Radio-disjoint Geographic Multipath Routing for Reliable Data Transfer in Lossy WSNs

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***Abstract*—In order to find a completely disjointed multiple routes, traditional multipath strategies try to get global topology information by using frequent flooding or end-to-end signaling. It is very useful, but too much expensive to directly adapt to the resource constrained wireless sensor networks. Thus, recently there has been proposed an energy-efficient localized multipath scheme (EDM), which exploits geographic information for multipath discovery and routing. However, EDM has a significant limitation that it does not consider the case of simultaneous transmission between adjacent paths. Because of the path interferences, the transmission fails or corrupted packet receptions might be frequently occurred even if EDM has made completely disjointed multiple paths. Therefore we propose an interference-free geographic multipath protocol by allowing the paths to separate each other. To implement that, we utilize a logical multipath pipeline approach. Each pipeline has to keep a certain distance between each other, and a route can be allowed to be made within a pipeline.**

***Index Terms*—Wireless sensor networks, multipath routing, radio-disjoint multipath, geographic multipath.**

I. Introduction

Multipath data delivery has known as one of the most effective strategy to improve the end-to-end reliability for the lossy wireless networks [1]. It can provide useful opportunities for data packets to be arrived at the network gateway such as a sink by path redundancy. It also can reduce frequent routing update and provide either high data throughput or a distribution of traffic load over the network [2]. A variety of multipath routing schemes [3-4] are studied in wireless mobile ad hoc networks (MANETs), they however cannot be directly applied to WSNs because of their stateful control and deterministic construction of the paths. Namely, they need too much control overhead or even the deterministic paths are vulnerable to the network dynamics.

Recently, geographic multipath routing schemes [5] have been proposed for WSNs. Utilizing characteristics of high node density and location awareness, these schemes try to get geographical positions which are used for both entry and exit points of each multipath instead of maintaining node and link states of constructed paths. After acquiring such positions, source's data is delivered through these positions by using geographic routing when only the data is generated by a source.

To improve end-to-end reliability, the primary goal of the geographic multipath routing schemes is to construct complete disjointed multiple paths [3-5]. These schemes consider the complete disjoint paths as a node-disjoint multipath that an intermediate node in a path is allowed to belong to only a single path, not two or more. It is because that if multiple paths share the one node, the node may be congested by multiple traffics. The shared node has high possibility to break down by depletion of energy since the node suffers from the concentrated traffic load.

However, even if such node-disjoint multipath schemes are used in WSNs, there might be another significant problem such as transmission failure or corrupted packet reception. Since practical sensor nodes can communicate with other nodes by broadcast through omnidirectional antenna, there always exist possibilities to bring collisions if separate paths are too close to disrupt each other. Namely, if the multipath schemes that do not take the interference issues into account, their expensive exertion for improving the packet reliability becomes useless or even cause injury to the reliability.

Therefore, we propose a novel radio-disjoint geographic multipath protocol. The design goal of the proposed protocol is to construct completely radio-disjoint multipath, which can avoid the collisions due to interferences without any additional interference metrics. The main idea of the proposed protocol is to allow multiple paths to keep a certain distance between each other; however, since this simple idea still remains inevitable interference regions, i.e., both source side and destination side, we therefore exploits an interference avoidance mechanism, which could prevent the simultaneous transmissions at the interference regions by local scheduling algorithms. We demonstrate that the proposed protocol shows better performance than the previous one via extensive simulation in terms of the packet delivery ratio, the average energy consumption, and the end-to end delay.

II. Network Model

We consider a wireless sensor network (WSN) that consists of randomly deployed N sensor nodes over a finite, two-dimensional planar region. We assume that each node knows its position and the positions of its neighbors within its transmission range R. These assumptions can be achieved by either an internal GPS device of sensor node or other localization protocols [6]. When an event occurs in the WSN, sensor nodes that perceive the event locally elect one data

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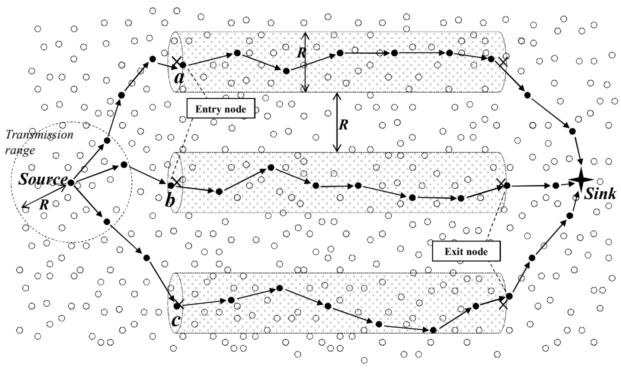

Figure 1. An overview of the proposed protocol: the source tries to send sensed data to the sink through the three logical pipelines

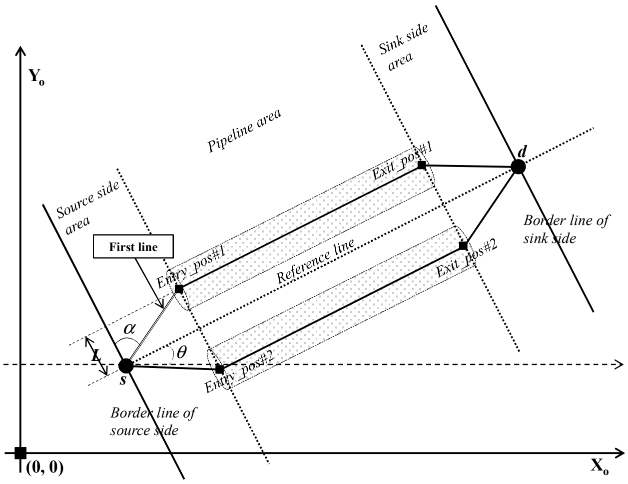

Figure 2. Calculating the entry positions in the proposed protocol

source to prevent massive data duplication and collision. Also, we assume that every sensor node could know the unique sink node's position a priory. This assumption is generally satisfied in a variety of emergency applications. In other cases, the data source can obtain the position of a destination through location service protocols [7]. The location of a node acts as its ID and network address.

III. Proposed Protocol

A. Overview

We present the basic idea of the proposed protocol. As shown in Fig. 1, three multiple paths between the source and the sink are constructed. The source sends the sensed data to each entry node of the paths, simultaneously. The source's data are forwarded to the each exit node by geographic routing, and then the data can reach to the sink. Since these paths are constructed to be apart from each other over transmission range *R*, they cannot disturb each other. However, two regions, both the source side from the source to each entry node and the sink side from each exit node to the sink, cannot free from interference due to the possibility of simultaneous transmissions at the different paths. Therefore especially in source side, each path has different additional delay time. For example, in Fig. 1, the path *Psa* from the source *S* and the entry node *a* has 1 *ms* delay time per each hop; however *Psb* has zero delay and *Psc* has 2 *ms* delay time per each hop. In sink side, the exit nodes keep the source's data before receiving the acknowledge message of the sink. Unfortunately if a node within the transmission range of the sink perceives the collisions, the node requests retransmission of the data to the exit node of the received data. After the sink successively receives the data, the sink sends the acknowledge message to whole exit nodes by broadcast. The exit nodes then release the data.

B. Constructing the multiple pipelines

In the proposed protocol, the area between a source and a sink is divided into three parts. The first one is the source side area between a source and an entry position of a pipeline. The second one is the collision-free pipeline area between the entry position and an exit position. The last one is the sink side area between the exit position and the sink. Since the reference points could define the size of such areas, obtaining the reference points such as both entry position and exit position become a significant challenge.

We define the straight line between a source and a sink as the *reference line*. We may also call the *border line of source side* as the vertical line to the reference line passing the source. Only the nodes at front area from the border line could be selected as a next hop node. On the other hand, the vertical line passing the sink referred as the *border line of sink side*. Suppose that the proposed protocol needs *k* number of multiple paths in order to satisfy the desired delivery ratio given by applications. Thus, we also need *k* number of entry and exit positions. To establish fully distributed pipeline, we evenly divide the border lines into *k*+1 number of angles. For example, as shown in Fig. 2, when the protocol requires only two paths, the border lines are divided by three angles of 60 degrees. In case of three paths are required, border lines could be divided by four angles of 45 degrees. We may call the first straight line from a border line of a source in a clockwise direction as a *first line*. We also define the angle between the border line and the first line as α. The y-axis distance between a source and the first entry position is referred to *L*.

Obtaining entry positions

To spread the logical pipelines out as much as *R* (transmission range of sensor nodes), the value of *L* varies with the number of multipath as follows. (Geographically top pipeline first)

$$2\ paths: \#1st \rightarrow R\ and\ \#2nd \rightarrow -R$$

$$3\ paths: \#1st \rightarrow 2R,\ \#2nd \rightarrow 0,\ and\ \#3rd \rightarrow -2R$$

$$4\ paths: \#1st \rightarrow 3R,\ \#2nd \rightarrow 1R,\ 3rd \rightarrow -1R,\ and\ 4th \rightarrow -3R$$

$$\vdots$$

$$n\ paths: \#1st \rightarrow L = (k-1) \cdot R$$

To facilitate expression, we first calculate an entry position of the first pipeline through the distance *L* and the angle α of the pipeline. After that, we calculate other entry and exit positions using the calculated entry position of the first pipeline. Since we calculate the reference points based on global coordinates, we should take a grade into account between the reference line (source to sink) and the absolute reference line (absolute x-axis). As shown in Fig. 2, we refer this angle as θ. Therefore, we could get the distance of the first line through L and α.

$$Dist(S, Entry\_pos\#1) = (k-1) \cdot R / \cos\alpha. \quad (1)$$

We could know the coordinate variations between the source and the first entry position through θ.

$$\Delta x_1 = \sin(\alpha - \theta) \cdot (k-1) \cdot R / \cos\alpha, \quad (2)$$

$$\Delta y_1 = \cos(\alpha - \theta) \cdot (k-1) \cdot R / \cos\alpha. \quad (3)$$

Using the equation (2) and (3), we obtain the entry position of the first pipeline.

$$Entry\_pos\#1 = (x_s + \Delta x_1, y_s + \Delta y_1). \quad (4)$$

where (x_s, y_s) is the coordinate of the source.

In accordance with the definition of the proposed protocol, the second entry position is located far away from the first entry position as much as *2R*. So we could get the second entry position through the following expressions.

$$\Delta x_2 = 2R \cdot \sin\theta, \quad (5)$$

$$\Delta y_2 = 2R \cdot \cos\theta, \quad (6)$$

$$Entry\_pos\#2 = (x_s + \Delta x_1 - \Delta x_2, y_s + \Delta y_1 - \Delta y_2). \quad (7)$$

Consequently, the general expression for an entry position is:

$$\begin{aligned} &Entry\_pos\#k \\ &= (x_s + \Delta x_1 - (k-1)\cdot \Delta x_2, y_s + \Delta y_1 - (k-1)\cdot \Delta y_2). \end{aligned} \quad (8)$$

Obtaining exit positions

In the proposed protocol, sensor nodes that can directly receive the broadcast message of a sink should become exit nodes of logical pipelines for local retransmission mechanism presented in section III. C. We call these nodes as *candidate nodes*. Among these nodes, the closest node from a source has to be selected as an exit node of a pipeline in order to reduce the communication costs. It is because that the path from the closest node to the sink is the shortest path. However, since the source cannot know information of the candidate nodes *a priori,* we exploit a heuristic approach. We consider the worst case that exit positions of each pipeline are on the border line of sink side. Since a data packet is forwarded from an entry position to an exit position by geographic routing, if the packet meets a candidate node, the node may be the closest node from a source node. After that, the packet is stopped and the candidate node becomes a practical exit node.

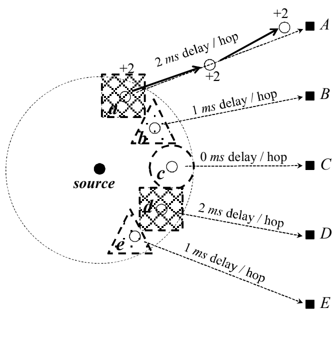

Figure 3. Local scheduling algorithm at the source side area

In other words, we first construct a perpendicular line through each entry position to the border line of sink side. And the cross points become exit positions. We define the coordinate variations between an entry position to its exit position as Δx_3 and Δy_3. This value can get using the center point of entry positions and the location of the sink.

$$\Delta x_3 = \{x_d - (x_{Entry\_pos\#first} + x_{Entry\_pos\#final}) / 2\}, \quad (9)$$

$$\Delta y_3 = \{y_d - (y_{Entry\_pos\#first} + y_{Entry\_pos\#final}) / 2\}. \quad (10)$$

Using the equation (9) and (10), the general expression for an exit position is:

$$Exit\_pos\#k = (x_{Entry\_pos\#k} + \Delta x_3, y_{Entry\_pos\#k} + \Delta y_3). \quad (11)$$

C. Data transmission

As above mentioned, the area between a source and a sink is divided into three parts: a source side area, a collision-free pipeline area, and a sink side area. In other words, we use three phase geographic routing according to these areas: the source to an entry position, the entry position to an exit position, and finally the exit position to the sink. We set the height of a pipeline to *R*, and each pipeline is set to stay away from each other by *R*. In the pipeline area, the data packet includes the height of a pipeline and the position of its own entry and exit points. Since the entry and exit positions are located in the middle of height of the pipeline, each forwarding node could know the region of its own pipeline when it receives the packet. Namely, only the nodes within its own pipeline could be selected as a next hop node for data forwarding.

However, the proposed protocol might not find a next hop node at both the source side area and the sink side area if the protocol uses same routing strategy above mentioned at the pipeline area. It is because that these areas are inevitably overlapped at some areas. So we present two different mechanisms that exploit the modified geographic routing to cope with this problem.

Source side – Adjust delay time

When a source constructs a multipath in a source side area, the source find the next hop nodes related to each entry position from its neighbor nodes. However, the next hop node of the geographic routing can be shared between the multiple paths according to where the sensor node is positioned in the real field. It is caused by the characteristic of the geographic routing scheme which selects the node in minimum distance from the destination as the next forwarding node. So in the geographic routing process, the proposed protocol conjugates the marking technique [5] in order to create the complete disjoint multiple path for the source side area on which the shared node does not exist. After that, the rest goal is to

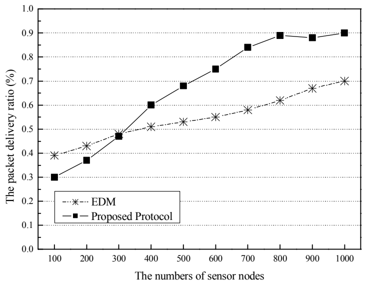

Figure 4. The packet delivery ratio vs. the numbers of sensor nodes

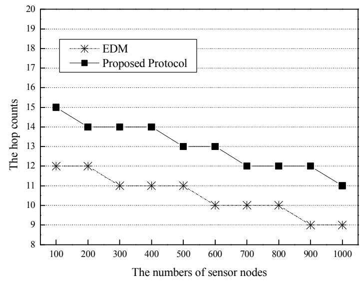

Figure 5. The hop counts vs. the numbers of sensor nodes

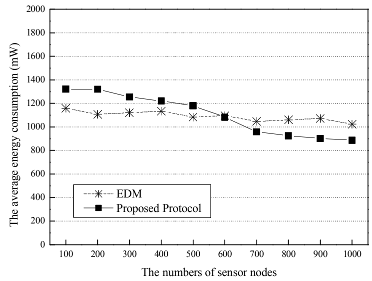

Figure 6. The average energy consumption vs. the numbers of sensor nodes

prevent the collision between paths due to simultaneous transmission.

In a source side area, there exist k number of geographic paths between a source and k number of entry positions. We give the different delay times to such paths except some paths cannot disrupt each other. These special paths can be grouped, and can be used simultaneously. Thus, they can have same delay times. For example, as shown in Fig. 3, the source wants to send its sensed data to both entry position A, B, C, D, and E. The source selects the next hop nodes from its neighbor nodes, which are the closest nodes from each entry position. We can see these nodes (a, b, c, d, and e) in this figure. We assume that each sensor node has the same transmission range and could know its neighbor nodes by beacon message exchanges, so the source node S could know whether the selected next hop nodes are interferable each other or not. It can be sorted by the number of the interferable nodes.

Namely, in order to avoid the interference, the c sends data in different time with $\{b, d, a, e\}$. Except the c, the b can simultaneously send with e, not with $\{d, a\}$. Since the d can send with the a, consequently, we can get the three different groups such as $\{c\}$, $\{b, e\}$, and $\{d, a\}$. Each group has different hop delay times for data forwarding from the source to each entry position. For example, the group $\{c\}$ has 0 *ms*, $\{b, e\}$ has 1 *ms*, and $\{d, a\}$ has 2 *ms* delay times per each hop transmission. We could get these delay times through the following expression.

$$delay(k) = \gamma\{(k-1)+\varepsilon)\}, \tag{12}$$

where k is the k-th multipath group, and γ is the scaling factor. ε is a random variable between -0.5 and 0.5 ($k \neq 1$) or zero (k=1). Consequently, the source sends the data packet including the differential delay times for each neighbor node. Then, the source's data is forwarded in each hop with the received delay times until the data reach its own entry position.

Sink side – Local retransmission

The source's data is forwarded from each entry node toward its own exit position by the geographic routing. When a data packet of a pipeline meets a node that is located within the transmission range of a sink during forwarding process, the node becomes the exit node for the pipeline. Note that in WSNs, a sink is more powerful and has longer transmission range than limited resourced sensor nodes. This property enables that whole exit node placed further apart could receive a message of the sink, simultaneously. Thus, we exploit an ack-based local retransmission mechanism for reliable data transfer. It is because that the scheduling mechanism which is used at the source side area cannot be directly adopted to the sink side area since the packet receiving time of each exit node might be different each other.

Firstly, each exit node which receives the data packet keeps the data in its memory, and then sends a copy of the data packet to a sink by the geographic routing. When the sink receives the source's data successfully, the sink broadcasts acknowledge message to every node within its transmission range, including the whole exit nodes. In the sink side area, if an intermediate node perceives the collisions, the node sends a data request message to the exit node of the received packet. Namely, each exit node works as a local source. Finally, if an exit node receives the acknowledge message, the exit node could release the data.

IV. PERFORMANCE EVALUATION

We evaluate the performance of the proposed protocol in terms of the packet delivery ratio, the average hop counts, the average energy consumption, and the end-to-end delay with EDM [5], a representative node-disjoint geographic multipath routing protocol in wireless sensor networks.

A. Methodology and Metrics

We implement the proposed protocol in the Qualnet 4.0 network simulator [8]. The model of sensor nodes are followed by the specification of MICA2 [9]. The transmission range of sensor nodes and sink are 40 *m* and 120 *m*, respectively. 700 sensor nodes are randomly and uniformly distributed in a 500 *m* × 500 *m* sensor field. The size of a data packet is 256 bytes. A source generates the data packet every two seconds. The number of paths is three. Each simulation lasts for 600 seconds.

B. Impact of the numbers of sensor nodes

We evaluate the packet delivery ratio, the average hop counts, and the average energy consumption in different numbers of sensor nodes from 100 to 1000.

Fig. 4 indicates the packet delivery ratio for increasing the number of sensor nodes. As we can see, with the increase of sensor nodes, the packet delivery ratio also increases. Because the number of nodes is associated with the node density, so a node could has the more neighbor in its forwarding area as the

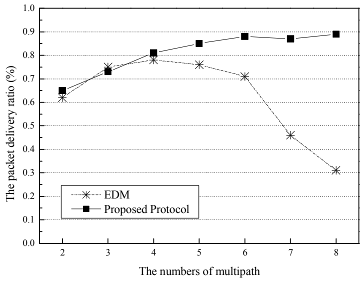

Figure 7. The packet delivery ratio vs. the numbers of multipath

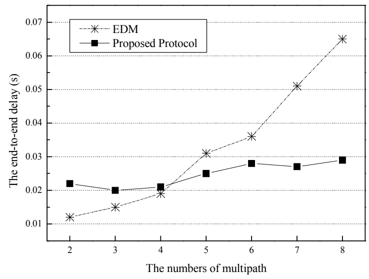

Figure 8. The end-to-end delay vs. the numbers of multipath

number of nodes increases. We observe that the packet delivery ratio of the proposed protocol is lower than EDM when the few number of nodes are deployed in sensor fields. It is because that a node in a pipeline of the proposed protocol may not find a next hop node if the number of sensor nodes is small. However, the graph rapidly increases in the proposed protocol as the number of sensor nodes increases. If the network could guarantee a certain degree of node density, a transmission fail is commonly occurred by interferences between paths. Fig. 5 shows a variation of the average hop counts. In both protocols, as the number of nodes are increases, the average hop count decreases. Because the node density increases, there are more neighbor nodes for each node. We also observe that the average hop counts of the proposed protocol are always larger than that of EDM. It is because that the proposed protocol more detour the path than EDM in order to avoid the interference. However, as shown in Fig. 6, we observe that the proposed protocol consumes less energy than EDM when the number of nodes is large although the proposed protocol has more hop counts. Because EDM requires more effort to accomplish delivery ratio given by applications than IGM, as the node density increases.

C. Impact of the numbers of multipath

We evaluate the packet delivery ratio and the end-to-end delay in different numbers of multipath from 2 to 8.

As shown in Fig. 7, both the proposed protocol and EDM increase the packet delivery ratio as the number of multipath increases. However, we observe that EDM rapidly decreases after the network has seven paths while the proposed protocol converges in the maximum. It is because that the collisions are continuously occurred when the multiple paths within the narrow area try to send the data, simultaneously. Namely, in this worst case, any packet can avoid such collisions. In Fig. 8, we can observe that the end-to-end delay of EDM rapidly increases as the number of path increases. It means the case that many individual paths are constructed within the narrow area. Thus in the case, the queuing delay of each node in this area may be significantly increased. However, since the proposed protocol constructs geographically separated paths, each node has low queuing delay than EDM. Also, we observe that the proposed protocol has more delay than EDM only when there is little number of multiple paths. If the queuing delays of both EDM and the proposed protocol are similar to each other, the proposed protocol that has the more average hop counts, it thus may take more delay times.

V. CONCLUSION

In this paper, we introduce a radio-disjoint geographic multipath scheme to effectively avoid the interferences between each path via multiple logical pipelines between a source and a sink pair. By separating each pipeline, geographically collision-free paths could be constructed. In addition, for inevitable overlapping areas in proximity to the source and the sink, the proposed protocol exploits localized scheduling algorithms that exploit the modified simple geographic routing. We have studied the performance of the proposed protocol relative to EDM, a representative node-disjoint geographic multipath protocol. We observe the proposed protocol shows better performance in the packet delivery ratio and the end-to-end delay.

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