route all generated packets during some hops but they will be dropped after that, before reaching their destination, because their deadline will be expire in overloaded single paths. Thus the energy of nodes during the first hops of these packets will be consumed unnecessarily by GPSR.

Fig. 12 (c) shows that GPSR do not generate many control messages compared to the others evaluated protocols. These messages are mainly broadcasted periodically by each node to announce its geographic location to its neighbors. But this interesting feature has not benefited GPSR in the packet delivery ratio as Fig. 12 (a) shows that SPEED-ab is the most efficient. In fact, GPSR uses the same routing path between each source and the destination node. This path becomes overloaded when sources' rate grows and then many packets are removed after expiration of their deadline. Thanks to its appropriate orientation of packets around the voids, SPEED-ab uses shorter and not too loaded routing paths enabling the delivery of many packets as shown in Fig. 12 (a).

7. Conclusion

In this paper, we have proposed an effective void-tolerant routing approach for WSNs. It uses two simple and complementarily void-avoidance mechanisms. The first one, called OVA-nb, handles open voids on a boundary of a deployed sensor network and the second one, called OVA-0h, handles closed voids that can appear inside the network. We have also proposed two simple and effective algorithms to discover and maintain the boundary of a deployed sensor network, where open voids are frequently formed. Finally, we have evaluated performance of our routing approach by integrating it in the well-known real-time routing protocol SPEED.

The first integration concerned OVA-nb, where the resulting protocol outperformed the protocols SPEED and GPSR, particularly in packet delivery ratio and sensor energy management. The second integration concerned both OVA-nb and OVA-0h, where the resulting protocol provides good performance in handling both open and closed voids. Thanks to its orientation of packets in optimal routes around voids, the proposed void-tolerant routing approach is efficient in terms of packet delivery ratio, length of used routing paths and energy of nodes, particularly the nodes located on boundaries of the voids.

Proposed void-avoidance mechanisms resolved the insufficiencies of the existing void-handling techniques. They are simple to implement, effective in handling both open and closed voids and can be easily associated with any geographical routing protocol. In future, we plan to implement our proposals in a real scenario based on Imote2 sensor nodes.

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Sensors & Transducers Journal

Guide for Contributors

Aims and Scope

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Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
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- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
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