PCAR: A Power-Aware Chessboard-Based Adaptive Routing Protocol for Wireless Sensor Networks

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Abstract

Increasingly, services operations which perform data sensing and data propagation in a dynamic environment are important tasks of wireless sensor networks. A limited unreplenishable energy supply at each sensor node makes these tasks more challenging. Therefore, increasing the network lifetime is the main contribution of this investigation. In this paper, we propose a novel power-aware chessboard-based adaptive routing (PCAR) protocol to support immobility management in wireless sensor networks. The paramount design challenge in this work is to scale-down network energy consumption, thus maximizing the network lifetime. Our PCAR protocol utilizes vector-oriented propagation, power-consideration decision, and multi-path routing protocols to guide the propagating data to its destination. Moreover, properties of clusters are combined in the PCAR to form cluster-plates in a chessboard-based clustered sensor network. The alternate usage of cluster-head nodes and sleep nodes increases energy efficiency. The opportune divide-and-conquer multi-path fusion mechanism slows down and balances energy consumption. Finally, a performance analysis shows that energy efficiency is achieved by the PCAR protocol.

Keywords: Wireless sensor networks, data fusion, data collaboration, power control, immobility management.

1 Introduction

Due to their small size, low power requirements, as well as programming, computing, communication, distributed sensing capability, and wide sensing applications, *Wireless Sensor Networks* (WSNETs) have recently been investigated [1, 3, 4, 10, 11]. WSNETs continually support services operating in a dynamic environment to perform sensing/propagating tasks, but each sensor node only has a limited energy supply. Consequently, determining how to increase the network lifetime is an important issue for WSNETs [2, 7, 13]. The design challenge in WSNETs is to scale-down the energy consumption, thus maximizing the network lifetime. Data forwarding consumes the largest proportion of energy resources at each sensor node [1]. A number of researchers have widely studied and investigated various energy-saving protocols [2, 3, 9, 15, 16, 18, 26, 27, 29]. Simultaneously, many reports have proposed using single-path routing as compared to multi-path routing for WSNETs. Neha *et al*. proved [2] that to minimize the communication and computational overhead, their scheme uses multi-path routing to spread the traffic over nodes lying on different possible paths. Schurgers *et al*. [3] proposed an energy-efficient protocol which allows nodes to periodically sleep and then wake up to listen for the beacon. Furthermore, Chen *et al*. [5] proposed a diagonal-based routing scheme on a hexagonal mesh for indoor wireless sensing environments, where *periodic active-and-sleep time-slot* scheduling is presented. Swades *et al*. [28] proposed a novel meshed multi-path routing scheme with selective forwarding of packages to improve the throughput performance over conventional disjoined multi-path routing. Recently, Salhieh *et al*. [4] proposed a power-directional source-aware protocol, namely Power-DSAP, to examine the relationship between usage and system parameters of a WSNET. In addition, Salhieh et al.'s simulation was clearly proven that the path selection affects the amount of power consumed in the network. We will obviously see more and more research approaches in the distributed adaptive signal-processing framework, and some efficient algorithms for wireless sensor network have been proposed to reduce energy consumption and prolong the lifetime of sensor networks [8, 9, 10, 11, 12].

In this paper, we combine the advantages of upper researches. In addition, wireless sensor nodes have also been installed in the ceiling or under the floor of buildings to monitor and service all of the coved area and form a large, dense multi-hop network. When large numbers of sensor nodes are densely deployed, neighboring nodes are usually very close to each other. By collaboration of active neighbor sensor nodes in the coverage region, the cover sensor nodes share the required power for transmission, thus decreasing the throughput and power consumption. Hence, employing alternate or collaborative schemes with each other for querying or data exchange is very useful for increasing the operational lifetime of a network [5]. In this paper, all sensor nodes were considered to be formed and organized into a *chessboard-based* mesh. Our PCAR protocol utilizes vector-oriented propagating, power-consideration decision, and multi-path routing protocols to guide propagating data to its destination. Moreover, the properties of clusters are combined in the PCAR to form cluster-plates in the chessboard-based clustered sensor network. The alternating use of cluster-head nodes and sleep nodes achieves energy efficiency. The opportune divide-and-conquer multi-path fusion mechanism slows down and balances energy consumption. Finally, a performance analysis confirms that energy efficiency is achieved by the PCAR protocol.

The rest of the paper is organized as follows. In Section 2, the basic idea and required notations are briefly described. This is followed by a discussion on PCAR schemes in Section 3. In Section 4, the performance evaluation of PCAR schemes is presented. Finally, Section 5 concludes this paper.

2 Basic Idea

The pure shortest-path routing (PSPR) protocol is a well-known WSNET protocol. The main strategy of the PSPR protocol is to search for the minimal number of hops along a routing path in order to reduce power consumption. However, in traditional PSPR protocols, the massed power consumption of routing along the same paths speedily decreases the energy of the active nodes. Our PCAR protocol was developed to reserve the PSPR's advantage of searching for the shortest path, and to modify the PSPR's disadvantage by prolonging the lifetime of WSNETs. Our PCAR protocol tries to avoid unnecessary power consumption with traditional random data forwarding or broadcasting routing methods. Incorrect routing strategies increase power consumption, and our PCAR protocol is designed to avoid wrong decisions in order to extend the lifetime of the network.

Our PCAR protocol is performed on a *chessboard-based clustered* mesh, which is defined in Definition 2. Before formally defining the *chessboard-based clustered* mesh, we first define the *basic cluster block*.

Definition 1: Basic Cluster Block (BCB) : In the PCAR protocol, a *basic cluster block* (BCB) is a combination of four separate grids and consists of nine nodes. Each grid has four nodes and four contiguous edges. Two adjacent grids have two nodes and one edge in common. If the two-dimensional coordinate of the *center node* (CN) of BCB is (x, y) then the BCB is denoted as β_y^x .

For instance as illustrated in Figure 1, β_y^x consists of nine sensor nodes and is denoted as $\begin{bmatrix} A & B & C \\ D & E & F \\ G & H & I \end{bmatrix}$. In β_y^x , node E is called the *cluster head* (CH), and is in charge of the task of major data flow control. The coordinate of the center node E is denoted $E(x, y)$. The four corner nodes of β_y^x are *sleep nodes* (SNs), and these normally enter into sleep mode when the center node is active. Similarly, the coordinates of the four sleep nodes A, C, G, and I are denoted $A(x\text{-}1, y\text{+}1)$, $C(x\text{+}1, y\text{+}1)$, $G(x\text{-}1, y\text{-}1)$, and $I(x\text{+}1, y\text{-}1)$, respectively. In addition, the remaining four nodes of β_y^x are *active nodes*, or ANs, and are active in data transmission and repetition at lower transmission power. The coordinates of the four active nodes B, D, F, and H are denoted $B(x, y\text{+}1)$, $D(x\text{-}1, y)$, $F(x\text{+}1, y)$, and $H(x, y\text{-}1)$, respectively. The cluster nodes and sleep nodes are exchanged periodically to equally share the power consumed by data exchange. The *periodic backbone-path-exchange* scheme is applied to deal with the energy-consumption fairness problem in WSNETs. Each sensor node has an equal opportunity to serve as the backbone path. Because cluster heads experience heavy use, the roles of sleep nodes and cluster heads are periodically exchanged to share power consumption and to extend the lifetime of the mesh sensor network. A common approach for saving power is to allow the active nodes to enter into sleep mode if they are not on the routing paths after the sink propagating phase. A *chessboard-based clustered* (CBC) mesh consists of many BCBs. Each BCB is surrounded by four cluster blocks, and adjacent BCBs overlap with each other. An overlapping edge has three overlapping nodes. Three overlapping nodes consist of one AN and two SNs. All of the CHs and ANs form the backbone paths of the CBC mesh. In an overall view of the CBC mesh, the grids of the mesh look like a chessboard, with ANs being black squares and SNs white squares. Incidentally, the mesh is called a *chessboard-based clustered mesh* (CBCM) and the backbone paths are called *chessboard-based backbone paths* (CBCBP).

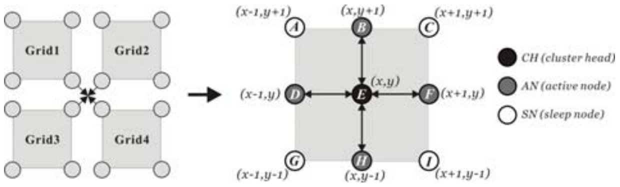
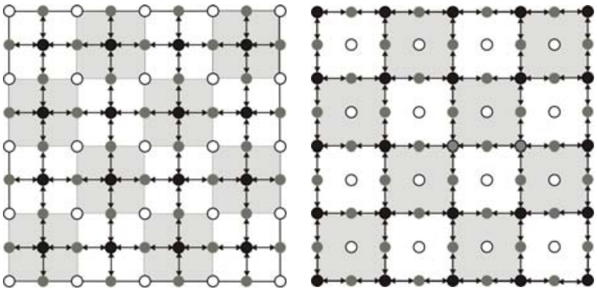


Figure 1 An example of a basic cluster block, β_y^x

Definition 2: Chessboard-Based Clustered Mesh (CBCM): If the sensor network mesh *S* has n disjointed meshes, then the names are defined as $CBCMS_1$, $CBCMS_2$, ... CBCMS_n. All of the central nodes in each *CBCM* differ and stand alone. Each pair of $CBCMS_i$ and $CBCMS_j$ is disjointed, where $1 \le i, j \le n$.

For example, if sensor network mesh *S* has exactly two disjointed *CBCM*s, then the names of the two *CBCM*s are $CBCMS_1$ and CBCMS_2, as shown in Figure 2. Therefore, PCAR schemes first calculate the distances from the currently active cluster head to the represent node of target region. In the PCAR scheme, the represent node of target region is adopted to the target region. The node nearest to the sink is chosen as the representative node. If the coordinate of the current cluster head *S* is (x_1, y_1) and the coordinate of represent node of target region *D* is (x_2, y_2). Then, the differential vector *V*(*S*, *D*) is defined, and the equation $V(S, D) = (\Delta x, \Delta y) = (x_2\text{-}x_1, y_2\text{-}y_1)$ is given. The differential vector *V*(*S*, *D*) is acquired by the difference in *S*'s coordinate and *D*'s coordinate. If Δx is positive then the represent node of target region will be to the right. If Δx is negative, then the represent node of target region will be to the left. Similarly, if Δy is positive, then the represent node of target region will be upwards. If Δy is negative, then the represent node of target region will be downwards. If both Δx and Δy are zero, then node *S* and node *D* are the same node and the destination is matched.

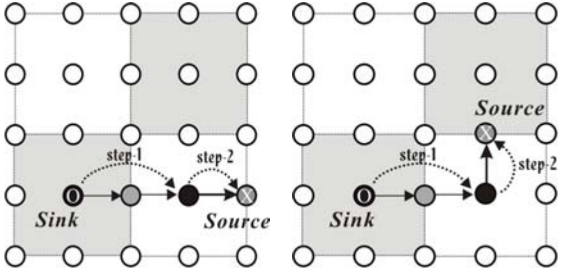
PCAR schemes try to balance the power consumption by each of the WSNET nodes, thus improving the network lifetime. In Salhieh *et al.*'s simulations [4], they found that if the power considerations are added to the routing protocol, then the overall power consumption is much better balanced than it is without taking power into account. So, the remaining energy of all nodes in the possible direction is compared in PCAR schemes. If the message needs to be split due to power considerations in PCAR schemes, then the packages of inquiry message are forwarded in several possible ways. The packages of inquiry message are fully forwarded into a single full-power next node. For example, if sink node *S*(*x*, *y*) = (1, 1) and represent node of target region *D*(*x*, *y*) = (3, 3), then, represent node of target region *D* is easy to find and is located in the right, upwards diagonal direction of sink node *S*; possible subsequent nodes are $D_1(1, 2)$ and $D_2(2, 1)$. The packages of inquiry message are split and forwarded into both nodes $D_1(1, 2)$ and $D_2(2, 1)$, respectively. Figure 3f shows one of the possible examples. Other examples of possible vector-oriented power-consideration dynamic multi-path routing in quadrant 1 are shown in Figure 3a-f.



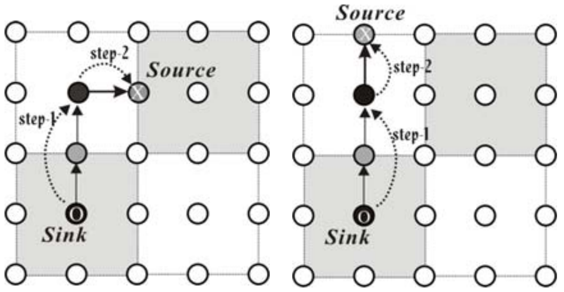
(a) $CBCMS_1$ (b) $CBCMS_2$

Figure 2 Two disjointed CBCMs of sensor network mesh *S*

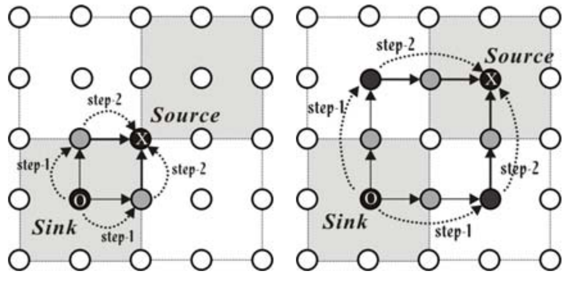
Recently, data fusion has been extensively used for data collection of WSNETs to reduce data traffic and improve the data transfer efficiency. Sensor nodes of classical WSNETs are close to their neighboring nodes. Therefore, neighboring sensor nodes collecting data are similar and overlap. Much research has proven that use of a combining or aggregating method to merge the sensed and received data will improve the energy efficiency. Fusion data are sent to subsequent nodes with no loss of information when the combined action is completed. In addition, the sensor nodes use the data fusion method to compare and modify uncorrelated data



(a) *V* (*Sink*, *Source*) = (+3, +0) (b) *V* (*Sink*, *Source*) = (+2, +1)



(c) V (Sink, Source) = (+1, +2) (d) V (Sink, Source) = (+0, +3)

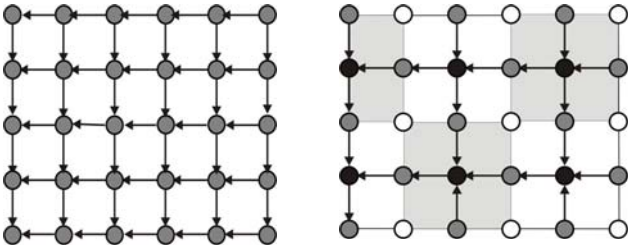


(e) V (Sink, Source) = (+1, +1) (f) V (Sink, Source) = (+2, +2)

Figure 3 Quadrant 1's two-steps data-forwarding routing paths measurements. In the PCAR protocol, sensor collaboration and the fusion property are supported in order to reduce energy consumption and improve the lifetime of the network.

In Figure 4, differences in data propagation between traditional protocols and the PCAR protocol are shown. The number of active nodes in the PCAR protocol is almost two-thirds those of traditional protocols. Because every node remains active for data collection and propagation in the traditional methods, sleeping nodes must be awakened when they are chosen to be members of the target region. Moreover, in traditional methods, the start node of the source are target region a needs to broadcast the sink information to every member of the target region when the inquiry message arrive. Then, the sensed data propagate back to the downlink nodes by the original sink paths as shown in Figure 4a. In contrast, the sleep nodes of the target region remain asleep in order to save energy in the PCAR protocol.

The sink propagation steps of nodes in the target region are the same of those of nodes in the normal area. Each cluster head propagates the inquiry message to all nodes of the same cluster and to every cluster head of neighboring clusters. When the routing paths are constructed, the sensed data still propagate and fuse back to the downlink nodes as shown in Figure 4b. The required sensing data of sleep nodes can be coordinated and fused by the neighboring nodes. For example, a node named central nodes if the node is not on the edge of target region. Similarly, if the node is on the edge of target region then we call the node as edge node. By the way, the required sensing data of central node C can be found by nodes C_1, C_2, C_3, and C_4 as shown in Figure 5a. The required sensing data of edge node C can be found by nodes C_1, C_2, and C_3 as shown in Figure 5b. Because the sensing area of C is covered by the sensing areas of C_1, C_2, C_3, and C_4 in Figure 5a, the required sensing data of C are found from the data of C_1, C_2, C_3, and C_4 using the schemes of data collaboration and fusion.



(a) Traditional method (b) PCAR method

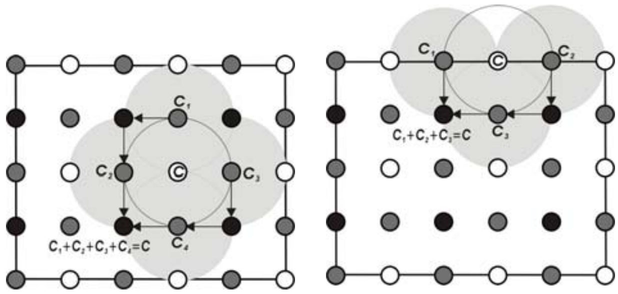
Figure 4 Examples of data propagation routing paths in the target region

3 PCAR Routing Protocol

The greedy method is a well-known strategy to solve some optimization problems in the analysis of algorithms. By the character of the greedy method, for each PCAR propagation step that uses the greedy method of algorithm, the decision is a locally optimal one. The locally optimal propagation of the PCAR ultimately adds up to a globally optimal routing. Consequently, the PCAR protocol adopts the greedy method to solve routing problems. The PCAR protocol is based on the vector-oriented directed data forwarding scheme, and the main challenge is to determine the propagating direction and maintain the shortest possible paths to avoid unnecessary power consumption. Therefore, the decisions for determining the next location and calculating the difference vector are very important in PCAR. The PCAR's routing algorithm is described below. First, the next cluster head is selected; by the difference vector of the current cluster head with the node of target region. Second, if the next direction is decided, data are forwarded to the next cluster head by the chosen divide-and-conquer routing strategy. Three routing strategies with different consideration, *Random Multi-Path Routing* (RMPR) *Multi-Path-Oriented Routing* (MPOR) and *Power-Oriented Multi-Path Routing* (POMPR) are proposed in the PCAR protocol and described below. The TDMA systems still support the multi-path routing in PCAR's routing strategy. Because of the fully digital format and the flexibility of buffering and multiplexing functions, time-slot assignments among multiple users are readily adjustable to provide different access rates for different users [6]. Three routing strategies are described as follows.

3.1 Random Multi-Path Routing (RMPR)

For the general average property, the RMPR scheme is first proposed. Due to the next direction having been decided, RMPR has only three different routing paths from which to choose. For direct perception through the



(a) Sample of central nodes (b) Sample of edge nodes

Figure 5 Examples of data collaboration and fusion in the target region senses, the RMPR scheme randomly chooses the next routing path. Moreover, the main propagation direction is bounded, and the dynamically randomly chosen interval routing maintains maximum flexibility from the current cluster to the next current cluster. The RMPR scheme consists of the following steps:

Step 1: The next cluster head is decided using the previously decided direction.

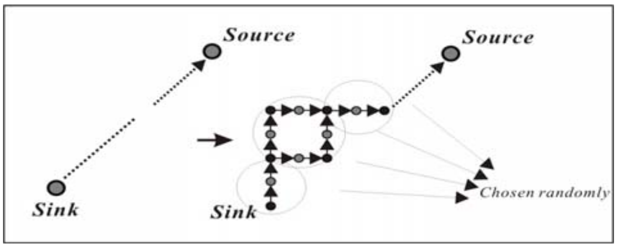
Step 2: The forwarding path is randomly chosen from the possible paths: x-axis routing, y-axis routing, or multi-path routing. For example, if the next cluster head is in the right, upward direction then the three possible paths are from β_y^x to β_y^{x+2} (x-axis routing), from β_y^x to β_{y+2}^x (y-axis routing), and from β_y^x to β_{y+2}^{x+2} (multi-path routing).

Step 3: If the energy of any node on the chosen path is empty, then that path is discarded and another path is chosen.

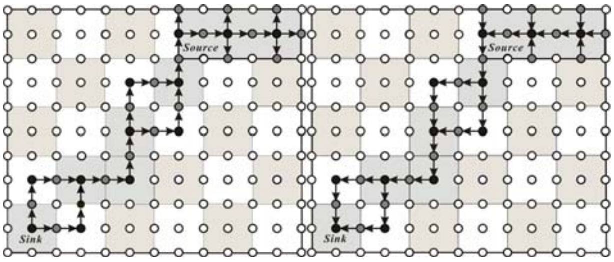
Step 4: If all possible paths are discarded, then the routing is discarded and the process jumps to Step 8.

Step 5: If the chosen path is a multi-path, then the inquiry message packages are split into two parts, and data are propagated to the next cluster head along the chosen paths. If the chosen path is a single path, then data are propagated to the next cluster head along the single chosen path. The required transfer and receiving power consumption is deduced from the passing nodes.

Step 6: If the target region is reached, then the inquiry message are propagated to all of the target region's nodes along multi-path routing. Otherwise, the process jumps to Step 1.



(a) Strategy for RMPR routing path selection



(b) Sink propagation (c) Data propagation

Figure 6 Examples of sink and data propagation using the RMPR protocol

Step 7: When inquiry message are being propagated to the target region, the routing path is constructed. In the target region, active nodes sense and fuse data, then data are propagated back to the previous node by the reversed routing paths. The active nodes in the routing paths fuse, split, and propagate data until the request is completed.

Step 8: The routing protocol is finished.

For the example shown in Figure 6, the sink node is located on the cluster head β_1^1, and the represent node of target region is located at the coordinate (7, 8). Therefore, the target region is located in the right, upward direction, and the next direction is to the right, upwards, or along a multi-path. Suppose the randomly chosen result is a multi-path, then the interval routing's target cluster head is node (3, 3). The routing is from β_1^1 to β_3^3. Therefore, the packages of inquiry message split into two parts and propagate to cluster heads (1, 3) and (3, 1) through nodes (1, 2) and (2, 1). Then, the packages of inquiry message fuse at node (3, 3) from nodes (3, 2) and (2, 3) as shown in Figure 6b. In Figure 6b, the second randomly chosen result is to the right, and the third result is upwards. So, the packages of inquiry message propagates from β_3^3 to β_3^5 and from β_3^5 to β_5^5.

3.2 Multi-Path-Oriented Routing (MPOR)

Different from the general average property of RMPR, data sharing is the first issue of the MPOR scheme. To divide the data into multi-path is the first consideration in any MPOR's propagation. In the MPOR, if the powers of the next two path's nodes are sufficient, then the packages of inquiry message are always divided into two parts by the ratio of the power, and data are propagated to the next cluster head through multi-path. Reducing the power consumption of each active node by cooperation is the main issue and contribution of the MPOR scheme. The routing algorithm of MPOR is described here.

Step 1: The next cluster head is determined using the previously decided direction. For example, if the next cluster head is in the right, upward direction of β_y^x then the next cluster is β_{y+2}^{x+2}.

Step 2: The next forwarding path from the current cluster head to the next cluster head is determined. For example, if the next cluster head is in the right, upward direction, then the multi-paths are from β_y^x to β_y^{x+2} and β_{y+2}^x, then from β_y^{x+2} and β_{y+2}^x to β_{y+2}^{x+2}.

Step 3: If the energy of any node on the multi-path is empty, then the failed path is discarded, and data are propagated using a single path. If one of the multi-paths is discarded, then the process jumps to Step 5. If both paths are discarded, then the routing is discarded and the process jumps to Step 8.

Step 4: The packages of inquiry message are split into two parts, and the next cluster head is propagated along the chosen multi-path route. The required transfer and receiving power consumption is deduced from the passing nodes. The process jumps to Step 6.

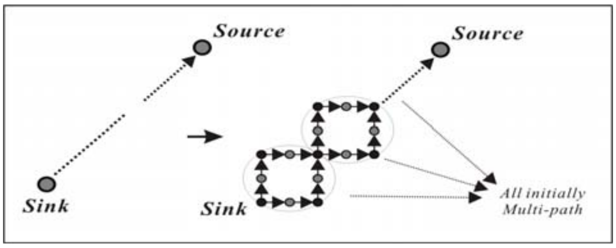
Step 5: Data are propagated to the next cluster head along a non-empty path.

Step 6: If the target region is reached, then the packages of inquiry message are propagated to all of the target region's nodes along multi-path routing. Otherwise, the process jumps to Step 1.

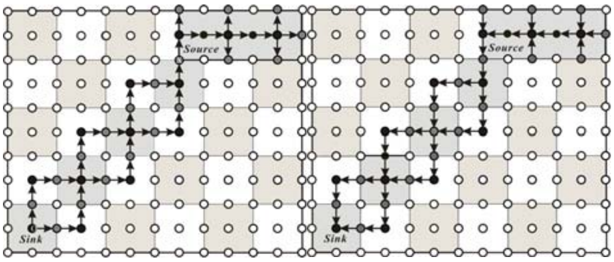
Step 7: When the packages of inquiry message are propagating to the target region, the routing path is constructed. In the target region, the active nodes sense and fuse data, then data are propagated back to the previous node by the reverse routing path. The active nodes in the routing path fuse, split, and propagate data until the request is completed.

Step 8: The routing protocol is finished.

For example as shown in Figure 7, the sink is located on the cluster head of β_1^1, and the represent node of target region is located at coordinate (7, 8). Therefore, the represent node of target region is located in the right, upward direction, and the interval routing's target cluster head is node (3, 3). The multi-path routing is from β_1^1 to β_3^3. The nodes of the routing paths are not supposed to include any with poor power. Therefore, the packages of inquiry message are split into two parts and propagated to cluster heads (1, 3) and (3, 1) through nodes (1, 2) and (2, 1). The packages of inquiry message fuse at node (3, 3) from nodes (3, 2) and (2, 3) as shown in Figure 7b. In Figure 7b, propagation of the second and third packages of inquiry message occurs are from β_3^3 to β_3^5 and from β_3^5 to β_5^5, respectively.



(a) Strategy for MPOR routing path selection



(b) Sink propagation (c) Data propagation

Figure 7 Examples of sink and data propagation using the MPOR protocol

3.3 Power-Oriented Multi-Path Routing (POMPR)

Decreasing the power consumption is the main goal of the POMPR protocol. The previous RMPR protocol attempted to use the general average property to balance the power consumption at every node. The MPOR protocol tries to use the multi-path data collaboration property to share power consumption at every node. In POMPR, properties of both RMPR and MPOR are adopted, and the power-consideration property is added to POMPR's scheme. Power levels of nodes in multi-path are evaluated and compared. First, POMPR finds the minimum power of nodes along each path. The two paths are defined as R_x and R_y. The nodes of R_x are denoted R_{x1}, R_{x2} ... R_{xn} and the nodes of R_y are denoted R_{y1}, R_{y2}... R_{yn}. Therefore, if the minimum power level of neither path is zero ($\forall i = 1,...n,$ $R_{xi} \neq 0$ and $R_{yi} \neq 0$) and the minimum power levels of both paths are in the same gap region (gap (n) $\leq$ Min (R_{xi}), Min (R_{yi}) $\leq$ gap (n+1)) then multi-path routing is adopted. If one of the paths has an empty power node ($\forall i = 1,...n,$ $R_{xi} = 0$ or $R_{yi} = 0$) or the minimum power levels of each path are not in the same gap region (gap(i) $\leq$ Min(R_{xi}) $\leq$ gap(j) $\leq$ Min(R_{yi}) $\leq$ gap(k) or gap(i) $\leq$ Min(R_{yi}) $\leq$ gap(j) $\leq$ Min(R_{xi}) $\leq$ gap(k)) then the single path with maximum power is adopted. In POMPR, if the power levels of the next two nodes are sufficient, then packages of inquiry message are always divided into two parts by the ratio of the power levels, and data are propagated to the next cluster head through multi-path. Reducing the power consumption of each active node by cooperation is the main issue and contribution of the POMPR protocol. The routing algorithm of POMPR is described below.

Step 1: The subsequent cluster head is selected based on the previously decided direction.

Step 2: The Max-Min remainder power levels of the multi-path routing paths are calculated.
M_1 = Min (R_{xi}) and M_2 = Min (R_{yi}), $\forall i = 1,...n$.
M_3 = Max (M_1, M_2).

Step 3: If only $M_1 \leq 0$, then path Rx is discarded and data are propagated using path Ry. For example, if the next CH is in the right, upward direction, then the path moves from β_y^x to β_{y+2}^x .

If only $M_2 \le 0$, then path *Ry* is discarded, and data are propagated using path *Rx*. For example, if the next CH is in the right, upward direction, then the path moves from β_y^x to β_y^{x+2}.

If both M_1 and M_2 are greater than zero and M_1 and M_2 are in the same gap, then data are propagated using multi-path. For example, if the next cluster head is in the right, upward direction, then the path moves from β_y^x to β_{y+2}^{x+2}.

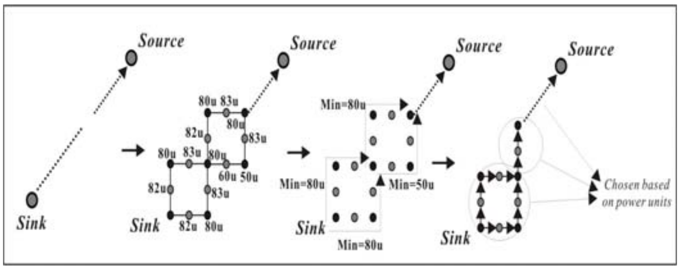
If both M1 and M2 are greater than zero and M1 and M2 are in different gaps, then are data are propagated using the single path with greater value. For example, if M_3 = Max (M_1, M_2) = M_1, then move from β_y^x to β_y^{x+2}.

If M1 $\le$ 0 and M2 $\le$ 0, then the routing is discarded and the process jumps to Step 6.

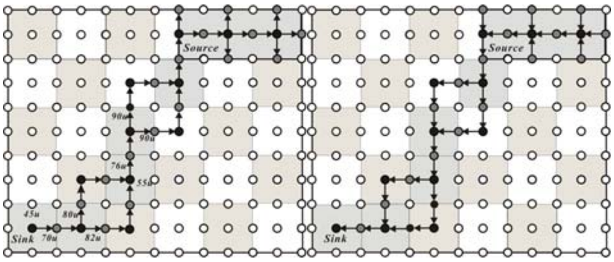
Step 4: If the chosen paths are multi-path, then the packages of inquiry message are split into two parts, and data are propagated to the next CH along the chosen paths. If the chosen path is a single path, then data are propagated to the next CH along the single chosen path. The required transfer and receiving power consumption is deducted from the nodes through which the data pass.

Step 5: If the target region is reached, then the packages of inquiry message are propagated to all nodes along the multi-path routing and the process jumps to Step 8. Otherwise, the process jumps to Step 1.

Step 6: If all of possible directions are discarded, then the routing is discarded and the process jumps to Step 8.



(a) Strategy for POMPR routing path selection



(b) Sink propagation (c) Data propagation

Figure 8 Examples of sink and data propagating using the POMPR protocol

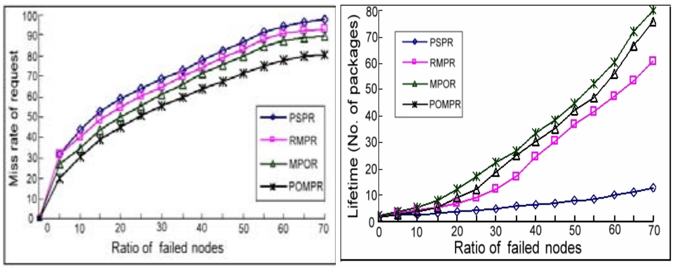
Step 7: A non-discarded direction is selected and the process jumps to Step 2.

Step 8: The routing protocol is finished.

For example as shown in Figure 8, the sink is located on the CH of β_1^1, and the represent node of target region is located at the coordinate (7, 8). Therefore, the represent node of target region is in the right, upward direction, and the interval routing's target cluster head is node (3, 3). The gaps are set at 0%, 25%, 50%, 75%, and 100%. Every node initially possesses 100 units of power. Figure 8b shows that M_1 = Min (R_{xi}) = 70 units of power and M_2 = Min (R_{yi}) = 45 units of power in the first run of packages of inquiry message propagation. M_1 and M_2 are not in the same gaps, and both are greater than zero. So, M_3 = Max (M_1, M_2) = M_1 = 70 units of power. Therefore, the next direction is to the right and the interval routing is from β_1^1 to β_1^3. In the second run of packages of inquiry message propagation, M_1 = Min (R_{xi}) = 82 units of power and M_2 = Min (R_{yi}) = 80 units of power. M_1 and M_2 are in the same gap, and both are greater than zero. So, the interval routing is a multi-path routing, and the data move from β_1^3 to β_3^5. Next, in the third run of packages of inquiry message propagation, M_1= Min (R_{xi}) = 55 units of power and M_2 = Min (R_{yi}) = 76 units of power. M_1 and M_2 are not in the same gap, and both are greater than zero. So, M_3 = Max (M_1, M_2) = M_2 = 76 units of power. Therefore, the next direction is upward, and the interval routing is from β_3^5 to β_5^5.

4 Simulation Results

To verify PCAR protocol's analytic observations, some simulations were constructed. The simulation module for the PCAR protocol begins on the periodically exchanged CBC mesh formation. Then, the PCAR system transfers initial coefficients to the PCAR engine and runs the PSPR, RMPR, MPOR, and POMPR routing schemes. Finally, the product data are tabulated. The PCAR scheme provides several coefficients and topologies to run the simulation and evaluate the performance. Java simulation programs were developed to achieve the PCAR's requirements. A sensor network



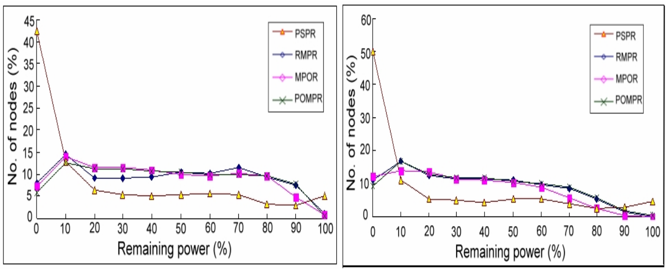
(a) (b)

Figure 9 Performance of (a) miss rate curves and (b) lifetime curves size of 100×100 was chosen. The nodes of the PCAR's WSNET were arranged and the positions were fixed. The sink node and target region of each request message were randomly generated. Furthermore, levels of power consumption of the message transitions and message receptions for each node were considered. The simulations were conducted for 5000, 10,000, 20,000, and 50,000 request messages. The length of the messages was randomly generated, and messages were bound in 200 to 1000 packages. To simulate a real scenario, PCAR adopted the power consumption's model of a Lucent ORiNOCO WLAN PC card, for which the levels of transmitting, receiving, and idling power consumption are 1.4, 0.9, and 0.05 W/s, respectively.

Figure 9a gives comparisons of miss rates and failed nodes for the PSPR, RMPR, MPOR, and POMPR schemes. At the beginning of the simulations, all nodes had full power and no failures, and the miss rate curves of the four schemes were similar. Only the active nodes located on the routing paths propagate data and consume energy. In the traditional PSPR, the routing path is a fixed single shortest path, and levels of power consumption are centralized on some fixed active nodes. Owing to the repetition of active nodes, the loads of power consumption were located on some fixed active nodes. As a consequence, the miss rate of the PSPR scheme was higher than those of the RMPR, MPOR, and POMPR schemes. The results of PSPR scheme's simulations showed that if failed nodes grow to 70% than the miss rate will grow to nearly 100%. In the PSPR scheme, if the sink nodes and target region are fixed, then the miss rate will grow rapidly, and the lifetime will be shortened. Because the POMPR scheme is concerned with power policy and locally dynamically decides the routing paths, consequently, the miss rate of the POMPR scheme is lower than those of the PSPR, RMPR, and MPOR schemes. Furthermore, RMPR and MPOR schemes have similar behaviors for the miss rate, and the curves almost overlap. Figure 9b shows the lifetime curves among PSPR, RMPR, MPOR, and POMPR schemes. Because the PSPR scheme uses fixed routing strategies to propagate data, the routing paths are static, and the lifetimes are limited. Different from the PSPR scheme, PCAR schemes adopt a power-sharing policy and load-balance strategies to dynamically process data propagation. Therefore, the overall lifetimes of PCAR schemes are largely improved over the traditional PSPR scheme. In PCAR schemes, the POMPR scheme adopts power-considering strategies to slow down the rate of power consumption and prolong the network's lifetime. Furthermore, POMPR schemes use the dynamic routing path to choose strategies to overcome the shortest-path single-direction problem. If the chosen direction has no routing path with sufficient power, then the POMPR scheme permits non-empty and non-backward routing paths to be used. Even if temporary routing paths are adopted, the vector-oriented strategies will guide the next routing path in the correct direction. In a word, POMPR scheme's lifetime is longer than others.

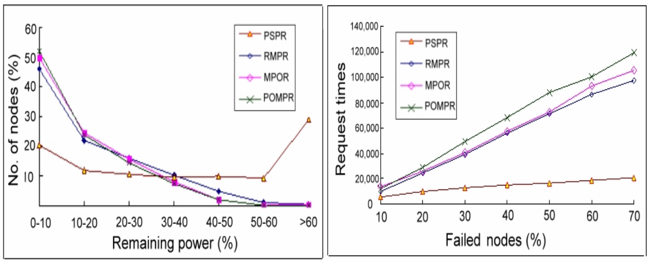
Figure 10a and b show a comparison of four schemes' power states when 10,000 and 20,000 requests were run. Furthermore, Figure 10a and b indicate that the levels of power consumption of nodes in the PSPR scheme are not better balanced than those of PCAR schemes. In the PSPR scheme, several nodes have failed, and several nodes still have full power after many requests have been run. Due to the strategy of the dynamic routing path, levels of power consumption of nodes in PCAR schemes are lower and more balanced than those of nodes in PSPR schemes. Consequently, the curves of PCAR schemes in Figure 10a and b are smoother than the curves of PSPR schemes.

To analyze failed nodes, another simulation is shown in Figure 11a. Figure 11a shows comparisons of power states between the four schemes when more than half of the nodes of each network have failed. Note that the request times of PCAR schemes are larger than those of PSPR schemes when half of the nodes of the network have failed. Figure 11a still indicates that because the power-consideration, direction-consideration, data-fusion, data-collaboration, and data-sharing policies are combined in PCAR schemes, the levels of power



(a) (b)

Figure 10 Power states after (a) 10,000 requests and (b) 20,000 requests



(a) (b)

Figure 11 (a) Power states after half of the nodes had failed and (b) Request times vs. failed nodes consumption in the RMPR, MPOR, and POMPR scheme were more scattered and balanced than in the PSPR scheme. Finally, Figure 11b shows relations between request times and failed nodes. Because the PSPR scheme adopts an inflexible routing strategy to process requests, some highly reused nodes fail quickly, and the curves are more even than those of PCAR schemes. Furthermore, the POMPR scheme adopts power-oriented and vector-oriented multi-path routing strategies to overcome the disadvantages of PSPR schemes, so the power efficiency is better than with other schemes.

5 Conclusions

The paramount design challenge in the PCAR protocol is to scale-down the energy consumption and maximize the network lifetime. PCAR schemes integrate vector-oriented propagation and multi-path routing schemes to guide propagating data to its destination. In particular, properties of clusters and cluster heads are combined to form cluster-plates in the CBC sensor network. Three multi-path routing strategies of CBC sensor networks, i.e., RMPR, MPOR, and POMPR, were proposed for PCAR schemes to generalize a more-powerful energy-efficient routing protocol. The PCAR protocol starts from the direct perceptions through the senses of the RMPR scheme, continues with data sharing of the MPOR scheme, and applies the power-consideration dynamic routing scheme of POMPR. When a new direction is selected, the three schemes work together to slow down energy consumption by active nodes, thus prolonging the network lifetime. Simulations showed significant improvements in the data loss rate, power consumption, and network lifetime with this chessboard-based cluster-meshed multi-path routing. Comparing the traditional shortest-path routing protocols; RMPR, MPOR, and POMPR are all the excellent protocols. In particular, RMPR and POMPR both have considerable effectiveness. Finally, we know that the MPOR, POMPR, and RMPR protocols are all suitable for indoor fixed-topology wireless sensor networks. Determining how to extend the results to mobile destinations and outdoor environments is the future work of PCAR schemes.

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