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A Routing Approach for Constructing Braided Multipath to Alleviate Congestion in WSNs

Chorng-Horng Yang[1], Long-Wei Lin and Chao-Wei Chou

Department of Information Management, I-Shou University
No. 1, Sec. 1, Syuecheng Rd., Dashu District, Kaohsiung City 84001, Taiwan R.O.C.

Abstract

In recent years many versatile applications have been developed on wireless sensor networks (WSNs) that consist of various types of sensors. Thus, the issues of the WSN technology have become hot topics for WSN research. One of the hot topics is congestion alleviation for WSNs. A Topology-Aware Resource Adaptation (TARA) approach was developed to alleviate the congestion in intersection hot spot. The TARA approach reacts to the congestion by creating a detour path after the congestion was detected. Therefore, the congestion is resolved slowly due to accumulated data packets. In order to resolve the congestion in the WSN quickly, a braided multipath routing (BMR) approach was proposed, in this paper, to alleviate network congestion. The BMR approach can create braided multiple paths before congestion occurs. Thereafter, as congestion is detected the traffic can be rerouted to another braided path. Simulation study was conducted to evaluate the BMR approach. The simulation results show that the BMR approach alleviates congestion in WSNs quickly and provides better protection ability by using less extra nodes and links than other approaches.

Keywords: wireless sensor network, multipath routing, congestion alleviation.

1. INTRODUCTION

In recent years, many versatile applications were deployed on Wireless Sensor Networks (WSNs) [1-3], which is a promising technology that can be used as the platform for these applications. A WSN consists of one or more sinks and a large number of sensor nodes. Each node is equipped with a microprocessor which can detect and collect environmental data and transmits data toward the sink by cooperating with each other. Thus, the issues of the WSNs have become hot topics for researchers in recent years. One of the hot topics is congestion control on hot spot in WSNs. As sensor nodes sense the environmental data, they send the data packets, which contain the detected data, toward the sink node. Since lots of data packets may be generated by sensors in s short interval and, unfortunately, the bandwidth between sensors is low, the network congestion, thus, would degrade the network throughout and lengthen the transmission delay in the WSN. Moreover, the congestion could cause that much energy is consumed on transmitting the re-transmitted data packets and, seriously, the network may collapse if the congestion is not resolved quickly.

In recent years, several studies showed that the congestion control can be employed to improve the energy efficiency of a WSN. However, as the network enters a congested state, the data rate arises quickly and a large amount of data is generated to quickly report the phenomena. In [4], Topology-Aware Resource Adaptation (TARA) approach was proposed. The TARA approach can build lots of new routes to handle the increased traffic data based on the capacity analysis model. As congestion is detected, TARA approach designates a distributor node to detour the congested path and also looks for a merger node which merges the detour path with the original path. Thus, the congestion in the intersection of two routes can be alleviated. However, to establish the detour path and then transmit data through the detour path after detecting the congestion may result in serious packet losses when congestion has occurred but the detour path is not yet built.

In this paper, a braided multipath routing (BMR) approach is proposed. The BMR approach can alleviate congestion in a WSN by establishing multiple paths for an active route before congestion occurs. Moreover, it can detour the data packets on the original path to another path when congestion is detected. Thus, constructing the braided multipath routes before congestion development can quickly resolve congestion in hot spot. Moreover, the BMR approach supports higher protection ability for the original path. It can find the alternate path quickly and isolate the failure effectively when congestion occurs. Furthermore, we conduct simulation study to validate and evaluate the proposed approach.

The rest of this paper is organized as follows. Section 2 presents the related work. Section 3 proposes the braided multipath routing (BMR) approach. Section 4 discusses the simulation results. Finally, Section 5 concludes this paper.

2. RELATED WORK

In this section, the important characteristics of WSNs are described. Then, the TARA approach and the multipath approaches are presented.

2.1 Characteristics of WSNs

There are several important characteristics of WSNs. These characteristics are traffic pattern, energy, bandwidth, buffer size, memory, processing capability, etc. We briefly described these characteristics as follows.

(1) Unbalanced and Redundant Traffic Data: When a lot of sensor nodes in an area detect events, the nodes transmit the sensory data toward the sink node(s). Thus, the unbalanced traffic is generated in the WSN. In other words, there are more upstream traffics (from sensors to sink) but less downstream traffics (from sink to sensors). Moreover, the congestion could develop around the sink node(s) since the sources suddenly inject high traffic volume in order to accurately depict and report the phenomena as soon as possible. Thus, the WSNs are characterized with high redundancy in the generated data. Although the data redundancy does help loosen the reliability/robustness requirements of data delivery, it might lead to network congestion.

(2) Limited Energy: One of the objectives of hardware design for WSN is how to save the energy in the tiny sensor node. The energy saved in the tiny sensor is not much due to hardware constraints. Moreover, the transmission power of radio is proportional to the square of the distance. If the sensor node is deployed closer to each other, the transmission power of radio can be reduced. However, the number of hops form source to sink is increased and the end-to-end transmission delay is also increased.

(3) Limited Bandwidth: The bandwidth constraint is one of resource constraints in WSNs. Generally speaking, a larger bandwidth is needed to support QoS of data transmission, since the burst traffic is a mixture of real-time and non-real-time traffic. As described above, the data redundancy might lead to reduce the bandwidth utilization. Thus, both the limited bandwidth and the data redundancy can cause serious congestion in WSNs.

(4) Limited Buffer Size: The other characteristics of sensor nodes are processing capability and storage space. When a data packet is received by the intermediate relaying node, the data is stored in the buffer and waits for relaying to the next hop. For the case of burst traffic in WSNs, most of data packets could be stored in the buffer and wait for relaying to the next hop. Furthermore, burst traffic may cause buffer overflow and then packet loss. It further results in data retransmission as well as serious congestion. Although to increase the buffer size can avoid the packet loss, it also increases queuing and processing delay. Thus, the buffer size is becoming a strict constraint in a WSN.

As presented in the above, to support QoS on data transmission in a WSN has to deal with the above characteristics of WSNs. Thus, congestion control must be investigated, so that the efficiency and throughput of a WSN can be improved.

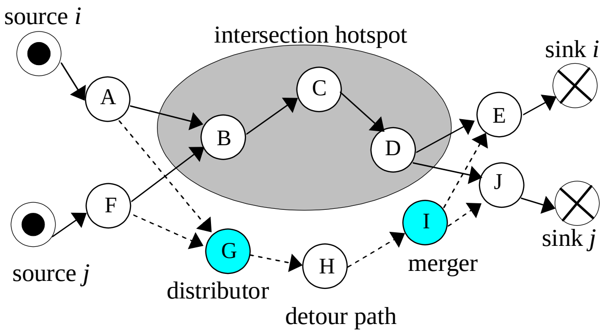

Fig. 1: Intersection hotspots and TARA approach

2.2 Topology-Aware Resource Adaptation Approach

Topology-Aware Resource Adaptation (TARA) approach, which is based on a resource control scheme, uses a capacity analysis model on resolving the needed topology and then increases route capacity and accommodates high incoming traffic during the emergent state. It detour the path to isolate the failure as the congestion occurred in the intersection hotspot is detected.

Figure 1 illustrates the intersection hotspot issue. Since the WSN contains multiple sinks and multiple sources, each source delivers data packets to the corresponding sink node, respectively. Thus, the traffic flows may coincide at the intersection nodes. And, the intersection nodes have to process and deliver more data packets and result in radio collision and network congestion.

When a WSN enters the crisis state and congestion occurs in the instersection nodes, the WSN has to respond the phenomenon as quickly as possible. TARA apporach finds a distributor node to detour the path away from congested area and then join the orginal path at a merger node. As shown in Fig. 1, the instersection hotspot occurs at node B and the disrtibutor, node G, will detour the path and merge the path at node J and node E. With the detour path, TARA can alleviate network congestion and improve network throughput.

2.3 Multipath Approaches

As discussed above, TARA approach builds a detour path and transmits the data packets via detour path toward the sink when congestion is detected. However, during the establishment of the detour path, data packets may be lost due to congestion and buffer overflow. Thus, to build alternate paths before congestion occurs is a possible approach to avoid packet loss. In literature, some multipath approaches were proposed. We briefly describe these approaches as follows.

(1) Disjoint Multipath (DJM) Approach: One type of multipath approaches is the Split Multipath Routing (SMR) protocol [5]. SMR approach could establish maximally disjoint paths which prevents congestion at the node under heavy traffic situations on a route. Moreover, it utilizes available network resources efficiently. The disjoint multipath is illustrated in Fig. 2-(a). Each path from source to sink does not cross each other and there is no interference among the paths. Thereafter, the congestion can be isolated well and quickly by transmitting data packets toward the sink through another path. The proposed disjoint multipath approach has some attractive resilience properties as discussed in [6]. However, its drawback is energy inefficiency since the alternate node-disjoint path is longer than the original path and, thus, consumes much energy.

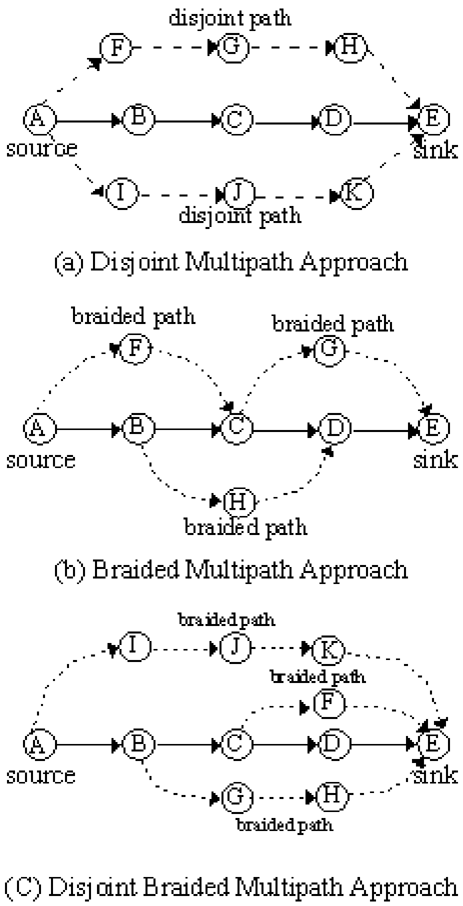

Fig. 2: Multipath approaches

(2) Braided Multipath (BMP) Approach: Another type of multipath approaches is the braided multipath routing [6]. The BMP approach can increase resilience to node failure. Figure 2-(b) illustrates the braided multipath approach. The BMP approach establishes multiple paths, which are partially disjoint from the original path. As shown in Fig. 2-(b), node A can send an alternate reinforcement to establish a route around node B that passes through node F and quickly rejoins the primary path at node C. Obviously, the DMP approach can establish several disjoint paths and can increase the resilience to node failure. However, it consumes much energy due to transmitting control packets. Furthermore, the braided multipath approach is more energy-efficient than the disjoint multipath approach. However, for the braided multipath approach (see Fig. 2-(b)), if both node B and node C are congested, the approach may fail to resolve the congestion quickly. So, the tolerance to node failure is degraded if two consecutive nodes are congested. Moreover, node B and node A are key nodes because the failures of the two nodes can result in the approach failure completely.

(3) Disjoint Braided Multipath (DBM) Approach: A disjoint and braided multipath (DBM) approach was proposed in [7]. Figure 2-(c) illustrates the DBM approach. If node D fails, node C can change the path to node F on alternate path. Similarly, when node C fails, node B can change the path through node G and H. Generally speaking, if any node on the primary path fails, there is an alternate path for delivering the data packets. For the serious case, which the three nodes (says, node B, C and D) fail at the same time, the data packet can be delivered successfully through the alternate paths. Note that the key nodes on the primary path are node B and I. Since the two key nodes fail simultaneously, the approach would fail. Furthermore, if node B fails, the path that consists of node B, C, D, F, G, H would fail to support data delivery and the resource is wasted. Generally speaking, the braided multipath approach has more alternate paths from source to sink but has lower failure tolerance. The disjoint and braided multipath approach has higher failure tolerance but pays much extra resource. In order to enhance the failure tolerance of braided multipath approach, we proposed a braided multipath routing (BMR) approach in Section 3.

3 BRAIDED MULTIPATH ROUTING (BMR) APPROACH

3.1 Proposed Braided Multipath Topology

The proposed BMR approach is illustrated in Fig. 3(a). The BMR approach builds an extra link on the alternate path between node F and node G. Similarly, node B and node F in the topology also introduce the key node problem. In other words, if the two nodes fail simultaneously, the approach would fail to resolve node failure problem when congestion occurs. On the other hand, it can create more paths from source to sink, so that the tolerance to node failure can be improved and the protection ability on

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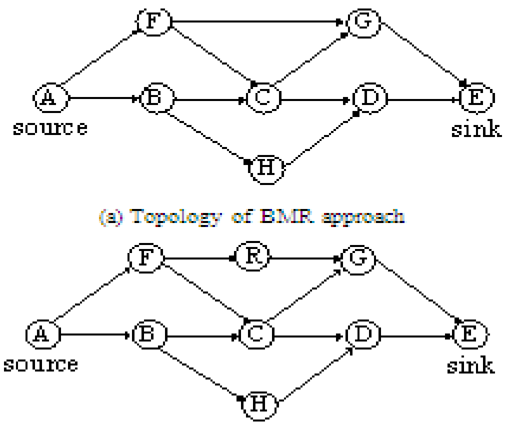


(a) Topology of BMR approach

(b) Another topology of BMR approach

Fig. 3: Proposed BMR approach

primary path is also improved with less cost. Besides, as the hop count of the primary path increases, it can establishes more alternate paths from source to sink.

In some case, it requires another node as a relay node to establish an extra link between node F and G due to the smaller radio range as shown in Figure 3(b). For this case node R is needed and must be located between node F and G to establish the two links from F to R and R to G. The node R is deployed between node F and G. Thus, the extra resource, i.e., one node and two links, are required for the WSN. If node F and G can communicate with each other and establish a link, the extra resource is just one link.

It is hard to verify the advantages of the proposed BMR approach directly by observing the topologies of BMR approach. The key contribution of BMR approach is that it can trade off the protection ability on the primary path and the required extra resources in terms of sensor nodes and communication links. In other words, the BMR approach can support more alternate paths with less extra resources. In the following subsection, we define some performance measures in order to compare the proposed BMR approach against the BMP and DBM approaches.

3.2Algorithm of BMR Approach

We present the algorithm of the proposed BMR approach as follows.

Step 1: Use general routing approach to create a route which is an important route to be protected from source node S to sink node D.

Step 2: S sends a control packet, LineUp, along the route to D. Each intermediate node between S and D records its sequence number and node address into the LineUp packet. As D receives the LineUP packet, D replies a ReplyLineUp, which stores the sequence number and address of each intermediate node to S.

Step 3: After receiving the ReplyLineUp, S sends CreateBraidedRoute in which the pairs of start and end nodes for each braided route are stored, to all intermediate nodes.

Step 4: Each start node makes use of the general routing approach to create a braided route to the end node. After creating the braided route, the end node replies the sequence number and address of the intermediate node(s) on the braided route to the start node. Then the start node resends this reply packet to S.

Step 5: After collecting all braided routes information from all start nodes, S sends ConnectBraidedRoutes in which the addresses of the head and tail nodes for connecting two braided routes are stored to the intermediate nodes of all braided routes.

Step 6: Each head node creates a route from itself to the tail node. Then the tail node replies the route information to the head node, which resends the information to S. Thus, all routes are created.

3.3Performance Analysis of BMR Approach

In order to measure and compare the performance of the BMP, DBM, and BMR approaches three performance metrics are proposed and defined as follows.

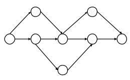
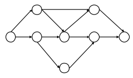
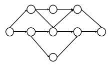
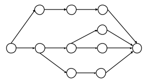
(1) Average Cost to Protect a Node/Link: The average cost to protect a node or a link for the braided multipath approach can be defined as follow.

$$C = \frac{n_e + l_e}{\sum_{i=1}^{a} (n_i^p + l_i^p)}, \qquad (1)$$

where n_e and l_e are the numbers of extra nodes and extra links, respectively, and a is the number of alternate paths and n_i^p and l_i^p are the numbers of nodes and links protected by the i-th alternate path. With the example shown in Fig. 3(a), the number of extra nodes and links is 10 and n_i^p and l_i^p for the five alternate paths are 1+2, 1+2, 2+4, 1+2 and 3+4, respectively. Thus, the cost for this case is 0.4545. Obviously, the smaller cost is preferred since the resource of a WSN is scarce.

(2) Average Protection Ability (AP) on Primary Path: Firstly, we assign a number, says i, to each node and link on the primary path as shown in Fig. 4. Moreover, the source and sink are assumed to be very robust so that they do not fail all the time. Let k denote the total number of nodes and links on the primary path from source to sink. And, n_i^a represents the total number of alternate paths for the i-th node if the i-th node on the primary path fails. Similarly, l_i^a represents the total number of alternate paths for the i-th link if the i-th link on the primary path fails. Thus, we can define the average protection (AP) ability acquired by each node and link on the primary path as follows.

Table 1: Comparison of four approaches

Approaches		Cost	AP	RPC
A		0.6	1.2857	2.1428
B		0.4545	1.8571	4.0860
C		0.5455	1.8571	3.4044
D		1	2.1429	2.1429

$$AP = \frac{\sum_{i=2,i+2}^{k-1} n_i^a + \sum_{i=1,i+2}^{k} l_i^a}{k}. \qquad (2)$$

The numbers of alternate paths for the link or node on the primary path shown in Fig. 4 are 1, 1, 3, 2, 3, 2, and 1. Thus, the average protection ability acquired by each node and link is 1.8571. Obviously, a better topology is with the higher AP value because more alternate paths are built for protecting each link or node on the primary path.

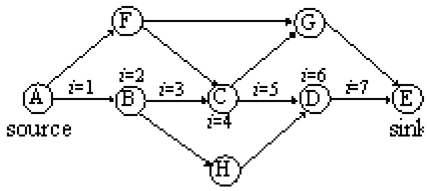


Fig. 4: Average protection ability

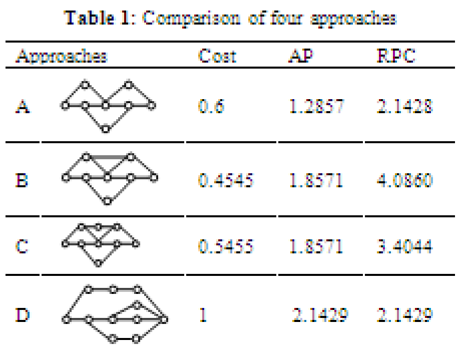


Table 1: Comparison of four approaches

Approaches		Cost	AP	RPC
A		0.6	1.2857	2.1428
B		0.4545	1.8571	4.0860
C		0.5455	1.8571	3.4044
D		1	2.1429	2.1429

(3) Ratio of Protection Ability to Cost (RPC): The goal of braided multipath approach is to construct a robust topology which can provide better average protection ability but make use of less resources (i.e., lower cost) to isolate failure and alleviate congestion. Thus, we define the ratio of protection ability to cost as follows.

$$RCP = \frac{AP}{C}. \qquad (3)$$

With the example shown in Fig. 4, the RPC is 4.086. Obviously, the higher the RPC value, the better the network topology.

With the above performance metrics, we can analyze and compare the different multipath approaches. Table 1 shows the comparison of the four braided multipath approaches. The proposed BMR approach (B and C) can achieve the better RPC values than BMP and DBM approaches. Moreover, if the total number of nodes and links on the primary path from source to sink increases, our analysis results also shows that the proposed BMR approach has higher RPC value than the other approaches. To further validate the analysis results, we conducted simulation study. In the following section, we present the simulation study.

4. SIMULATION STUDY

We conducted simulations experiments by making use of MATLAB to compare the performance of the four multipath approaches. The performance is measured in terms of C, AP, and RPC. And, two factors, which affect the performance, are considered in the simulation study. The two factors are node failure probability on primarily path and the path length between the sources and sink. In the simulation study, the braided multipath approach is denoted as approach A, the proposed BMR as approach B, the proposed BMR with the medium node as approach C, and the disjoint braided multipath as approach D. The simulation results are discussed as follows.

(1) Cost: In this simulation experiments, the hop count of the path from source and sink is 4. Figure 5 shows the cost, in terms of extra nodes and links, of the four multipath approaches. The cost of Approach D is the highest. It is obvious because Approach D establishes disjoint and braided multiple paths, which consist of more nodes and links. On the other hand, the cost of Approach B is the lowest among the four approaches. Moreover, suppose that the failure probability of the node on primary path rises. More extra nodes and links are required to isolate failure and alleviate congestion. So, the cost rises too. Figure 6 shows how the path length affects the cost. When the path length is lengthened, each multipath approach naturally requires more extra nodes and links to protect the primary path and prevent the congestion. The proposed approach B and C have better performance than approach A and D. Thus, the proposed BMR approach needs less extra nodes and links to construct the braided multiple paths than the BMP and DBM approach.

(2) Average Protection Ability on Primary Path: Generally speaking, the alternate path that can protect longer segment of the primary path can provide much protection on the primary path. And, the AP value represents the protection ability to isolate failure and alleviate congestion. Figure 7 shows the average protection abilities for the multipath approaches. The DBM approach is with the highest protection ability since it uses more extra nodes and links to protect the primary path. Although the proposed approach B and C have lower protection ability than approach D, their protection abilities are closer to approach D and higher

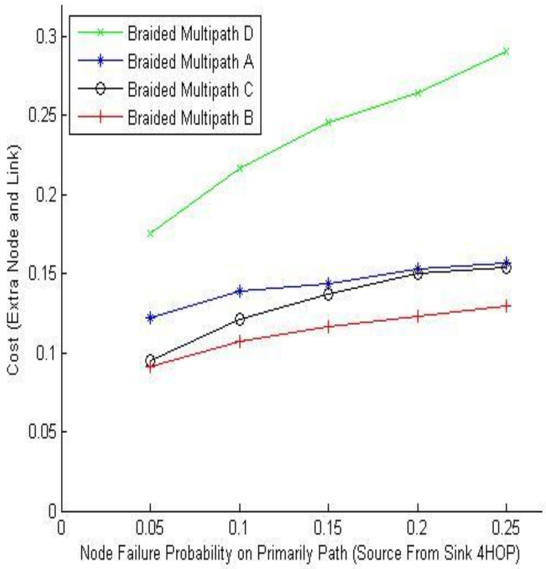


Fig 5: Cost vs. node failure probability

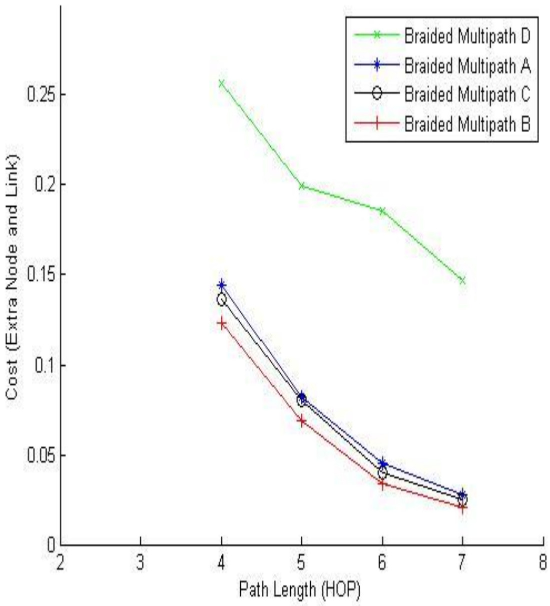


Fig. 6: Cost vs. path length

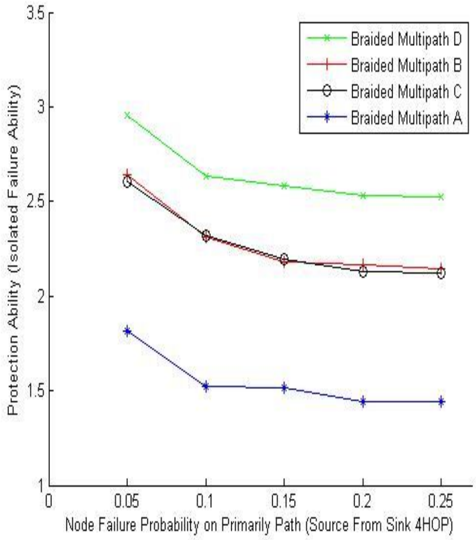


Fig. 7: AP vs. node failure probability

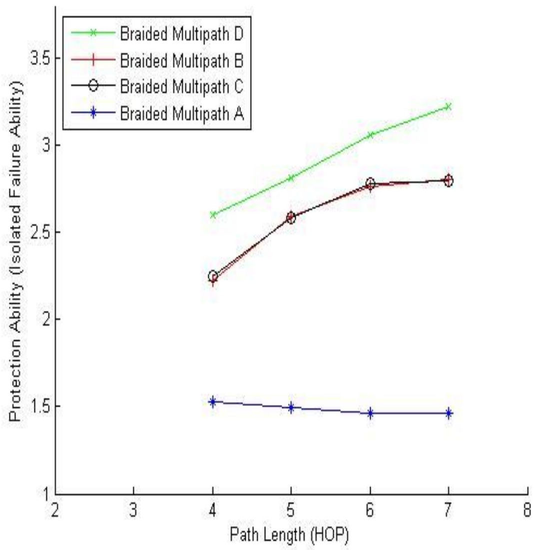


Fig. 8: AP vs. path length

than approach A. Furthermore, the simulation results show that the higher the node failure probability the lower the protection ability to isolate failure or alleviate congestion. This is because each multipath topology has the key node(s) problem. If the key node fails, the protection ability would degrade seriously. Figure 8 illustrates the relationship between the path length and protection ability. The longer the distance between source and sink the higher the protection ability to isolate failure and alleviate congestion. This is because there are more alternate paths to be used to protect the primary path.

(3) Ratio of Protection to Cost: Figure 9 shows the simulation results of the RPC values for the four multipath approaches. Approach B and C can provide higher RPC values than approach A and D do. Although approach D has the highest protection ability as shown in Fig. 7 and Fig. 8, it requires more extra nodes and links, so that the average protection ability contributed by each node and link for approach D is lower. If the node failure probability on the primary path rises, the key node failure probability rises too and the protection ability degrades accordingly. If the length of the primary path is lengthened, average protection ability contributed by each node and link decreases because more extra nodes and links are needed to establish the alternate paths as shown in Fig. 10.

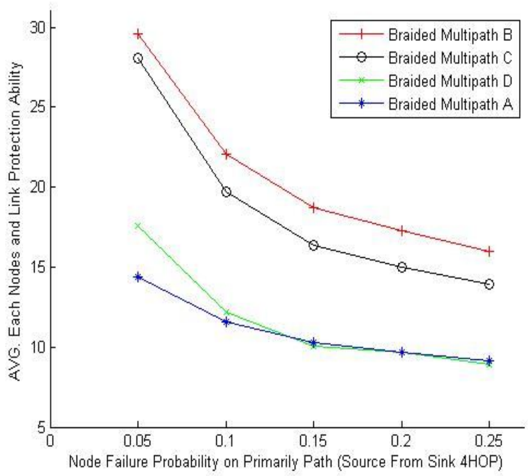


Fig 9: RPC vs. node failure probability

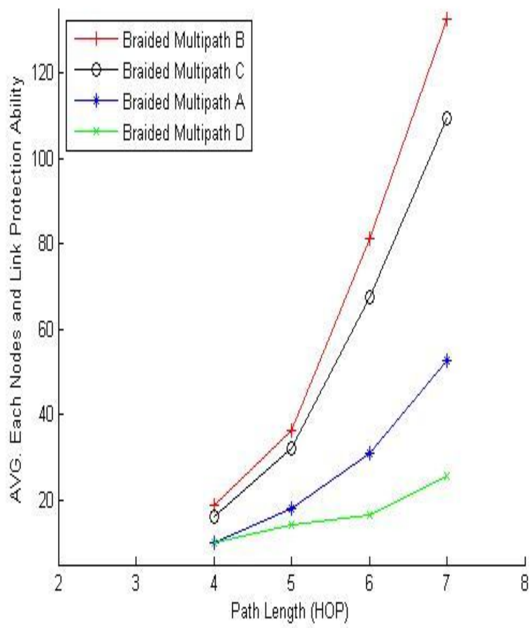


Fig. 10: RPC vs. path length

(4) Topology created by BMR approach: Figure 11 shows one of the topologies created by making use of proposed BMR approach in this simulation study.

From the above simulation results, the proposed approaches can achieve better protection ability per extra node and link than the other approaches. It spends less cost than BMP approach. Moreover, its protection ability is closer to the DBM approach. Although the DBM approach has the highest protection ability, it requires more extra nodes and links. Thus, the proposed BMR approach can achieve the better performance than the other approaches.

5. CONCLUSIONS

In recent years, Wireless Sensor Networks (WSNs) are employed as a promising platform on which versatile applications can be deployed. Several strict constraints, such as energy, memory space, processing capability,

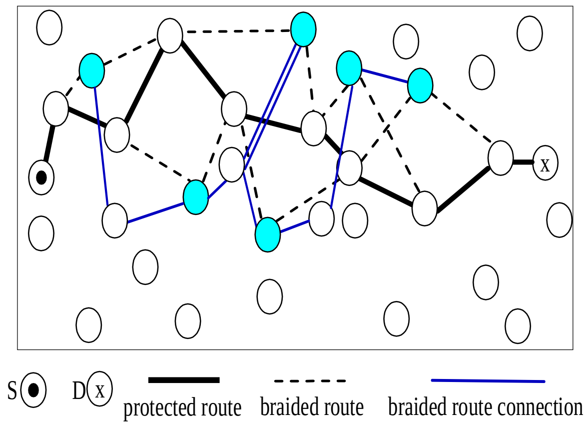


Fig. 11: A topology created by BMR approach

bandwidth, etc., must be considered as the applications are developed on WSNs. Due to unbalanced traffic and data redundancy in WSNs, congestion, a critical issue, may occur in the intersection hotspot. Thus, TARA approach was proposed to resolve the intersection hotspot issue. It reacts to congestion at intersection of two routes by making use of detour path. However, during establishing a detour, lots of data packets may be lost for TARA approach. Thus, in this paper, a braided multipath routing (BMR) approach is proposed to resolve the congestion quickly. The proposed BMR approach not only can react to congestion faster but also can isolate the node failure. In addition, three performance metrics were proposed and defined in order to analyze the four multipath approaches (i.e., BMP, DBM, BMR, and BMR with relay node). Moreover, simulation experiments by making use of MATLAB were conducted to validate and compare the performance of the four approaches. The simulation results show that the performance of BMR approach is better than those of the other multipath approaches. In other words, the proposed BMR approach can provide better protection ability with less extra nodes and links.

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AUTHOR

Chorng-Horng Yang received the B.S. degree in Electrical Engineering in 1992 from National Taiwan University of Science and Technology, and M.S. and Ph.D. degrees in Electrical Engineering from National Chung Cheng University, Taiwan, in 1994 and 2001, respectively. In 1999, he was a visiting scholar at the Ohio State University, USA; and from 2005 to 2007 he was the Chief of Networking Section of Computer Center in I-Shou University, Taiwan. He is currently an assistant professor at the Department of Information Management, I-Shou University. His research interests include information systems, wireless networks, performance analysis, and protocols.

Long-Wei Lin had graduated from the Department of Information Management, I-Shou University, Taiwan.

Chao-Wei Chou is currently an assistant professor at the Department of Information Management, I-Shou University, Taiwan.